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AN IN SITU EVALUATION OF SOIL WATER SENSORS

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ABSTRACT

This thesis presents the results of comparative in situ soil water measurements with several types of soil water sensors in Ascalon soils. The field location for these measurements was the Pawnee Intensive Site in northeastern Colorado which is a shortgrass prairie vegetative type. The sensors evaluated were the double-junction thermocouple psychrometer, Colman fiberglass electrical resistance units, cylindrical gypsum resistance units, and the neutron scattering device.

Four 1.45 m^2 calibration plots were identically instrumented with thermocouple psychrometers, Colman resistance units, and gypsum resistance units at soil depths of 2, 7, 15, 30, and 45 cm. In addition, three access tubes were installed in each plot for the neutron scattering probe. Three of these plots were subjected to artificial applications of water in addition to the natural precipitation. The fourth plot served as a control and received only natural precipitation.

The sensors in these plots were monitored on an intensive basis from June 13th through August 31st of 1973. The results indicate that the Colman and gypsum type resistance units can have significant lags in their responses to changes in the soil water status. This is especially true in dryer soil water conditions. Diurnal fluctuations in the soil water potential were measured with the thermocouple psychrometers. The corresponding resistance type sensors indicated little or no fluctuations in soil water status during the same period.

The soil water potential data obtained with the thermocouple psychrometers in the control plot had a close relationship to the growth stages or phenology of blue grama grass (Bouteloua gracilis) during the study period. These results pointed out the utility of using a combination of thermocouple psychrometers and the neutron probe for measuring plant-soil-water relationships.

A statistical correlation was used to test the possibility of an in situ calibration technique for either the Colman or gypsum resistance sensors with the thermocouple psychrometer. These results indicate that neither type of resistance sensor can reliably predict the soil water potential.

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TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

The investigation of soil water dynamics has been a major effort in the hydrologic process studies at the Pawnee Site, near Nunn, Colorado, U.S. International Biological Program (IBP). This information is useful in determining the water balance for a shortgrass prairie ecosystem and relating soil water to ecosystem processes. It has been pointed out by Striffler (1969) and others that water is a limiting factor in the productivity of this system. The over-riding importance of soil water particularly for plant growth, transpiration, and decomposition cannot be overemphasized.

In a general water balance equation of state, the following components are considered (Slatyer, 1967):

$$P - R - D - E \pm \Delta W = 0$$

where: P = precipitation

R = net runoff

D = drainage below the root zone

E = evapotranspiration

ΔW = changes of soil water content of root zone.

All components of this water balance have been monitored at the Pawnee Site on a regular basis since the summer of 1970.

The status of the soil water is usually expressed in one of two ways. The most common and direct measure is of concentration or soil water content (θ). This measurement can be used to describe soil water

on a gravimetric basis, in terms of weight of water per weight of oven dry soil; or on a volumetric basis which is the volume of water per unit volume of soil. Another measure of soil water is based on the energy status of the soil water.

Free energy is related to the forces acting on the soil water (gravitational, pressure, osmotic, and adsorptive). When expressed in terms of force, the free energy of soil water is often expressed as bars of water potential ($ergs/cm^3$). By definition, the water potential of pure water at atmospheric pressure and a given elevation is equal to zero. The potential of the soil water solution is less than zero or negative (Salisbury and Ross, 1969).

Different techniques for the measurement of soil water have been utilized on the IBP Pawnee Site study are for the monitoring of soil water phenomena. The continuous soil water measurement for the hydrology studies has been the neutron scattering technique. The neutron scattering technique measures the soil water content on a volumetric basis. Another technique in use for soil water measurement involves the measurement of electrical resistance within some matrix. The change of matrix resistance is a function of its water content. At the Pawnee Site, two types of resistance sensors are used, one has a gypsum matrix and the other one uses fiberglass. The matrix water content is a function of the soil matric potential (Kohnke, 1968). The matric potential is the adsorptive force between the soil particles and the water present.

Two other soil water sensors which have been utilized by the IBP are the thermocouple psychrometer and the tensionmeter. Both sensor

types give a direct measurement of water potential. The tensiometer has a 0 to -1 bar range and measures the soil matrix potential. Due to the limited measurement range of the tensiometer, it has only been utilized on irrigated plot studies at the Pawnee Site.

The thermocouple psychrometer, however, has been utilized along with many aspects of the IBP field studies (photosynthesis, respiration) and has not been restricted to just the hydrology studies. The psychrometer, in contrast to the tensiometer, has approximately a 0 to -60 bar range and can be used in a variety of field conditions. The psychrometer measures the total soil water potential.

The final method utilized for soil water measurement on the Pawnee have been the gravimetric techniques. This sampling method is a destructive technique since field samples must be taken to the laboratory to be weighed, then oven dried to constant weight (usually about 24 hours) at $105^{\circ}C$. The water content can be interpreted on a volume basis if bulk density values are obtained.

During the course of the IBP hydrology studies, some of the advantages and limitations of the different techniques for measuring soil water have become apparent. No one sensor or technique is the ultimate solution to all of the information needed about the status of the soil water. In addition, for practical reasons it is often necessary to convert soil water content to soil water potential and vice versa. For this reason, it was decided that a study to compare and evaluate the sensors in use on an in situ basis would be useful.

The objective of this study was to gain further insight about the responses of these sensors to soil water dynamics and to define their utility in studies of plant and soil water relations and soil water hydrology.

CHAPTER II

REVIEW OF LITERATURE

Much work has already been completed concerning the various hydrologic phenomena of the shortgrass prairie ecosystem. Striffler (1969) reported on the status of grassland hydrologic studies. In 1971, Galbraith reported on the "Soil Water Regime of a Shortgrass Prairie Ecosystem" and developed a water balance for the Pawnee Site research area. Van Haveren (1974) reported on "Soil Water Phenomena of a Shortgrass Prairie Site." The scope of this literature review is therefore confined to those techniques of soil water measurement which were evaluated in, or are related to the previous studies.

The Status of Water In Soils

Two types of information are generally needed in the study of soil water phenomena:

(a) the amount of water contained in the soil

and (b) the energy status of soil water.

While these are usually measured independently they are functionally related. This relationship is termed the soil water retention curve. This characteristic curve expresses the influence of many soil properties such as texture, porosity, pore size distribution, and adsorption on the state of soil water (Hillel, 1971). Hysteresis, related to whether the soil is wetting (sorption) or drying (desorption), is reflected in the soil water retention curve.

Volumetric Expressions

Soil is a disperse system of solids and voids. The mineral and organic compounds of soil form a solid matrix. The boundaries of the many irregularly shaped intersticial pores in soil are controlled by this matrix. That portion of the soil not occupied by the matrix is defined as the pore space or voids. These voids can be filled with soil air, water vapor, and liquid water. In a particular volume of soil (V) will be contained a volume of solids (V_s) , volume of water (V_w) , and volume of air and water vapor (V_a) such that:

$$V = V_s + V_w + V_a \quad \text{(Rose, 1966)}$$

Arbitrary conventions have been established to describe the water in soil. Saturation is defined as the point when all the pore space in a given volume of soil is completely occupied by liquid water. Field capacity is the soil water content after a thoroughly wetted volume of soil has been allowed to drain by gravitational forces for 1 to 3 days, (no evaporation). The water remaining in the soil at this point is considered capillary water since the bonding force is due to the adhesion of water to the soil matrix (matric potential). The field capacity of a given soil is highly dependent on the properties of the matrix and pore space geometry for that soil. Field capacity is considered to be the upper limit for water storage in the soil (-1/3 bar matric potential or greater) and is often referred to as a "constant." It is however, not an equilibrium condition.

The lower limit for soil water availability to plants is usually referred to as the "permanent wilting percentage." Briggs and Shantz

(1912) first defined this soil water value and called it the "wilting coefficient." They made this determination by growing plants in small containers until adequately developed. Then the containers were sealed and the plants allowed to deplete the soil water until wilting occurred. The plants were then placed in a humid environment overnight and again exposed to normal growing conditions the following day. If the plants did not regain turgor, then the permanent wilting point had been achieved and the soil water content was determined. Later investigations show that the permanent wilting point is reasonably approximated for many soils by the 15 bar percentage. Thus, it is common to use the water content at a matric potential of -15 bars as an estimation of the wilting percentage. This percentage has become a standard or "constant" for the lower limit of soil water availability for plants.

"Available soil water" became the term which expressed the total amount of soil water which is useful to plants. The upper limit for available soil water is field capacity and the lower limit is considered the permanent wilting percentage. The available soil water to plants for a given soil will be influenced by many factors. Soil porosity and pore geometry will regulate the amount of storage available for soil water. Soil texture will influence the water availability. As the soil clay content increases the "bound" water in the soil will be greater and water held in this manner is not readily available to plants (Kramer, 1969).

Due to the hysteretic behavior of soils a given water content may indicate a wide range of possible water potentials (or vice versa). The actual water potential that is associated with this single

measurement will depend on the condition of the soil at the time of measurement. If the soil has been undergoing drying conditions prior to the measurement, then the associated water potential may be less (more negative) than for the same water content if the soil had been wetting at the time of measurement (Cary and Taylor, 1967). Each soil has an ideal sorption (wetting) and desorption (drying) curve which relates the soil water content to soil water potential. However, between these two curves may lie an almost infinite set of "scanning" curves. These curves represent interruptions or reversals of the normal wetting or drying curves. There are several factors which may account for most of the hysteretic behavior of soils (Klute, 1969). These factors are the irregular pore geometry which causes the "inkbottle effect" (Figure 2.1), air entrapment during the sorption process, swelling and shrinking properties of the soil, and the contact-angle effect. The contact-angle effect is caused by the increased radius of curvature of an advancing miniscus by comparison to a receding miniscus.

Energy or Potential Expressions

At the present level of technology, there are two approaches to the measurement of soil water. One approach is the measurement of soil water content (θ) and the other is the measurement of the energy status of the soil water or soil water potential (Ψ). Due to the effects of hysteresis, a measurement of water content may or may not give a reliable prediction of soil water potential. In other words, a
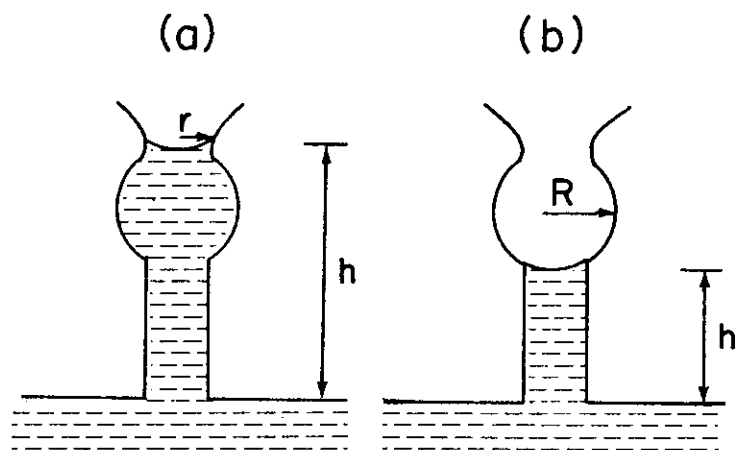
Figure 2.1. The "inkbottle" effect determines the equilibrium height of water in a variable width pore: (a) in capillary drainage (desorption); (b) in capillary rise (sorption) from (Hillel, 1971).

measurement of the amount of soil water available for growing plants may not give an accurate indication of the energy these plants have to expend to obtain water to meet their evapotranspiration needs.

The energy status of soil water is a thermodynamic relation that is based upon Gibbs free energy function (Brown and Van Haveren, 1972).

$$G_w = U - TS + PV$$

where: G_w = Gibbs free energy

U = internal energy of element

T = absolute temperature

S = entropy

P = pressure

V = volume

Slatyer (1967) shows the following derivations to obtain the soil water potential from the Gibbs free energy function. The differential form of the Gibbs equation is written as:

$$d\overline{G}_w = d\mu_w = -\overline{S}_w dT + \overline{V}_w + \sum \left(\frac{\delta \mu w}{\delta N_s}\right)_{nj} dN_s$$

where: $d\mu_w$ = partial molal Gibbs free energy of water

N_s = number of moles of solute whose chemical species changes

n_j = number of moles of solute whose chemical species does not change

In a non-swelling soil this equation has been rewritten to the form:

$$d\mu_w = \overline{V}_w dP - \overline{S}_w dT - \overline{V}_w \, d\tau - \overline{V}_w d\pi$$

where: $d\tau$ = matric pressure component

 $d\pi$ = osmotic pressure component

If the temperature is allowed to remain constant, but the soil system is changed from the condition of pure free water at atmospheric pressure to a condition where the pressure on the soil water is different, this change in state can be written as:

$$\Delta\mu_w = (\mu_w - \mu^0_w) = \overline{V}\Delta P - \overline{V}_w\Delta\tau - \overline{V}_w\Delta\pi$$

where: superscript $(^0)$ denotes the new molal GibLs free energy of water. This relationship now simplifies to

$$\frac{\Delta\mu w}{\overline{V}} = \psi = P - \tau - \pi \; \text{(Slatyer, 1967)}$$

where: ψ = water potential

An alternative notation is:

$$\psi = \psi_{soil} = \psi_p + \psi_m + \psi_s$$

where: ψ = total water potential

 ψ_{soil} = soil water potential

 ψ_p = pressure potential

$$\psi_m = \text{matric potential}$$

$$\psi_s = \text{solute potential}$$

The soil matric potential (ψ_m) is the force per unit area due to the capillary adhesion of the water present to the soil particles. Pressure potential (ψ_p) is the force per unit area due to any externally applied pressures on the soil water. Solute potential (ψ_s) is related to the osmotic pressure and is due to the presence of solutes in the soil water solution.

Soil water potential is the energy status of the water in the soil. In order to obtain water in the soil, the plant must maintain a potential gradient which will conduct water to the plant roots for assimilation. This water potential in the root system must be at least equal to or less than (more negative) the water potential of the surrounding soil. If this does not occur, the plant will wilt. This loss of gradient is often due to the depletion of soil water by evapotranspiration to the point that soil water potential exceeds the water potential of the plant tissues (Kramer, 1969).

The Measurement of Soil Water

Gravimetric Soil Water Measurement

Gravimetric methods are one of the oldest quantitative soil-water measurements. Russell used results from soil-moisture studies started at Rothamsted, England in 1843 (Russell, 1950). Gravimetric methods are still the most widely used approach for obtaining soil water records. It is a direct method for measuring soil water and is a calibration standard for many indirect methods of measurement (Lull and Reinhart, 1955).

The gravimetric technique consists of obtaining a field soil sample, usually with a coring tool. This sample is immediately placed in a container and sealed to prevent evaporative losses to the atmosphere. The sample is taken to the lab for weighing and is dried for 24 hours at 105 to $110^{\circ}C$. The sample is then reweighed and the weight loss due to drying is recorded (Millar, Turk, and Foth, 1965). The water content on a weight basis is expressed as a percentage, calculated from the formula:

$$\theta_{wt} = \frac{Wt\ Water}{Wt\ Soil}\ X\ 100$$

Some of the disadvantages to the gravimetric approach are the time and labor required in sampling. Repeated sampling destroys the experimental area. For continuous soil water records, there is an inherent sample variation because a new sample must be obtained at each sample date.

A modification of the gravimetric technique to infer water potential is the filter paper method. In this approach, a filter paper whose weight has been calibrated with solutions which have different water potentials is placed in a container with the soil sample, sealed, and allowed to come to vapor equilibrium. The filter paper is then removed and weighed to infer the sample water potential using the calibration relation (McQueen and Miller, 1968).

Measurement of Soil Water with Electrical Resistance

The electrical resistance of various porous media inserted in the soil has found much use as an in situ means of following soil water

status changes at a particular point in the soil profile. The resistance of the porous media can then be measured with some form of wheatstone bridge. This idea was first put to use by the Department of Agriculture in 1896 (Whitney, 1896-1899). The results of this study were inconclusive because resistance was measured between two electrodes and the surrounding soil particles to give an unreliable measurement of the soil water status.

The first successful device was developed by Bouyoucos and Mick (1940). The unit introduced by Bouyoucos and Mick consisted of two electrodes embedded in a porous plaster-of-Paris block. The block can be placed at any depth in the soil and insulated wires lead from it to the surface. The resistance of the porous block is a function of its water content which in turn depends on (Taylor, Evans, and Kemper, 1961):

    (a)   the relative affinity of the soil and porous material for water,

    (b)   the amount of water present,

    (c)   the rate that water transfer can be made from one material to the other,

and   (d)   the electrical conductivity of the water or solution that is within the influence of the electrodes.

A more recent modification of this design consists of two concentric circular stainless steel screen electrodes embedded in plaster-of-Paris (Figure 2.2). This configuration helps to confine the resistance measurement within the block. The modification helps eliminate the effects of the soil-block contact and nature of the soil itself on the measured resistance (Bouyoucos, 1956).
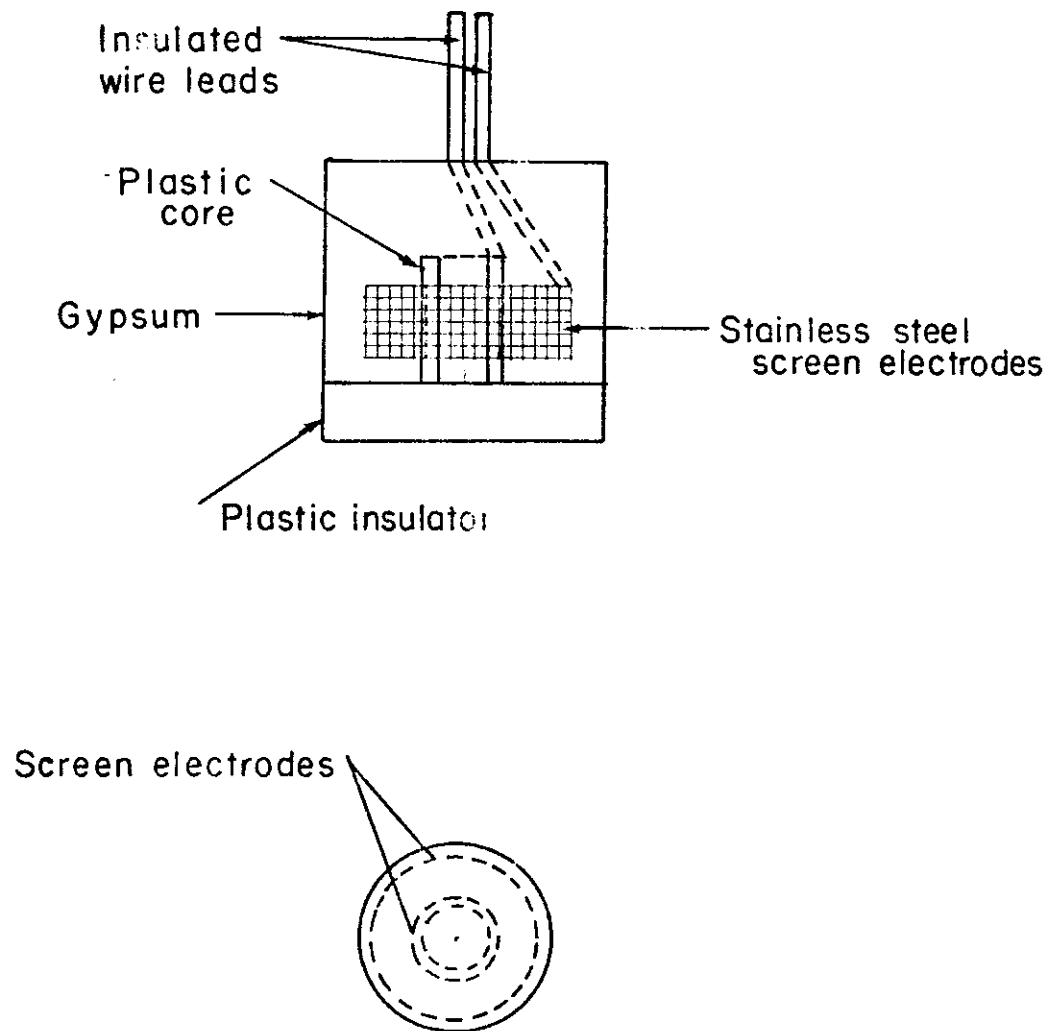
Figure 2.2. The cylindrical gypsum resistance block.

In 1949, Colman and Hendrix introduced a fiberglass electrical resistance unit (Colman and Hendrix, 1949). This unit consists of two monel screen electrodes separated by and wrapped in a fiberglass cloth matrix (Figure 2.3). This sandwich is then enclosed in a metal case which serves as a shield to the elements. The case minimizes the tendancy for electrical currents to move through the soil surrounding the unit.

Both the Bouyoucous or gypsum blocks and the Colman units tend to equilibrate with the soil matric potential (Aitchison and Butler, 1951). This potential is the attraction of the soil matrix or particles for the water present. Therefore, it is appropriate to calibrate these units against soil matric potential and not the soil water content. This is especially true when using disturbed soil samples for the calibration (Hendrix and Colman, 1951).

The conductivity of the matrix in a resistance type soil water sensor is a function of the fluid present. If electrolytic solutes are present in the soil water, the conductivity will be increased and the resistance will be decreased within the matrix. Blocks which have a plaster-of-Paris (gypsum) matrix maintain an electrolyte concentration corresponding to that of a saturated calcium sulfate solution. The fiberglass or Colman unit, however, has an inert matrix (primarily silica) and no buffer is available in the unit. Salt concentrations in the soil water of 1000 ppm can have a pronounced effect on this sensor and the resolution will be greatly reduced (Ewart and Baver, 1950). A new unit has been introduced that has a nylon matrix and is similar in design to the Colman unit. This unit, however, has a gypsum

**Electrode Sandwich
Wrapping Diagram**
(End view, schematic)

Fiberglass

Screens

Assembly View
(Electrode Sandwich cut-away.
Top half-case removed)

Fiberglass

Screens

Waterproof
coating
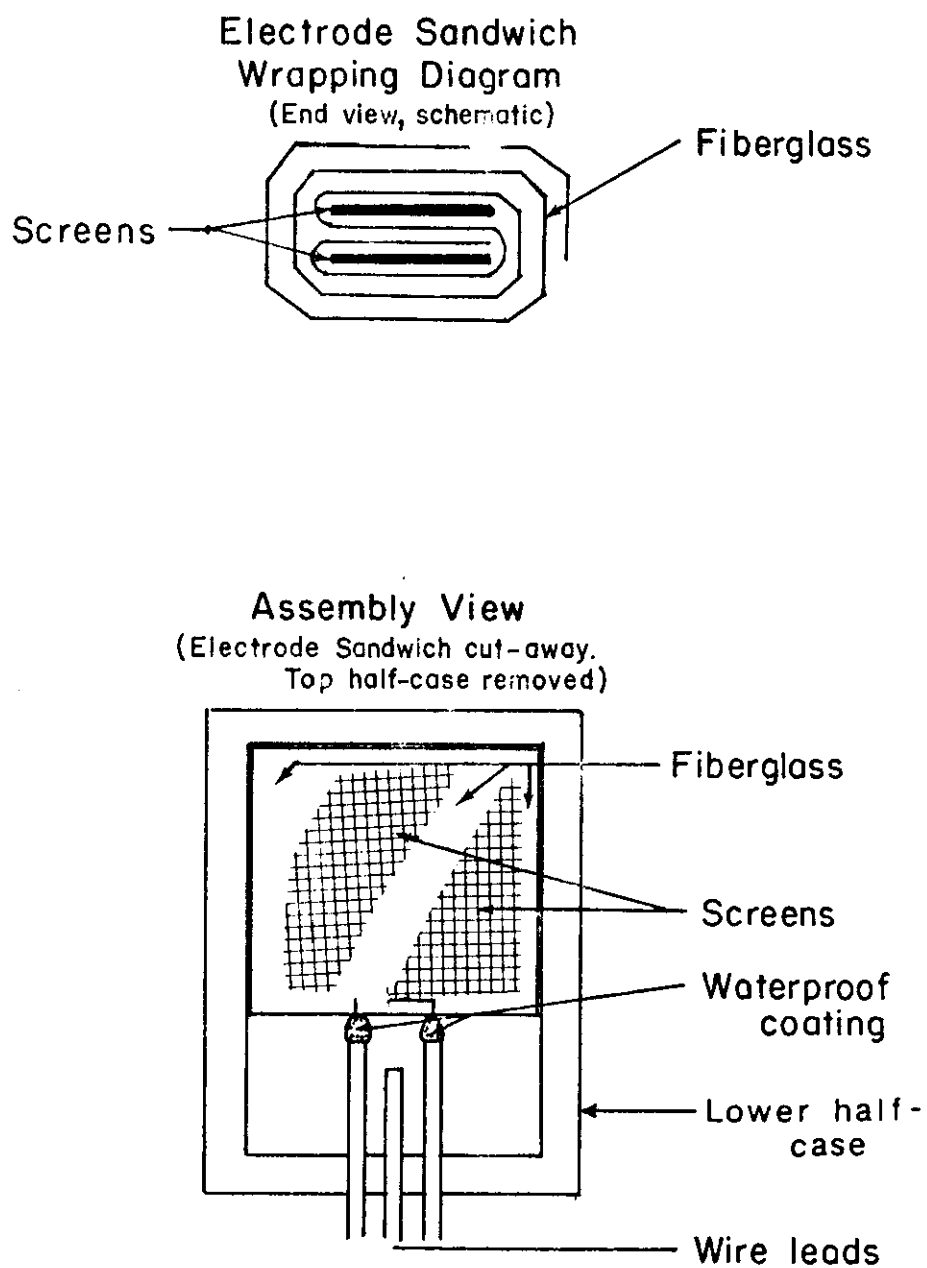
Lower half-
case

Wire leads

Figure 2.3. The Colman fiberglass electrical resistance unit.

impregnated nylon matrix which will tend to offset the adverse effects of salts in the soil water solution (Bouyoucos, 1973).

Salt and hysteresis effects are the main descrepancies in soil water measurement with the electrical resistance method. The accuracy of these units is affected by four main factors which are:

(a) magnitude of hysteresis in the unit,

(b) uniformity of the units (unless individually calibrated),

(c) sensitivity,

and (d) deterioration (aging of the units).

The electrical resistance is higher and the moisture content lower at a given tension on a wetting scanning curve than the corresponding resistance for the same water content in a drying scanning curve (Bourget, Elrick, and Tanner, 1958).

The fiberglass units normally have a greater range of operation than the gypsum block. However, both sensors have poor resolution at higher soil water contents (field capacity to saturation) due to the corresponding small change in resistance in this range (Johnson, 1962). The greater mass of the gypsum block causes it to be influenced to a greater extent by hysteresis than the more compact fiberglass unit. Another problem with electrical resistance units is the soil-sensor interface. If the unit is not in adequate contact with soil, there will be abnormal lag in response to the soil water phenomena.

A temperature measurement is necessary for electrical resistance units to obtain a precise resistance since temperature has a direct effect on resistance readings (Colman, 1946).

Measurement of Soil Water with Thermocouple Psychrometers

In 1951, D. C. Spanner introduced a revolutionary instrument for the measurement of water potential (Spanner, 1951). This instrument, the thermocouple psychrometer, is capable of measuring different water potentials as a microvolt (μV) output. This sensor is useful in a water potential range from 0 to -60 bars.

The thermocouple circuit has two bimetrallic junctions, one of which is maintained at a known temperature and is called a reference junction. When the measuring junction is heated or cooled to a temperature other than that of the reference junction, an electromotive force is created in the circuit. The electromotive force (EMF) will be in proportion to the difference in electrical potential of the two junctions due to their temperature differential. The EMF will increase linearly with the temperature difference and will move from the wire of higher electrical potential. With a chromel-P and constantan junction constructed from 40 gauge wire, a $1^{\circ}C$ temperature difference between the reference and measuring junctions will produce an EMF of approximately 60 μV (Hoffman and Herkelrath, 1968). Therefore, a small thermocouple is capable of measuring very minute temperature differentials.

The thermocouple junction has been adapted to psychrometric measurements in the following manner. When a droplet of water is placed on the measuring junction, a temperature change will correspond to the wet bulb depression of a sling psychrometer used in the measurement of relative humidity. Water potential can be related to relative humidity in the following formula (Rawlins, 1965):

$$\Psi = \frac{RT}{V} \ln R.\,H.$$

where: R = gas law constant

          T = temperature in degrees Kelvin

          V = molar volume of water

      $R.H.$ = relative humidity

          Ψ = water potential (-bars)

The thermocouple psychrometer requires no complex computation to obtain the soil water potential. If the ambient temperature is constant throughout the measurement range (0 to -60 bars), then the resulting EMF produced by wet junction cooling should be constant for any given potential in this range. Therefore, a thermocouple psychrometer can be used to give the water potential of unknown materials such as soil once the unit has been calibrated over solutions of known water potential. Preferably, a multi-point calibration curve should be established but a one-point calibration is theoretically possible since the thermocouple has a fairly linear response to decreasing water potentials (Wiebe, et al., 1971).

There are currently two basic types of thermocouple psychrometers in use. One is the Richards or droplet type and the other is the Peltier or Spanner type psychrometer (Lang and Trickett, 1965). The Richards or droplet psychrometer is a laboratory instrument which must have a water droplet manually placed on the measuring junction before a water potential reading is made. A precise temperature control and a sample chamber is required for the Richards psychrometer.

The Spanner psychrometer uses a unique feature of bimetallic thermocouple junctions, the Peltier effect. When a current is introduced through a thermocouple circuit one junction will be heated while the other cools. More specifically, if the current is passed through the measuring junction from the negative potential wire (constantan) to the positive potential wire (chromel-P) cooling will occur at the measuring junction (CRC handbook, 1964-65). Since the relative mass of the reference junction is many times that of the measuring junction, a significant cooling affect at the measuring junction will have relatively no temperature effect on the reference junction. Thus, at high relative humidities (95-100%) Peltier cooling can be utilized to lower the measuring junction to the dewpoint temperature so that a droplet of water can be formed on its surface. The thermocouple is then switched to a galvanometer and the resulting EMF produced by the droplet evaporation corresponds to the chamber relative humidity and therefore the soil water potential.

For the in situ measurement of soil water potential, a precise temperature control is not necessary with the Spanner psychrometer. Wiebe et. al. (1970) found that a $\pm 4^{o}$C/hr. temperature change caused an error of only +0.3 bar during cooling and -0.3 bar during the warming cycle. When temperature control is not used a temperature measurement must be obtained at the time of reading. A temperature measurement is required due to the effects of temperature on psychrometer output (Campbell and Gardner, 1971). This reading can then be used to correct the thermocouple psychrometer output. In this approach, temperature effects on psychrometer readings can be minimized.

Neutron Scattering

The neutron scattering method for soil water measurement was first developed in the early 1950's (Belcher, Cuykendall, and Sack, 1950). The neutron moisture meter is composed of two main parts:

(a) a source of fast neutrons, in a probe which is lowered into a soil access tube

(b) a scaler or ratemeter to monitor the flux of slow neutrons, which is proportional to the soil water content (Hillel, 1971)

In principal, the measurement of the soil water content with the neutron scattering method is not too complicated. As described by Hillel (1971), fast neutrons are emitted radially into the soil from the source. These neutrons collide elastically with other atomic nucleii and gradually lose some of their kinetic energy. This loss is maximal when a neutron collides with a particle of mass nearly equal to its own. One such particle is the hydrogen nucleii of water (Weinberg and Wigner, 1958). In soils it has been found that the attenuation of fast neutrons is proportional to the hydrogen content of the soil. Slower thermal neutrons scatter randomly in the soil forming a cloud. Some of the thermal neutrons return to the probe where they are counted by a slow neutron detector tube which emits a pulse for each encounter. The scaler then measures the number of pulses as a function of time.

The radius of the sphere of influence of a neutron source is dependent on the source strength and the soil water content (Van Bavel, Underwood, and Swanson, 1956). This makes the neutron probe very useful for measuring the average water content of that volume of soil in this sphere of influence. However, near the atmosphere-soil

interface there will be an error in measurement due to the loss of neutrons into the atmosphere. Lawless, Mac Gillivray, and Nixon (1963) found that the neutron probe underestimates the water content near the soil surface. The magnitude of this error is dependent upon the soil water content near the surface. The effect extends deepest in dry soil, to as much as 45 cm or more. The absolute error is greatest in wet soil, where it may exceed 2 cm of soil water. Neutron probes also tend to underestimate the soil water contents of stratified soil water profiles.

CHAPTER III

STUDY AREA

The International Biological Program, Grasslands Biome

The US/IBP Grassland Biome Program (IBP) was initiated in 1968.
The goal of the IBP is to investigate, "the biological basis of pro-
ductivity in human welfare," (Van Dyne, 1969). A systems approach was
chosen for the Grassland Biome ecosystem research. The flux of energy
and the cycling of water and nutrients will be related to the producer,
consumer, decomposer, and abiotic components of the ecosystem. A
systems analysis is the main technique of processing the information
gathered by the many individual studies. A major result of this
research is the Ecosystem Level Model (ELM) which incorporates the many
constituents of the ecosystem into a mathematical model so that a better
understanding of the interaction of the different trophic levels can
be achieved.

The Pawnee Site Experimental Area

The Grasslands Biome has utilized both comprehensive and intensive
research areas located in different types of grasslands. The Pawnee
Site is the intensive site where the most detailed ecosystem level
research has been conducted.

Location

The Pawnee Site is located in northeastern Colorado approximately
56 km northeast of Fort Collins and 40 km north of Greeley. This site

is located on the westernmost portion of the 46,540 ha Pawnee National Grasslands which is administered by the U.S. Forest Service. The land which is used for IBP studies is a portion of the Central Plains Experimental Range, administered by the Agricultural Research Service (ARS). The experimental range is located on the extreme western edge of the Pawnee National Grasslands. The ARS rangeland has been utilized for grazing intensity research since 1940.

Climate

The climatic regime of the Pawnee Grasslands is continental and the climatic classification cool steppe (Rasmussen, Bertolin, and Almeyda, 1971). Continental climates characteristically have large annual temperature fluctuations and low precipitation. The 30 year average annual precipitation for the Pawnee is approximately 300 mm (12 inches). The average annual temperature is $8.3^{\circ}C$ ($47^{\circ}F$) for the Pawnee.

A major climatic influence for the Pawnee Site is the rain-shadow effect created by the Rocky Mountains which lie about 50 km west of the grasslands. The prevailing winds in this region are westerlies and as a result most major winter storm systems which move across the Pawnee Grasslands must first ascend the Continental Divide. Orographic lifting cools these eastbound moist air masses. This orographic effect essentially removes most of the precipitable moisture from these air masses before they reach the Pawnee Grasslands.

The primary source of moist air for the Pawnee is the Gulf of Mexico, 1600 km to the south. In the summer, a high pressure system is established over the Atlantic Ocean. This system occasionally allows a northerly flow of moisture laden air from the Gulf of Mexico. This moisture is usually precipitated by convective thunderstorms during the growing season. These storms are highly variable in their intensity and areal distribution. As a result, the ARS 30 year precipitation records have varied from an annual minimum of 110 mm (4.3 inches) in 1964 to a maximum of 582 mm (22.9 inches) in 1967. The seasonal distribution of precipitation is less variable with approximately 80% of the annual rainfall occurring between April and October (Galbraith, 1971). Snowfall accounts for 10 to 15% of the annual precipitation on the Pawnee Grasslands (Van Haveren, 1974). A storm probability analysis by Bertolin and Rasmussen (1969) shows that annual rainfall is closely correlated to the prcipitation events of approximately 25 mm (1 inch) or greater during the April to October period. Most of the annual precipitation occurs from a few major storms which are primarily frontal.

Physiography

The Pawnee Site is located on the northern edge of the Colorado Piedmont. The relief is generally less than 100 m and the topography is flat to gently undulating. Elevations for the Pawnee National Grasslands are between 1500 and 1800 m (4900 and 5900 feet) above sea level.

Drainage of this region is in a southeasterly direction. Most major streams in the area are intermittent and a few closed drainage basins exist. Small shallow potholes are present which are occasionally filled with water whenever runoff producing storms occur. These low lying areas appear to have little or no internal drainage due to high soil clay contents and most of the runoff collected in them is subsequently lost to evaporation. The presence of potholes and deflation basins indicate aeolian erosion and deposition.

Bedrock in the region is a part of the Pierre formation which consists of interbedded sandstones and shales. Most of the soil parent material on the lower slopes is alluvial in origin.

Soils

There are four major soil series and six major types present within the Pawnee Intensive Site. The differences in these series are apparently related to the type of parent material from which each series has developed (Van Haveren, 1974). Of the four series, the Ascalon soil series is the most widespread in the study area.

The Ascalon series is derived from fluvial outwash parent material. This soil is texturally classified as a fine sandy loam and in the Seventh Approximation classification is a member of the fine loamy, mixed, mesic family of Aridic Argiustolls formed from fluvial outwash materials. Van Haveren and Galbraith (1971) found a mean surface bulk density of 1.42 $(gm\ cm^{-3})$ for the Ascalon soils. The mean A horizon texture (0 to 15 cm) was 69% sand, 14% silt, and 17%

clay. The mean B horizon texture (16 to 45 cm) was 60% sand, 15% silt, and 25% clay. Soil structure is granular at the surface. Structure changes from subangular blocky in the B2 horizon to massive in the parent material. Soil pH ranges from 7.0 at the surface to 8.2 (basic) in the parent material. At depths of 50 cm or greater deposits of calcium carbonate are often visible. Soluble salts are low in the surface layers with specific conductance generally less than 1 millimho per cm.

The Ascalon soils have relatively high infiltration rates and good internal drainage. Rauzi and Smith (1972) found that the infiltration rate was primarily influenced by soils during the first 10 minutes of infiltration. After 15 minutes, grazing and soil effects are important. Sundberg and Smith (unpublished data) found that the Philips' equation adequately accounted for the wetting front movements during these tests.

Vegetation

The vegetation association of the Pawnee Grasslands is classified as a shortgrass prairie. It has been demonstrated that shortgrass prairie can be derived from mixed grass prairie due to grazing effects. This situation led Weaver and Clements (1938) to classify the shortgrass prairie as a grazing disclimax of the mixedgrass association. However, there are also climatic limitations that can and do fix shortgrass prairie over a large area of the Central Great Plains (Hyder, 1969).

The obvious climatic differences between the shortgrass and mixedgrass prairie types are the amounts of precipitation received in

the fall, winter, and spring. High precipitation during these three seasons coupled with less favorable summer precipitation tends to favor the cool season grasses and forbs. Cool season plant species are the predominate species in the mixedgrass prairie association. At the Pawnee Site, the major portion of the precipitation is received during the summer. This timing of precipitation tends to favor warm season plants which are the major constituents of a shortgrass prairie ecosystem. Cool season plants are present in this system but due to the less favorable moisture conditions in early spring and late fall their frequency of occurance is much lower than in a mixedgrass community (Hyder, 1974).

The structure of the shortgrass prairie is relatively simple and uniform. At the Pawnee Site, over 300 species of vascular plants have been identified, so composition can be fairly diverse. The average vegetation height is 5 cm. The sod is discontinuous which is a major feature of the plant distribution. However, even under bare soil surfaces there is a well developed root system.

The major plant species by frequency of occurence are blue grama (Bouteloua gracilis), buffalograss (Buchloe dactyloides), and plains pricklypear (Opuntia polyacantha). Blue grama and buffalograss are perennial warm season grasses while the plains pricklypear is a warm season cactus.

CHAPTER IV

METHODS

Experimental Design

Three primary objectives were used as guidelines for the experimental design. The first was to obtain simultaneous readings of thermocouple psychrometers, Colman units, and gypsum resistance units at each soil measurement depth. This sampling method would provide information about the responses of the different sensors to the same soil water conditions. The second goal was to obtain this data over a wide range of soil water conditions to determine the relative range and accuracy of the three sensors. This was accomplished using irrigated plots. The third objective was to obtain a continuous record of the various sensor readings at different soil depths during the period of field study. This record would provide information about the changes in the soil water status through the growing season.

The primary method for collecting abiotic data for the eco-system research conducted at the Pawnee Site has been through the use of automated tape systems. However, very little soil water data has been obtained by this method. The reason for this was the inherent problem of reliably interfacing soil water sensors to a data acquisition system. Soil water content has been manually monitored using the neutron probe.

Thermocouple psychrometers offer the most useful measurement of soil water for plant growth studies, namely the soil water potential

(Ψ) . The psychrometer is basically simple in design and operation. However, the electronic equipment necessary to operate and record psychrometer readings automatically from a remote location is very expensive, complex, and often unreliable.

Resistance-type soil water sensors are easily interfaced for automatic data acquisition but their readings cannot be directly interpreted as a soil water potential without extensive calibration. Therefore, one of the objectives of the study was to determine if the resistance units could be adequately correlated with the soil water potential as measured with the thermocouple psychrometer. If so, the resistance units could then be automatically read to avoid the complex switching and interfacing materials needed for the automation of thermocouple psychrometers.

Four calibration plots (1.45 m^2) were located on the Ascalon sandy loam soil, the major soil type of the Pawnee Site. These plots were all within the grazing exclosure at the IBP lysimeter. Each plot was identically instrumented with thermocouple psychrometers, Colman resistance units, cylindrical gypsum resistance blocks, and 1% YSI (Yellow Springs Instruments) thermisters (1,000 ohms @ 25°C). This series of sensors was embedded at depths of 2, 7, 15, 30, and 45 cm in the wall of a 15 cm diameter auger hole. The auger hole was at the center of each plot. The sensors were placed in a spiral pattern so their location would not impede the movement of water to other sensors at lower depths (Figures 4.1a, 4.1b).

A section of 11 cm diameter poly vinyl chloride (PVC) irrigation pipe was placed in the auger hole to serve as an access tube and
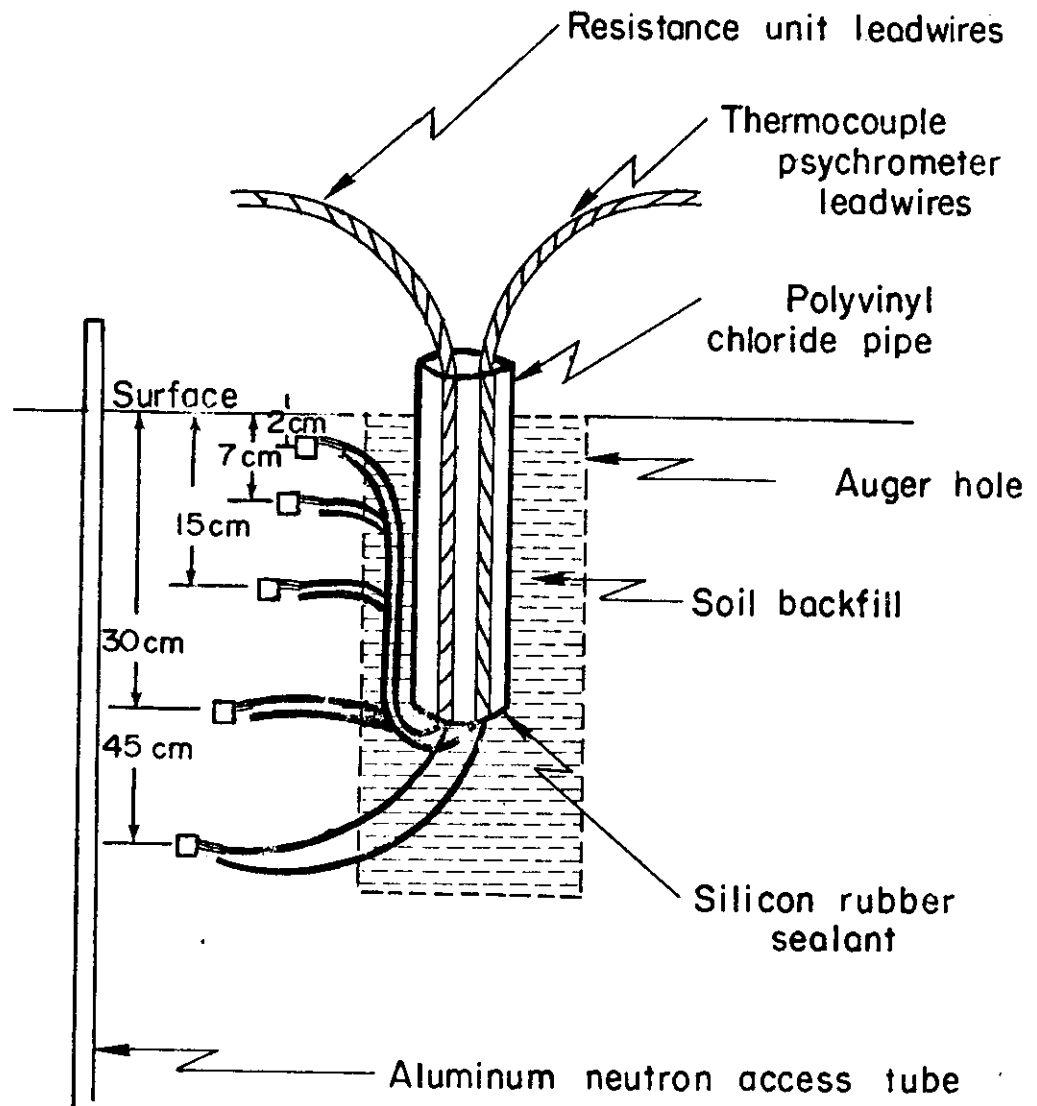
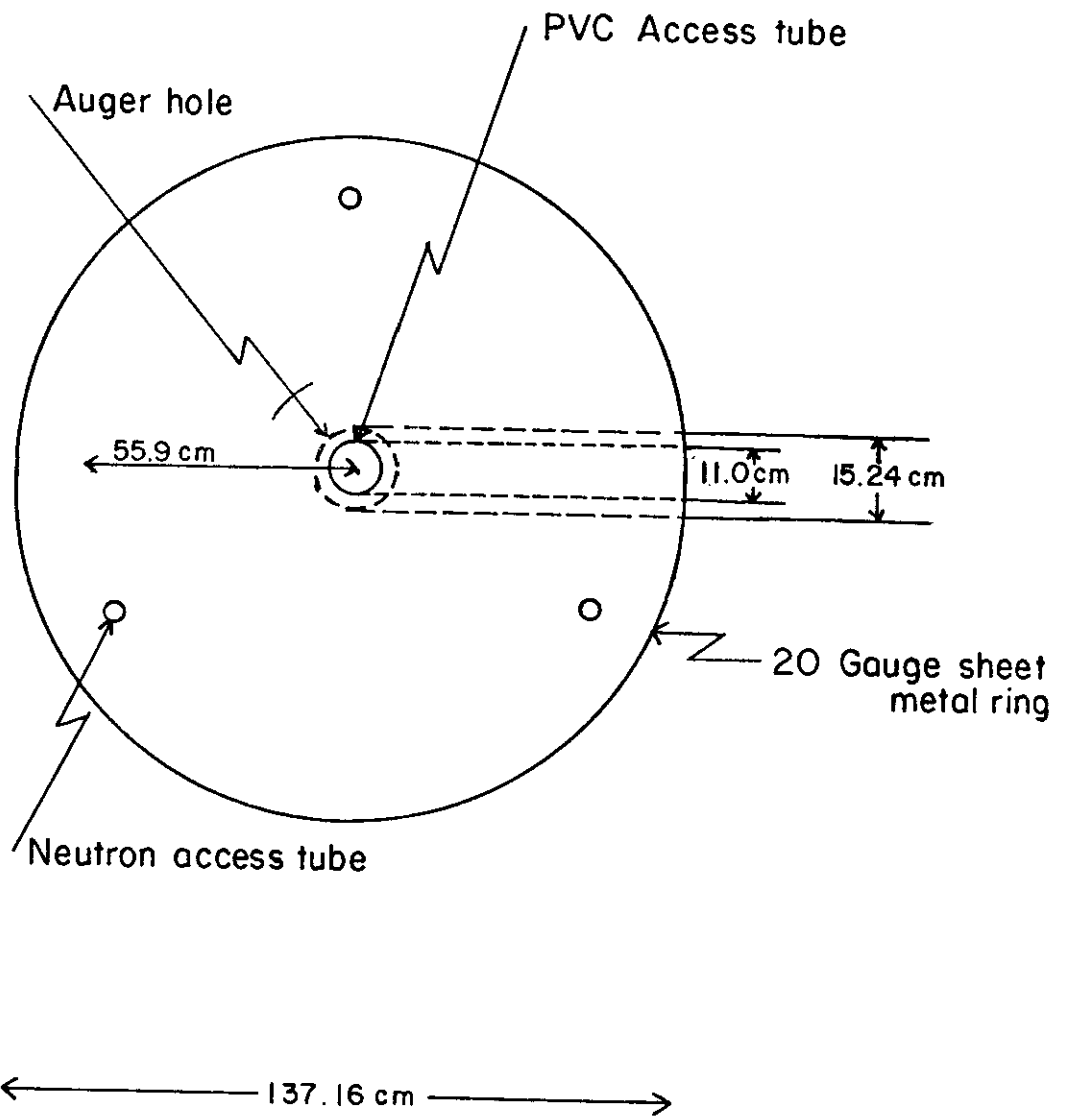Figure 4.1a. Side view of calibration plot installation.

Figure 4.1b. Plan view of the calibration plots.

storage container for the sensor lead wires. All of the psychrometer leads in each plot were given additional thermal shielding and strength with a length of flexible PVC tubing. The auger hole was backfilled with soil around the pipe. The lower opening of the pipe was sealed with silicon rubber sealant. The top of the pipe was covered with a removable PVC cap. The backfill soil in the auger hole was compacted to a bulk density similar to the surrounding undisturbed soil profile. The reason for compaction was to minimize abnormal infiltration rates or percolation in the disturbed soil. Higher rates of water movement in this backfilled area could lead to lateral movement of water to the sensors and create an artificial effect on the timing of sensor responses to changes in the soil water status.

At a distance of approximately 56 cm from the center of each plot three aluminum neutron access tubes were installed in a triangular pattern. Tubes were installed with the use of a truck-mounted coring tool and the cores were saved for determination of the soil bulk density for each plot. Due to the dryness of the soil at the time of installation, tube depth varied between 120 and 180 cm.

Each of the four plots was encircled with a 30 cm high 20 gauge sheet metal cylinder with a radius from the plot center of 68 cm (Figure 4.2a). The cylinders were driven approximately 5 cm into the soil to serve as a barrier to prevent trampling and as a support for a drip pan used for artificial precipitation applications (Figure 4.2b). This pan had a radius of 75 cm with a bottom perforated with 1.6 mm drill holes in a 2.54 cm grid spacing.
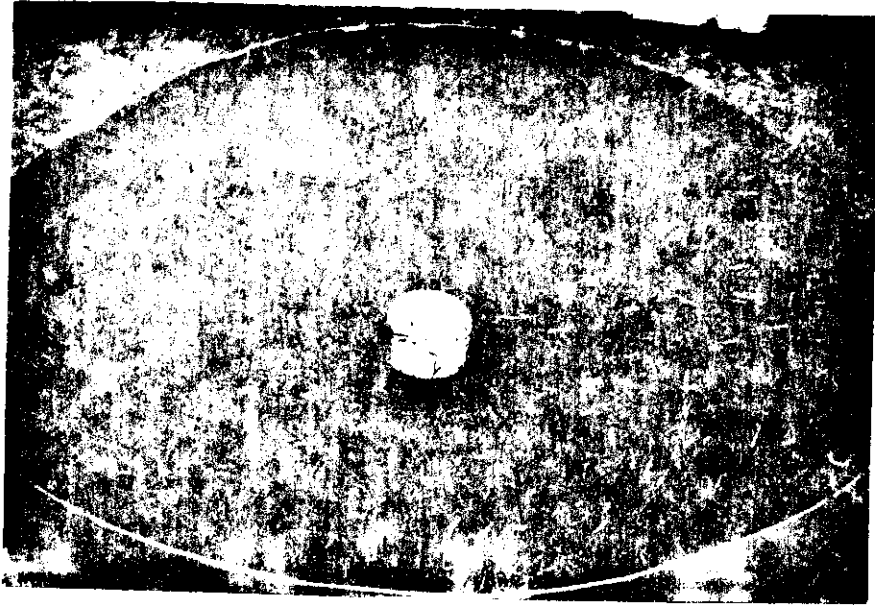
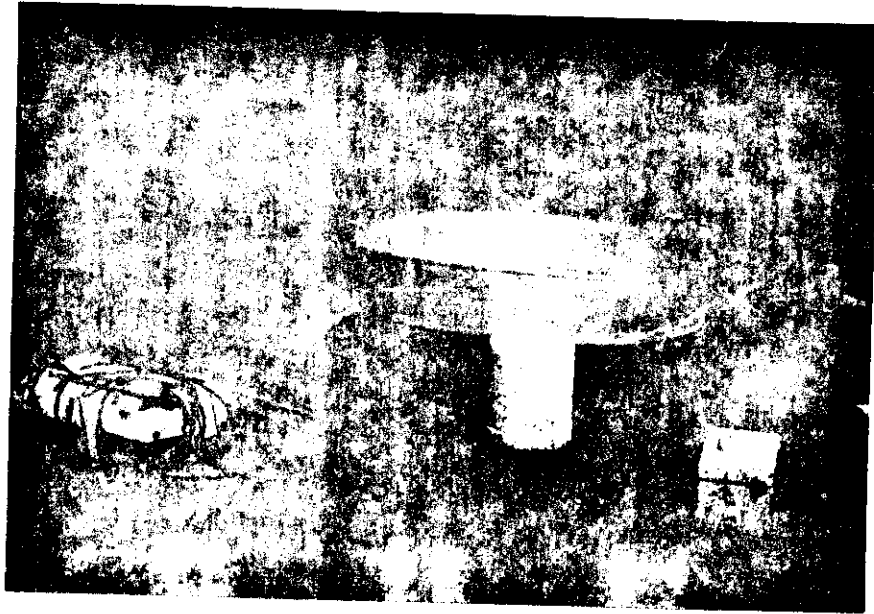Figure 4.2a. Typical calibration plot layout.

Figure 4.2b. Calibration plot with drip pan in place.

Three of the four plots were selected for artificial applications of water in addition to any natural precipitation which might occur during the study. The fourth plot served as a control and received only natural precipitation. The artificial applications were used to increase the number of wetting and drying cycles to which the sensors were exposed. This would give an indication of sensor responses to a wider range of soil water conditions. Rainfall events were recorded with a Belfort weighing raingage (calibrated in mm) which had a 24 hour rotation chart drive. Artificial water applications were recorded in a notebook along with the date, time, and size of the application.

The physical and chemical soil characteristics which are pertinent to the different sensor measurements are listed in Table 4.1. Soil texture was determined by the hydrometer method. Bulk density was calculated by gravimetric techniques. Soil pH was measured using the paste extract method and by a distilled water-soil solution technique. Specific conductivity was measured by the CSU Soils Testing Laboratory.

Sensor Calibrations

In addition to studying the behavior of different snesors, one objective of this study was to explore the possibilities of an in situ calibration technique for resistance-type soil water sensors. The primary tool for this calibration procedure was the thermocouple psychrometer. Sequential readings of psychrometers at each plot depth were to be correlated with the corresponding resistance sensor readings to see how well each type could predict the soil water potential. Only the thermocouple psychrometers were calibrated prior to the installation of the calibration plots.

Table 4.1. Soil physical and chemical properties for the calibration plots.

DEPTH (cm)	AVERAGE BULK DENSITY (gm/cm³)	AVERAGE TEXTURE			TEXTURAL CLASSIFICATION	pH	SPECIFIC CONDUCTANCE (millimho/cm)
		% SAND	%CLAY	% SILT			
0-5	1.39	54.4	31.9	13.7	Sandy Loam	6.92	1.35
5-10	1.40	57.2	28.6	14.2	Sandy Loam	6.95	1.00
10-20	1.38	56.2	26.8	17.0	Sandy Loam	7.03	0.75
25-35	1.43	52.2	27.6	20.2	Sandy Clay Loam	7.10	0.65
40-50	1.40	44.2	31.2	24.6	Loam	7.06	0.35

The thermocouple psychrometers used for this study were double-junction psychrometers manufactured by Emco (Figure 4.3). They are a modification of the original Spanner design. Chow and De Vries (1973) found psychrometers of this type to have 40 times the thermal stability of the Spanner design. The reason for this increased stability is that both of the psychrometer junctions are located in the same thermal environment and are subject to the same ambient temperature fluctuations. These junctions produce opposing thermal EMF's which cancel each other with very little or no effect on the overall psychrometer output.

Thermocouple Psychrometer Calibrations

Laboratory calibration of the Emco double-junction thermocouple psychrometers consists of taking readings over saline solutions of known water potential. Each microvolt (μV) reading was plotted with the corresponding water potential for the individual psychrometer to establish a calibration curve. Since both the psychrometer output and solution water potentials are temperature dependent a series of temperatures and solutions were used with each unit to obtain a family of temperature related calibration curves.

The basic calibration procedure followed guidelines suggested by the manufacturer. Sodium chloride solutions of different molalities were prepared using tables from Brown and Van Haveren (1972). Temperature control for calibration was achieved with a refrigerated water bath. This bath had a temperature range from -15°C to 70°C and a temperature control accurate to ± 0.02°C.

psychrometer cable

Constantan lead
(26 AW6)

Teflon cup

reference junctions

Copper leads
(26 AW6)

chromel
(.0025 cm)

sensing junctions

chromel
(.0025 cm)
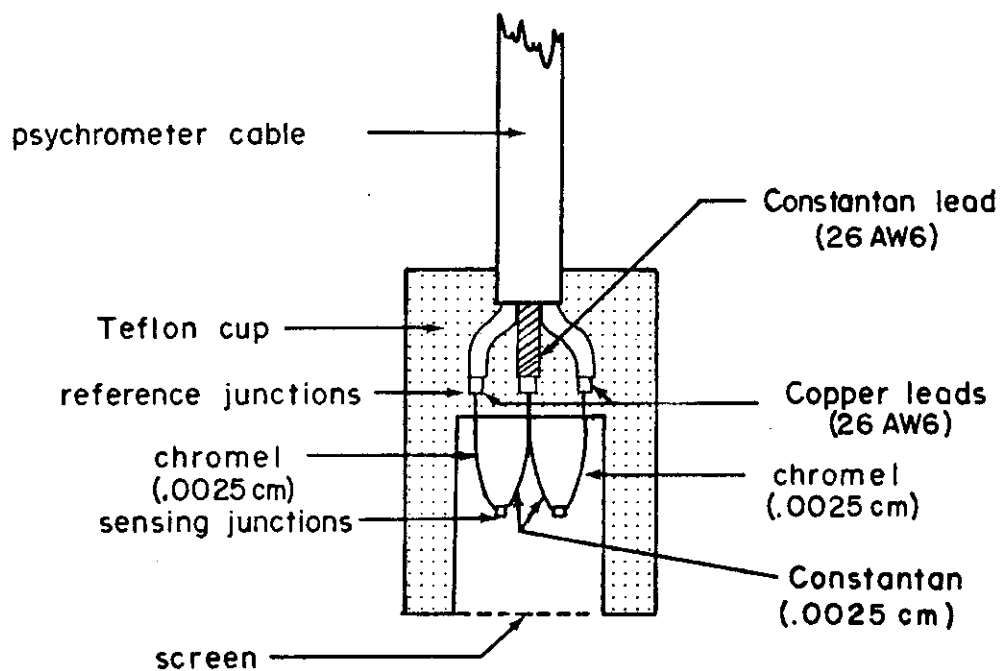
Constantan
(.0025 cm)

screen

Figure 4.3.   The Emco double-junction thermocouple psychrometer.

A teflon calibration chamber was designed and constructed which held 14 thermocouple psychrometers simultaneously (Figure 4.4). When the chamber was sealed, the psychrometers were positioned directly over a filter paper disc which was saturated with a sodium chloride solution of known water potential. The chambers were built from teflon due to its non-absorbent surface. The non-absorbent surface is needed to prevent changes in solution water potential due to solution adsorption by the chamber walls. The chamber volume was approximately 1 cm^3 per psychrometer. The psychrometers were fastened into the chamber with silicon rubber sealant.

Each psychrometer was calibrated over salt solutions of 0.05, 0.2, 0.4, 0.7, 1.0, and 1.3 molality. These solutions have water potentials at 25^oC. of -2.34, -9.16, -18.23, -32.1, -46.4, and -61.19 bars respectively. The same series of temperatures was used with each of these solutions to generate the family of temperature dependent calibration curves. These temperatures were 1°, 10°, 20°, and 30^oC.

A standardized calibration procedure was adopted for calibrations over each of the six sodium chloride solutions. A standardized procedure was required to minimize any measurement errors which could occur during the calibration. After the psychrometers had been secured into the chamber they were washed with boiling distilled water and rinsed with acetone. This was necessary to remove any contamination from the chamber and the units themselves that could affect the solution potential or the measuring junction output. After washing, the units were dried in an oven at 60^oC for 5 or 6 hours. Next, they were placed in a walk-in freezer ($\approx -5^o$C) until they had reached temperature
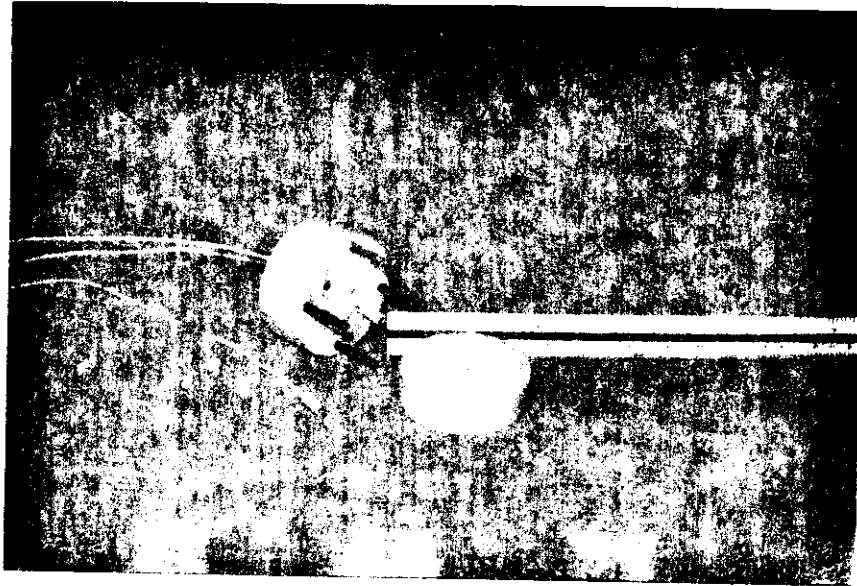
Figure 4.4.   Teflon thermocouple psychrometer calibra-
tion chamber with (3) thermocouple
psychrometers.

equilibrium. Cooling reduced the possibility of solution condensation on the thermocouple psychrometer measuring junctions when they were placed in the water bath at 1°C.

The filter paper disc was placed in the bottom of the chamber and saturated with salt solution. Then the chamber was sealed and wrapped in a plastic bag. This bag was a precaution against chamber leakage while submerged in the water bath. Next, the chamber was taken from the freezer and submerged in the water bath which had been preset to a temperature of 1°C. The chamber was allowed to reach thermal stability in the bath for approximately 2 hours before any psychrometer readings were taken.

After the 1°C readings were completed, the bath temperature was raised to 10°C and a 2 hour equilibration period was again allowed. This procedure was repeated at 20° and 30°C. When the 30°C readings were completed, the chamber was removed from the bath and the same wash-down, rinse, drying, and cooling procedures were used prior to the calibration run over the next solution.

A record of the output for the individual psychrometers at the various water potentials was kept by plotting the output on graph paper. Actually an average of three readings at each measurement point was used to develop the calibration curve. Later, this data was plotted on a Hewlett-Packard (HP) programmable calculator with an X-Y plotter to select the coefficients of the regression equation for each calibration curve (Figure 4.5). Since thermocouple psychrometer output is affected by both the temperature and the actual water potential, a
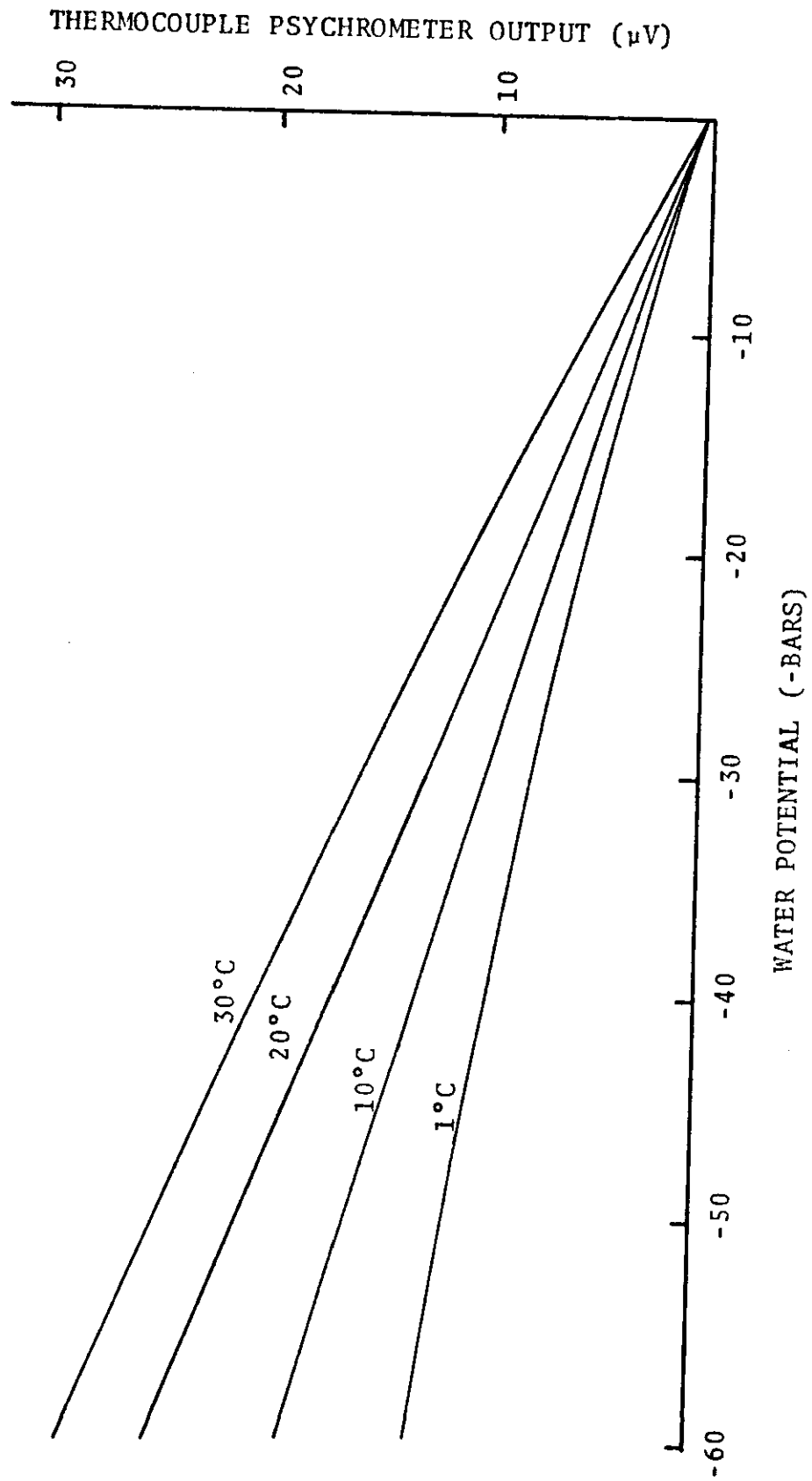
Figure 4.5. Calibration curves for a double-junction thermocouple psychrometer.

parabolic regression equation was used to obtain a more precise fit of the data. The basic format of this equation is:

$$\hat{Y} = a + bX + cX^2$$

where: $\hat{Y}$ = estimated water potential

a = Y intercept

b,c = slope coefficients.

The three coefficients (a,b,c) are part of the output of the HP parabolic regression program.

Neutron Probe Calibration

A surface and deep calibration for the neutron probe used in this study was completed by Galbraith (1971). A series of neutron attenuation counts were taken at two depths (15 and 30 cm) under different soil water conditions. A set of 400 cm^3 bulk soil samples were then taken from the vicinity of the access tube at the source depth. These samples were immediately placed in sealed containers. Later, the volumetric water content of these samples was determined. A calibration curve was established relating neutron counts per unit time to the soil volumetric water content (θ_v) . Due to the high stability of the fast neutron flux rate of an AM^{241}Be neutron source this calibration curve is still valid (Figure 4.6).

Field Measurement

All resistance readings were taken with a Soiltest MC-300A soil moisture meter. The MC-300A is a 90 cycle alternating current version
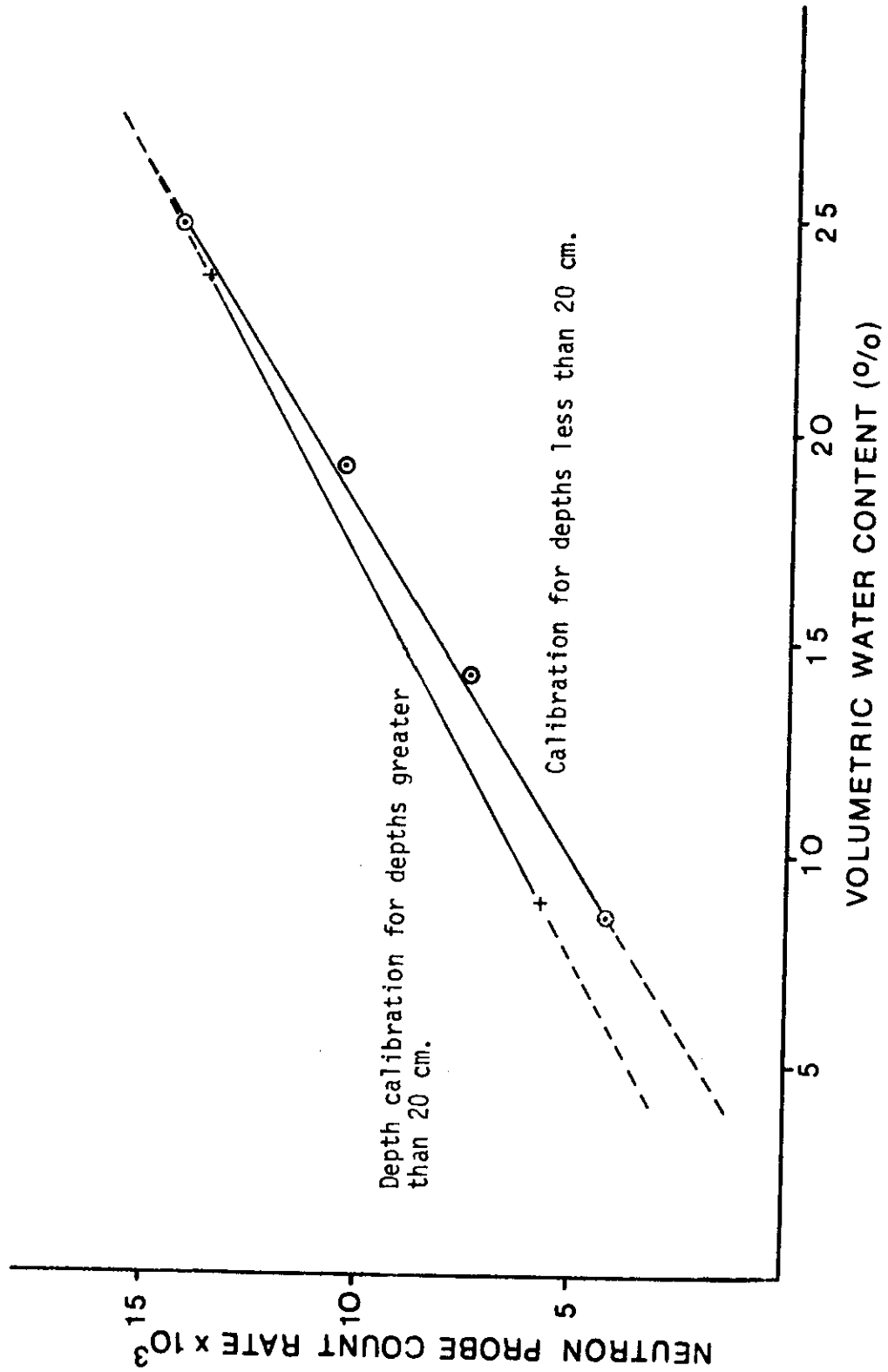
Figure 4.6. Surface and depth calibrations ($\frac{1}{2}$ minute count) for the neutron probe (Van Haveren and Galbraith, 1971).

of the wheatstone bridge (Colman and Hendrix, 1949). An alternating current source is used to prevent the polarization of the electrodes within the resistance sensors which can cause a loss of accuracy. This instrument has two scale ranges the "lo" scale has an effective range from 50 to 10,000 ohms. The "hi" sclae has a range from slightly less than 10,000 ohms to 3,000,000 ohms. Dial readings are in microamperes and a calibration chart is provided to convert microamperes to ohms.

For this study, the MC-300A was modified to decrease the time required for individual sensor readings. A small electrical chassis box was attached to the moisture meter case. The chassis box contained a 16-position single pole rotary switch which was connected to an Amphenol MS receptacle. The chassis box was jumpered to the MC-300A with a 3-wire harness (Figure 4.7).

The individual resistance sensors were connected to the mating MS plug. The rotary switch was used to select the appropriate sensor for measurement. This modification eliminated the problem of individually connecting each sensor for measurement. All 15 of the resistance sensors in each plot could be connected to the MC-300A and measured in about 5 minutes.

Thermocouple psychrometer output was measured with a Keithley 155 microvoltmeter. The switching unit used for selecting, nulling, cooling, and reading the psychrometers was constructed from a circuit diagram provided by Ray Brown of the Intermountain Forest and Range Experiment Station at Logan, Utah (Appendix A). The switching unit also contained an S-B Systems programmable $0^{o}C$ copper-constantan reference junction for thermocouple temperature measurement. The switching unit

48
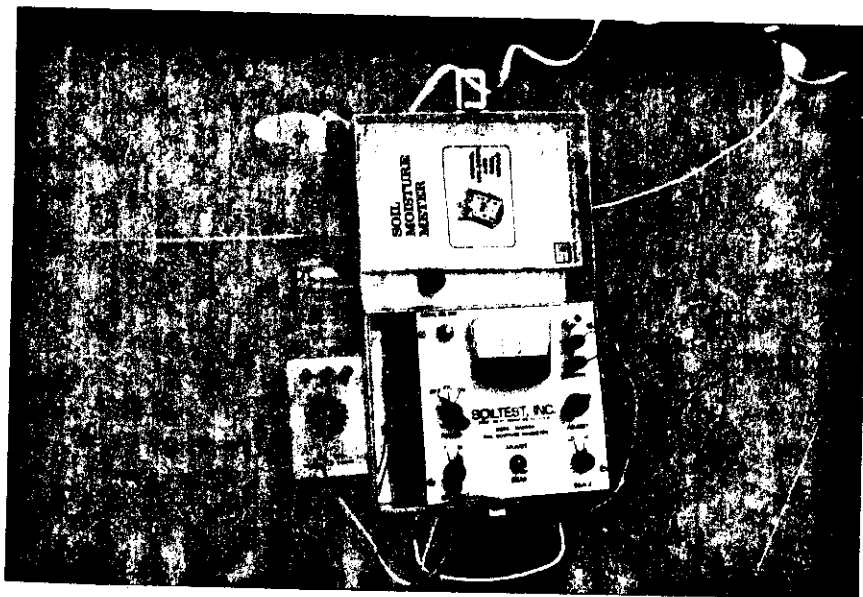
Figure 4.7. The soiltest MC-300A soil moisture meter with chassis box and MS connector.

was modified with an Amphenol Series 57 microribbon chassis connector. This connector, with the corresponding microribbon plug, allowed all five psychrometers in each plot to be connected to the switching system simultaneously (Figure 4.8).

Neutron attenuation measurements were taken with a Nuclear Chicago Corporation depth moisture probe and scaler. The source is an $Am^{241}Be$ type with a 30 millicurie strength.

Data Collection

Two standardized field data forms were utilized to record observations during this study (Appendix B). The first form was used for all thermocouple psychrometer and resistance unit readings. Each line of data on the form listed the date and military time for the sensor readings at a specified depth in a single calibration plot. The sensor readings were taken sequentially from the surface 2 cm depth to the greatest (45 cm) depth. The sequence was to first record the five thermocouple temperatures, psychrometer outputs, thermister temperatures, gypsum block resistances, and then the Colman unit resistances. The data on these forms was later keypunched for computer analysis.

The second standard data form was used for recording neutron probe data. This data was also keypunched for computer analysis. A computer program had been previously developed for the analysis of this data. The program derives the soil water content at each measurement depth in either centimeters of water or in terms of volumetric soil water, expressed as a decimal fraction.
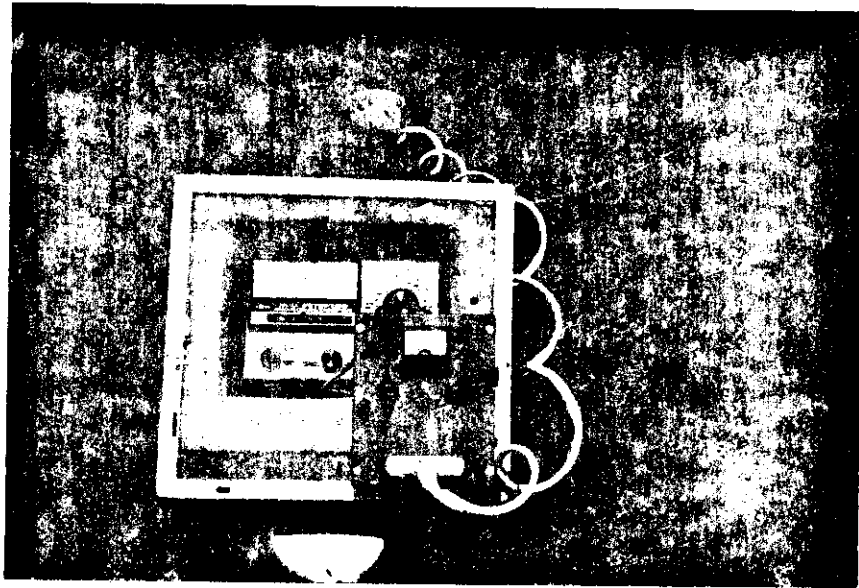
Figure 4.8. Keithley microvoltmeter and double-junction
thermocouple psychrometer switching unit with
micro-ribbon connector.

In the field, a 1/2 minute counting interval was used on the scaler to determine the amount of fast neutron attenuation. Prior to the actual soil water measurements a 1/2 minute count was taken and recorded while the probe was in the shield as an equipment checkout. This shield reading is also utilized in the computer program as an error check. Sampling depths for the probe were 15, 30, 45, 60, 75, and 90 cm in the soil.

Program Calplot was developed to convert field readings of thermocouple psychrometers, thermisters, gypsum resistance units, and Colman resistance units to standard readings (Appendix B). A temperature correction is necessary to eliminate the effects of changing soil temperature on the internal properties of the sensors themselves. In this manner, the effects of temperature change will be confined to its effects on the soil properties. Psychrometer output was corrected to a standard temperature of $20^{o}C$. A linear function was used to convert thermocouple temperature readings to a centigrade temperature.

Thermister readings were converted to a Farenheit temperature for us in the temperature correction of Colman and gypsum unit resistance. For this study, temperature corrections were made using tables prepared by the USFS Waterways Experiment Station. These tables relate the MC-300A dial reading and temperature of the units to a common temperature of $60^{o}F$. The related resistance is listed as a log_{10} resistance in ohms. A series of polynomial regression equations were developed which predict the temperature corrected log_{10} resistance for gypsum and Colman units from the MC-300A dial reading. A series of these temperature dependent equations were used and the program selected the

appropriate one by using the corresponding thermister temperature and the MC-300A microampere dial reading as an independent variable. Program Calplot contained two sets of equations for the temperature correction of the resistance unit data. The first of these sets was for the "lo" meter scale and a temperature range of 50 to 115°F. The second set of equations describe the "hi" scale resistance in the same temperature range.

Sampling Schedule

The sampling scheme for this study was designed to obtain a fairly continuous record of measurement with the various sensors over a wide range of soil water conditions. Measurements were taken from -1/3 bar at shallow depths to the stages of drought dormancy for the plants located on the plots (approximately -30 to -40 bars at 15 cm depth).

The four calibration plots used in this study were installed in late May 1973. The units were allowed to equilibrate with the soil water conditions until June 13th. On the 13th of June, data collection began and continued on a regular basis through August 31st. In order to obtain a background level of the soil water status, the plots were monitored for approximately two weeks before any artificial precipitation was applied.

Readings were obtained from all of the in situ electrical sensors on each of the plots at least once daily during the measurement period (June 13 to August 31). One plot served as a control with natural conditions determining the soil water status during the study (Figure 4.9a). On the other three plots artificial applications of known
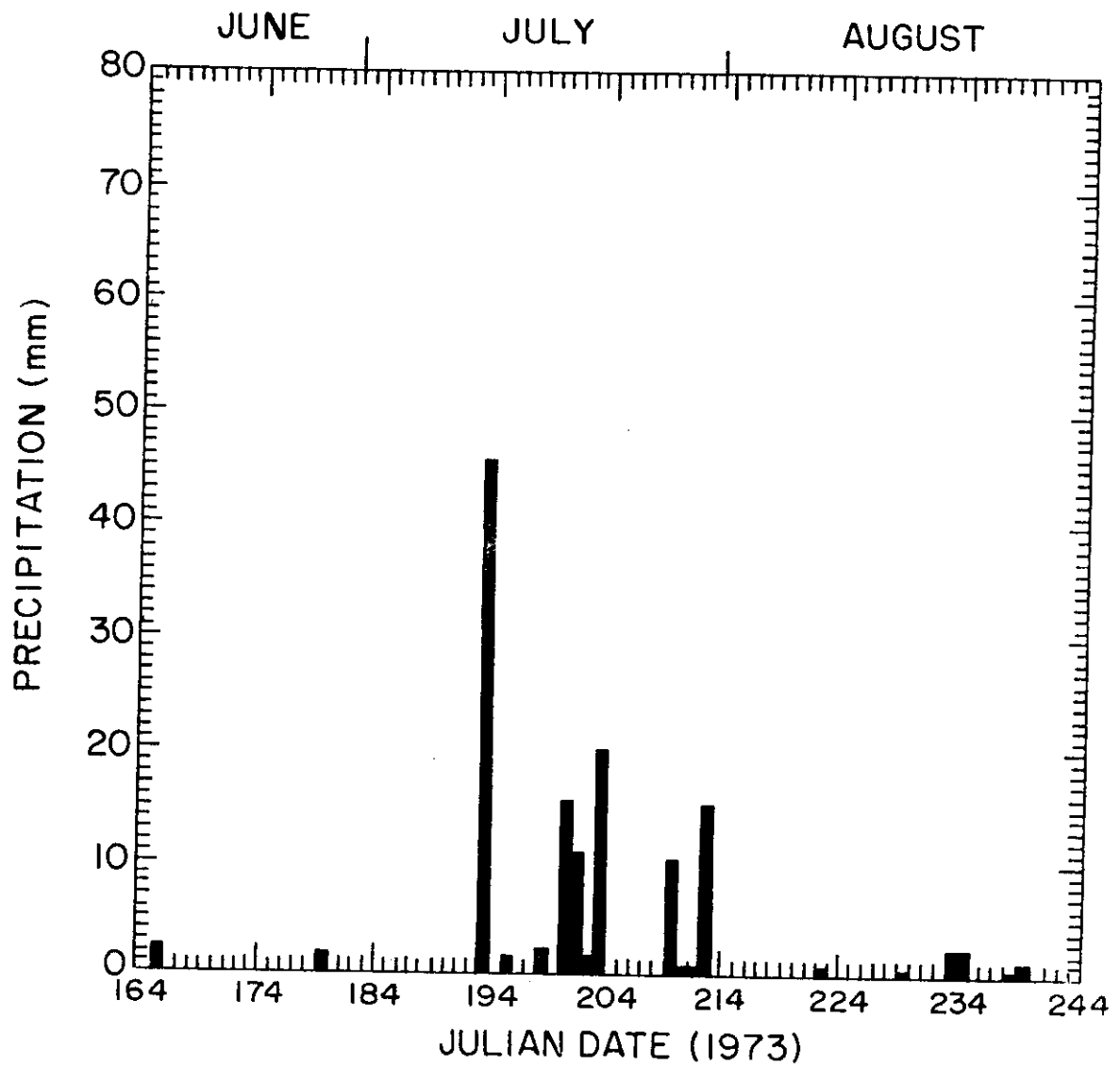
Figure 4.9a. Precipitation events, June 13 - August 31, 1973.

amounts of water were made to increase the soil water content (Figures 4.9b, 4.9c, 4.9d). Sensor readings including neutron probe were recorded immediately prior to these applications. After the application was completed, the sensors were monitored on an intensive basis until water movement had begun to stabilize. At this point, the intensity of sampling was reduced since the evapotranspiration flux of soil water is much less pronounced.

Each treated plot was allowed to dry for a period of at least one week, in most instances, before another application was made. No set schedule was used for these treatments. Instead, water was usually applied on the plot when the water potential at 2 cm had exceeded the measuring range of the psychrometer at that depth (-60 to -70 bars). Different types of treatments were made in which the amount of water was applied uniformly to the plot surface.

In mid-July, a series of large rainstorms recharged the soil water content. No further artificial applications were made until this water had been depleted (-20 bars) by the plants to a depth of 30 cm (mid-August). Each plot was subjected to a series of wetting and drying cycles. The control plot was subjected to the smallest number of cycles and produced a precise record of the natural soil water conditions during the study period.
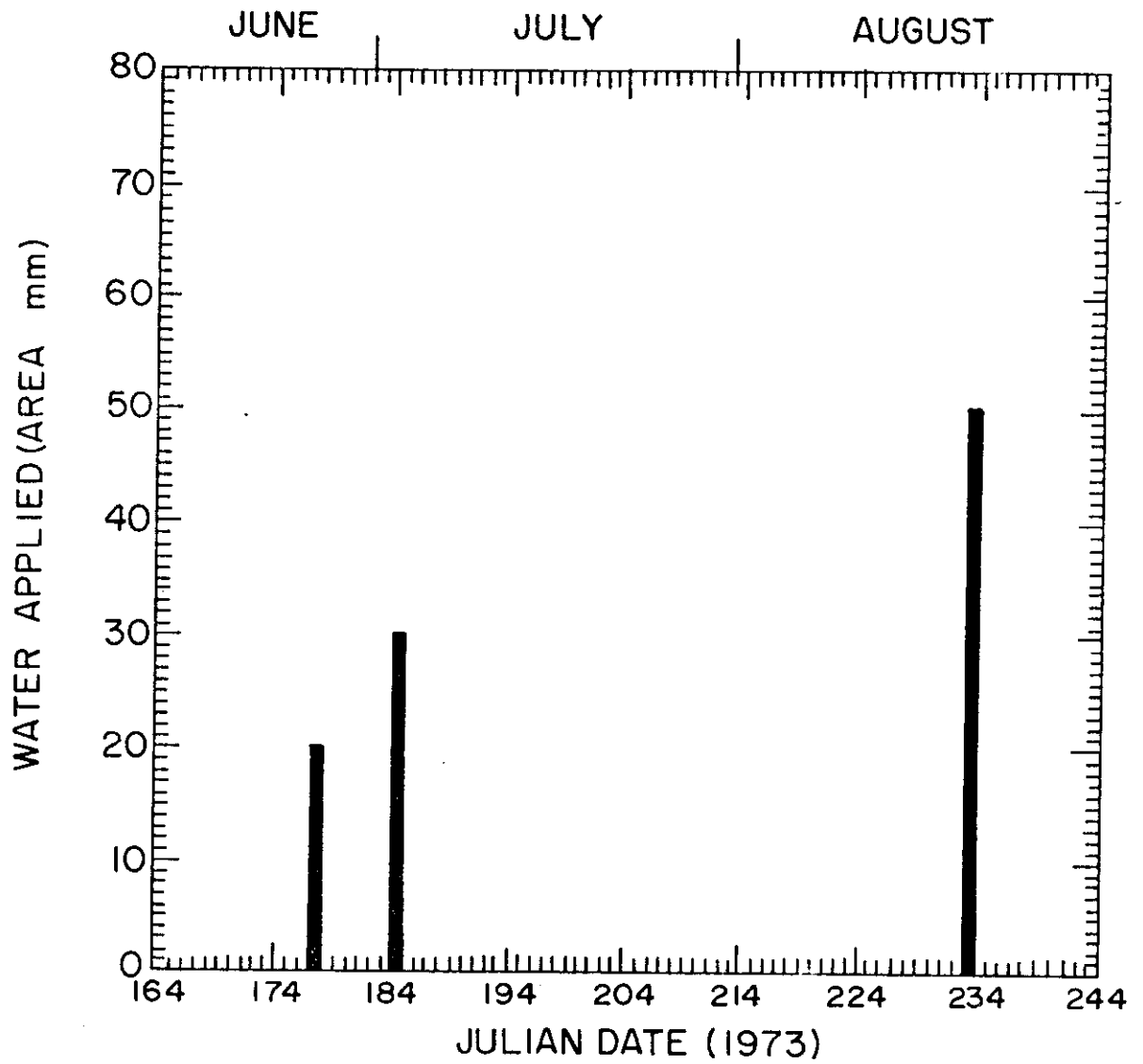
Figure 4.9b. Supplemental water applied to plot A.
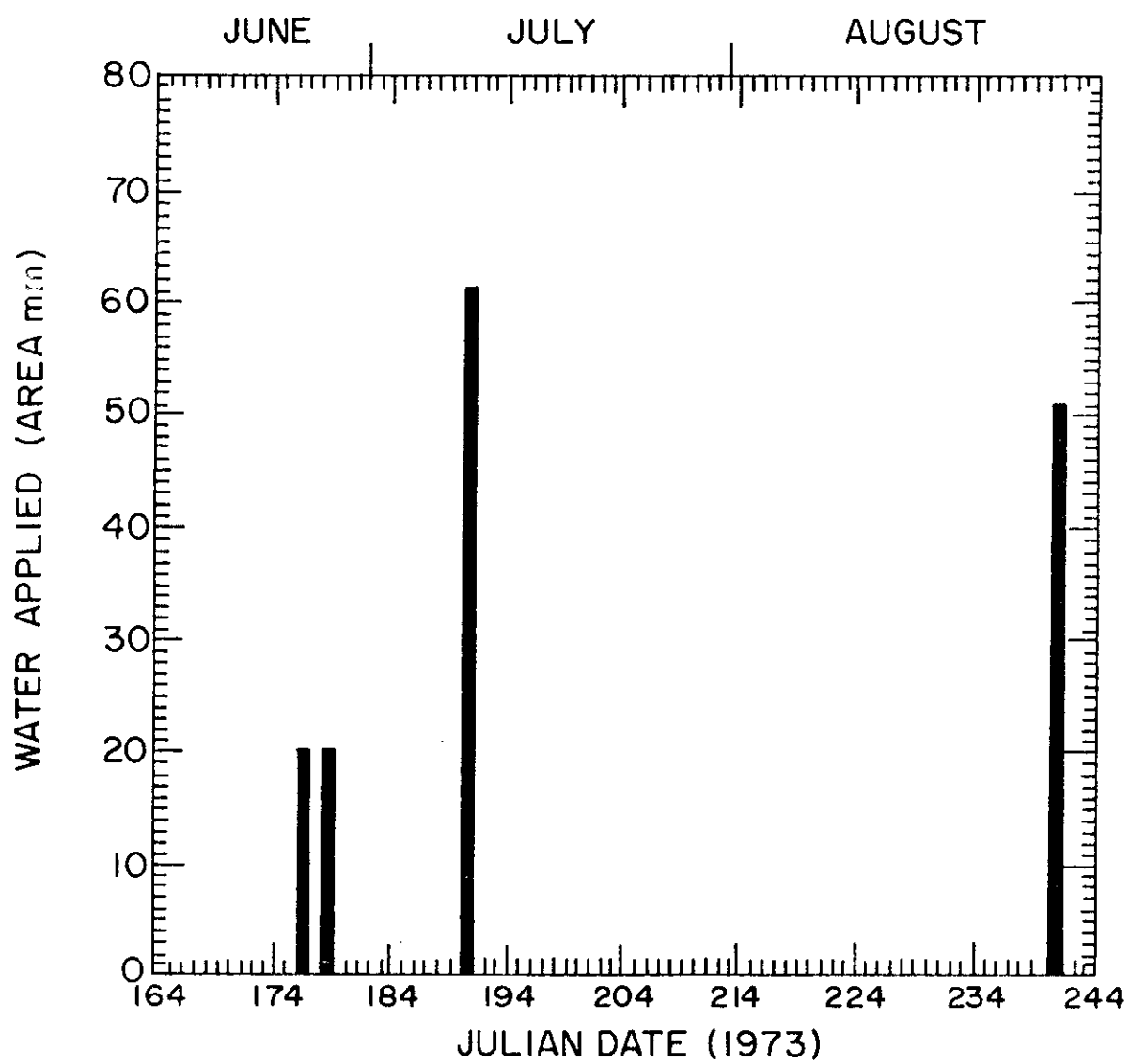
Figure 4.9c. Supplemental water applied to plot B.
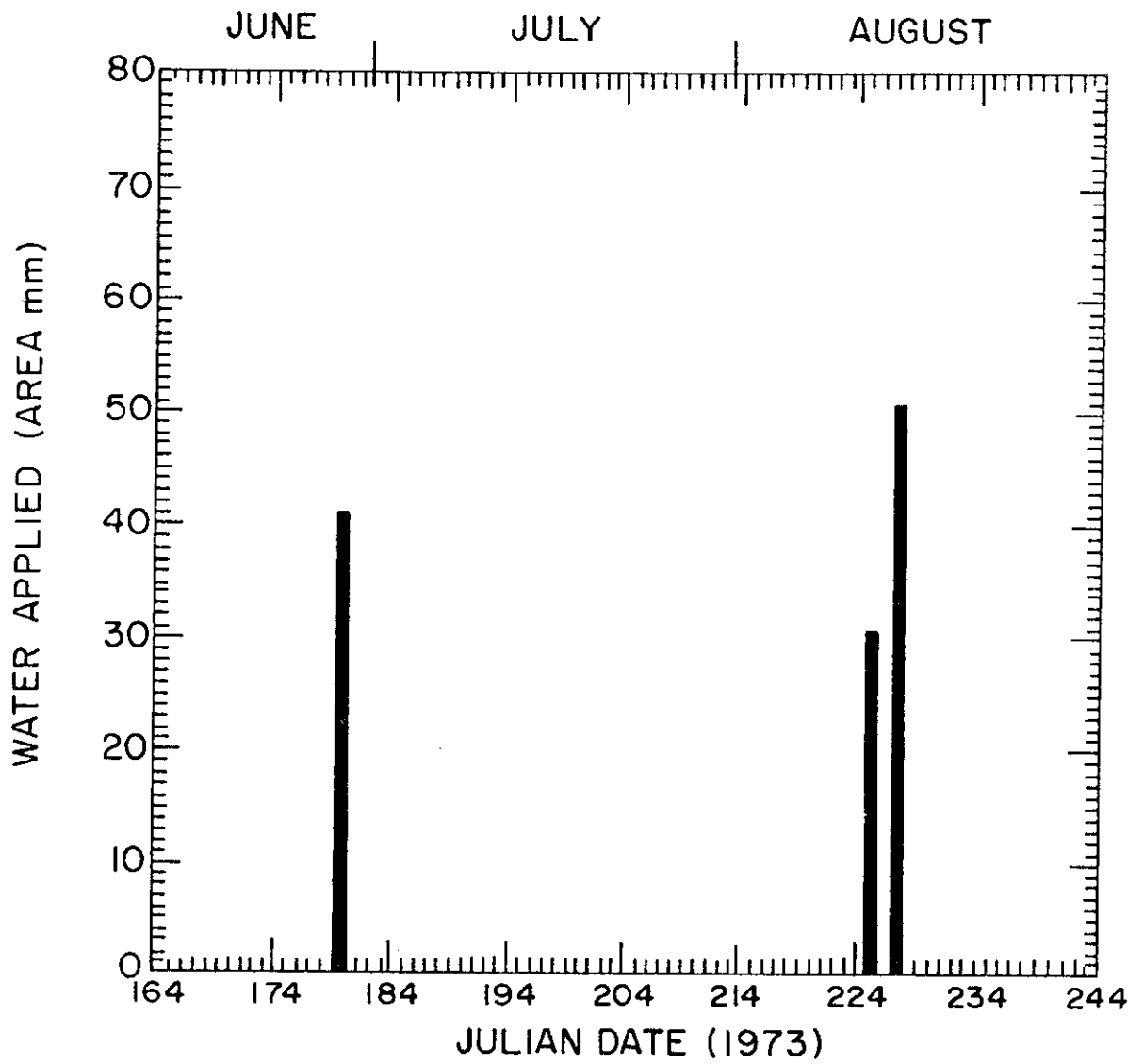
Figure 4.9d. Supplemental water applied to plot D.

CHAPTER V

RESULTS AND DISCUSSION

The soil water data which was collected with the different sensor types in the calibration plots was used in a series of analysis and comparisons. Microfilm plots were made with the computer for visual data interpretation. In addition, the soil water potential data in the control plot was compared with the growth stages (phenology) of blue grama grass during the study period. Next, a series of graphical comparisons were made with readings from the different sensor types. These comparisons were used to examine how closely related the soil water measurements were between the different sensor types. Finally, a statistical correlation program was used to test the possibility of using thermocouple psychrometers for the in situ calibration of either gypsum or Colman resistance units.

Much information can be obtained from the characteristic shapes of the sensor time traces. One noticeable characteristic is the rapid fluctuation of the water potentials measured with the thermocouple psychrometer. Both the gypsum and Colman units have slower responses to these same soil water dynamics (Figures 5.1a, 5.1b, 5.1c). The magnitude of change for the different sensors to the soil water conditions is misleading in these traces since the Colman and gypsum unit readings are logrithmic values. Logrithms were used to linearize the resistance changes of the Colman and gypsum units. Another characteristic of these traces is that the sensor readings are plotted as a continuous trace. The traces between actual data points can only

PLOT D DEPTH 3

Figure 5.1b. Coleman unit resistance, at 15 cm, plot D.

PLOT D DEPTH 3

Figure 5.1a. Soil water potentials, at 15 cm, plot D.
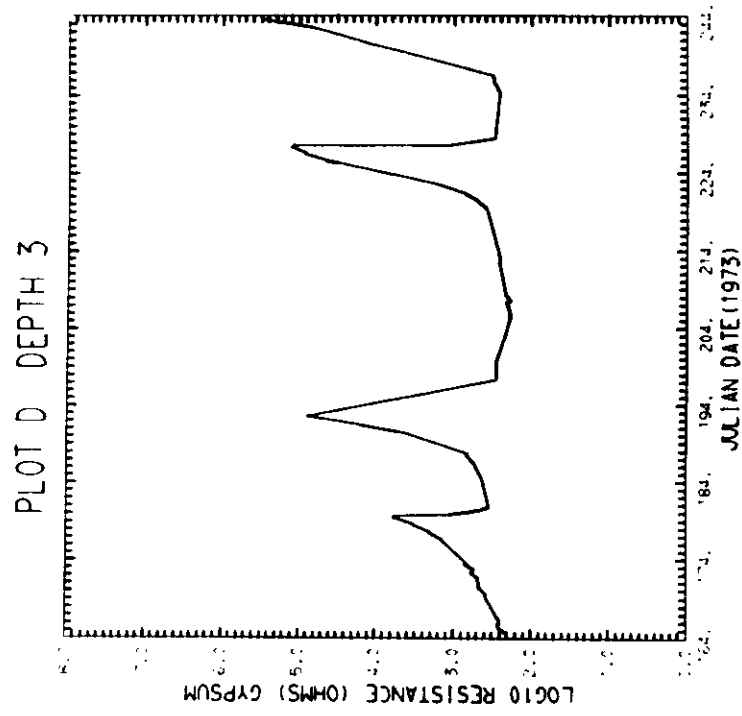
Figure 5.1c. Gypsum block resistance, at 15 cm, plot D.

be used to imply the rate of change or flux and direction of change for the soil water conditions between actual measurements.

The time traces yield a characteristic drying curve for each of the three sensor types. The thermocouple psychrometer has an almost linear downward (more negative) drying curve. In the same drying conditions, the Colman unit has a convex upward (higher resistance) curve on the log scale. The gypsum unit has a concave upward curve during the same time interval.

These characteristic curves are a function of the individual sensor volume, sensor design, and the soil properties in relation to the sensor. The gypsum units have their own internal water capacity due to their large volume. The Colman unit also has an internal water capacity but due to its smaller volume the effect is not as pronounced as in the gypsum block. Since the thermocouple psychrometer is only measuring the vapor pressure of a very minute volume of the soil atmosphere its internal hysteresis is very small as compared with the gypsum and Colman units.

Another noticeable characteristic in these time traces is the decrease in fluctuation of sensor readings with depth (Figures 5.1d, 5.1e). These changes are due to the fewer wetting and drying cycles of soil water as depth increases. Small precipitation events have a greater effect on the soil water status near the soil surface and 50% of the below ground biomass is located in the top 10 cm of soil (Bartos and Simms, 1974). Therefore, the main interaction of precipitation, soil water, and water uptake by plants occurs in this thin surface layer of soil.
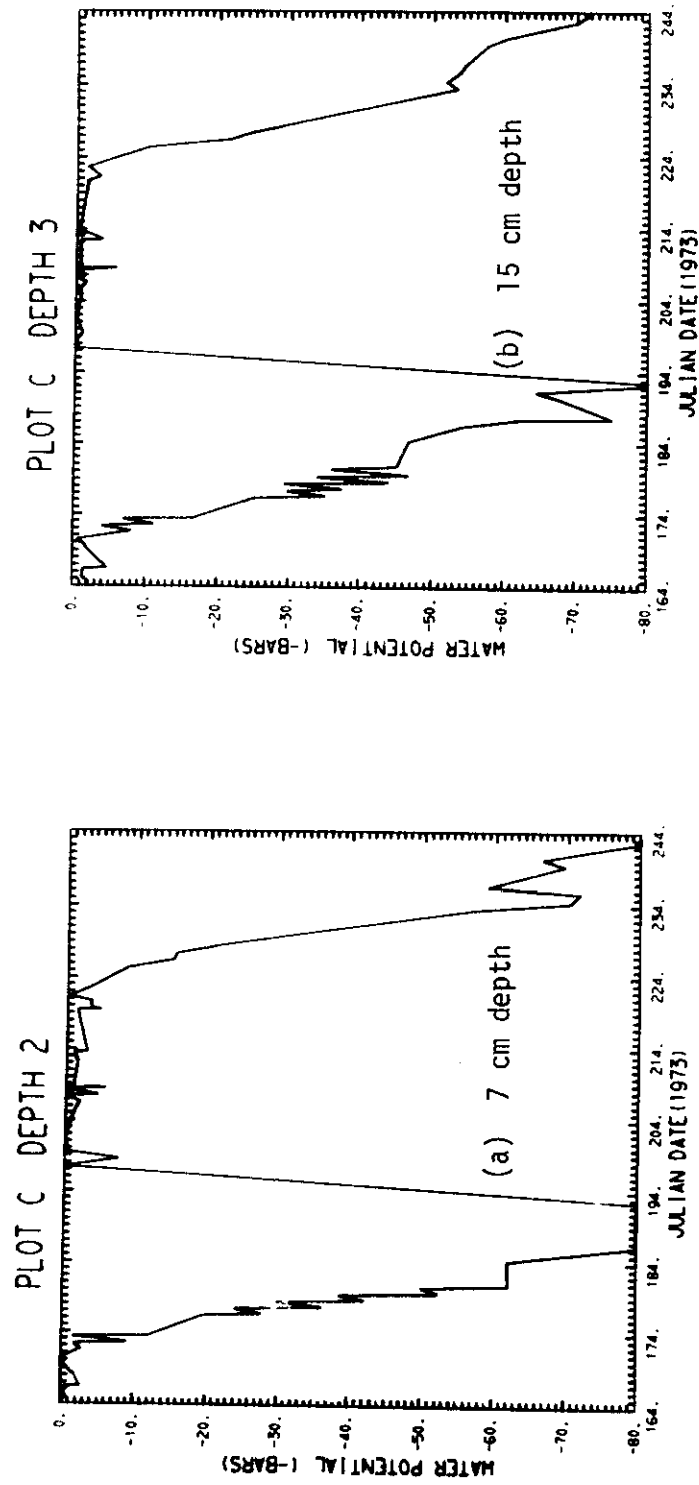
Figure 5.1d. (a,b) An illustration of the decreasing soil water dynamics with increasing soil depth (control plot).
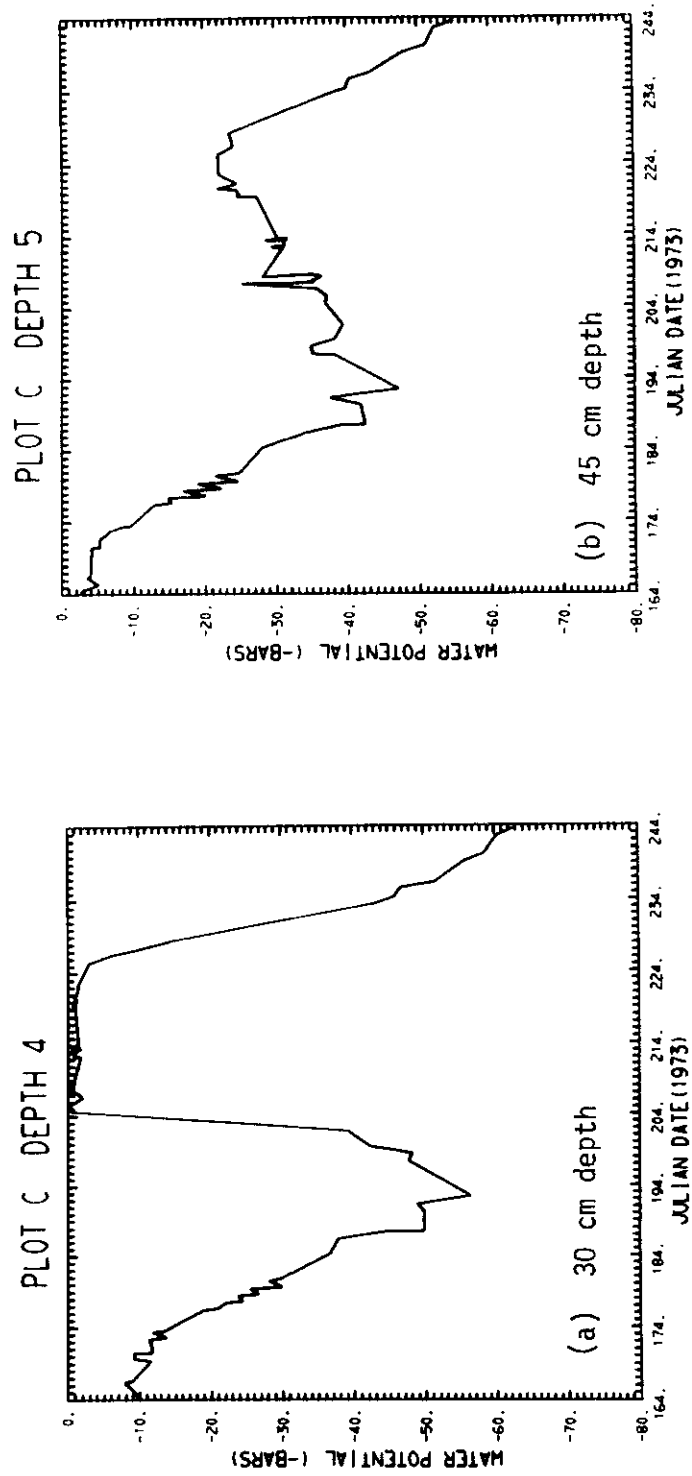
Figure 5.1e. (a,b) An illustration of the decreasing soil water dynamics with increasing soil depth (control plot).

The ability of shortgrass prairie plant species to respond very rapidly to an increase in available soil water is illustrated by a comparison of the 15 cm water potential data in the control plot with the plant phenology which was observed on the D treatment (control) in the Environmental Stress Area (Figure 5.2a). In this figure, phenology is based on an ordinal scale (1 to 14) representing distinct stages of plant development where 1 signifies preemergence growth/winter dormancy and 14 signifies flowering-induced dormancy (at the end of the growing season). By visual inspection, the blue grama grass (Bouteloua gracilis) phenology was constant (leaves fully expanded) from June 13th (Julian day 164) until July 12th (Julian day 193). At this time, a series of large precipitation events caused the blue grama to develop floral buds (Figure 5.2b). The plants remained in this phenological stage until the soil water became depleted and the 15 cm water potential began to decrease. As the water potential decreased the phenological stage of blue grama advanced to the more mature stages of development (a combination of both green and ripe fruits).

During the study, two 30-hour data runs were made to determine the diurnal temperature and evapotranspiration effects on the soil water potential. In the first, the soil water status had not been influenced by artificial water applications. In the second trial, 4 cm of water were applied in 1 cm increments at about 2 hour intervals at the beginning of the run.

In calibration plot B, no water was applied and an apparent temperature effect on the soil water potential is present at the 2 cm depth (Figure 5.3a). However, as the soil temperature declined in the
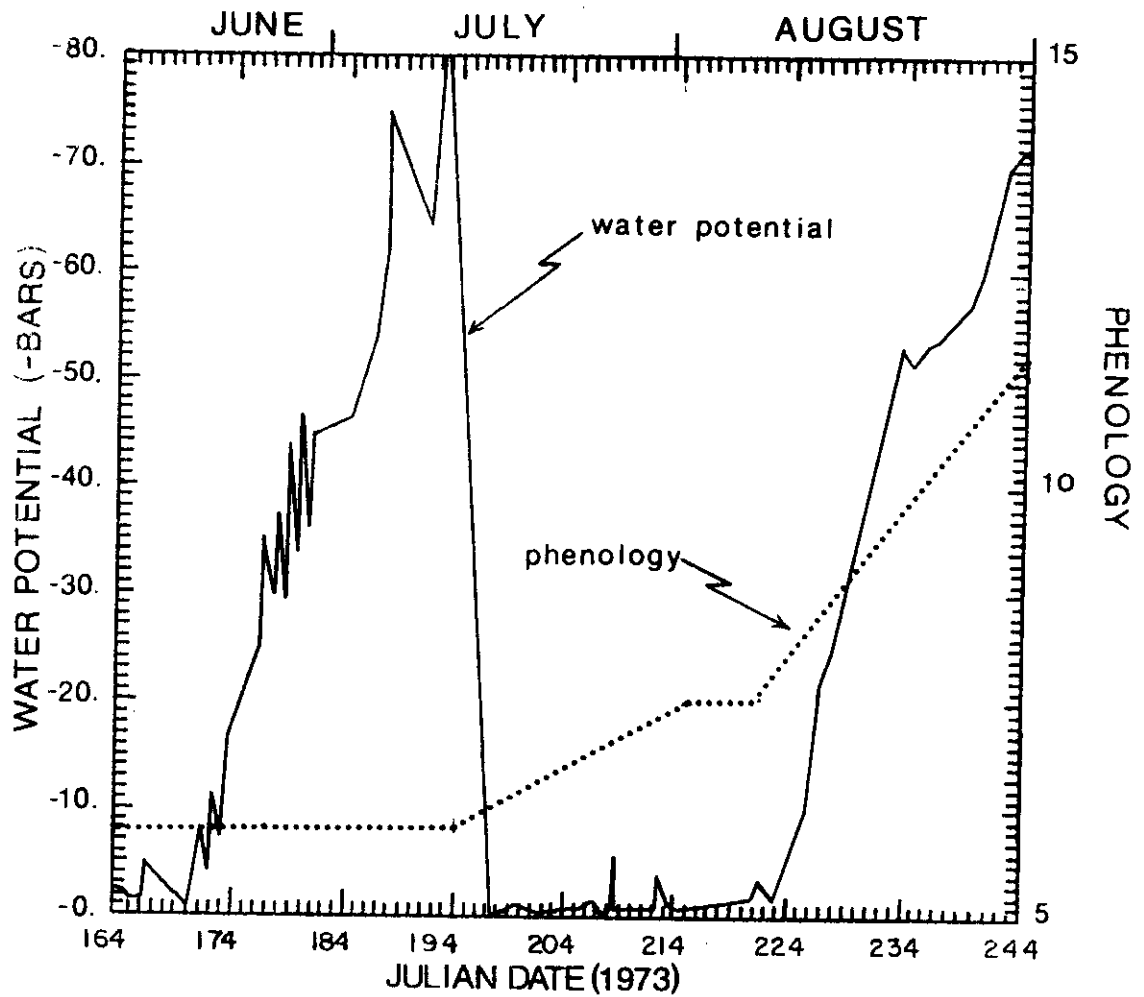
Figure 5.2a. Soil water potential (15 cm) and phenological response of blue grama (control plot).
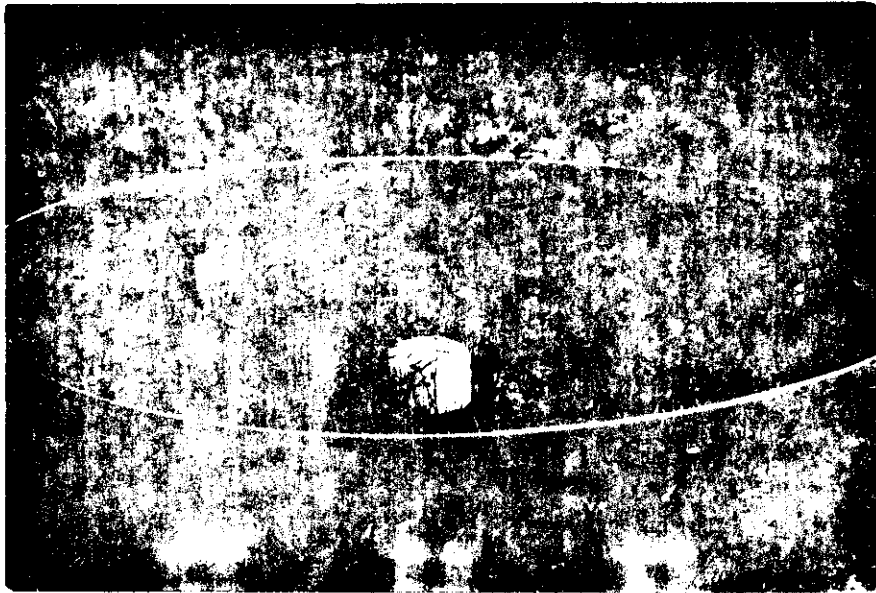
Figure 5.2b. Blue grama seed head production.

PLOT B DEPTH 1

(a) 2 cm depth

PLOT B DEPTH 1

(b) 2 cm depth
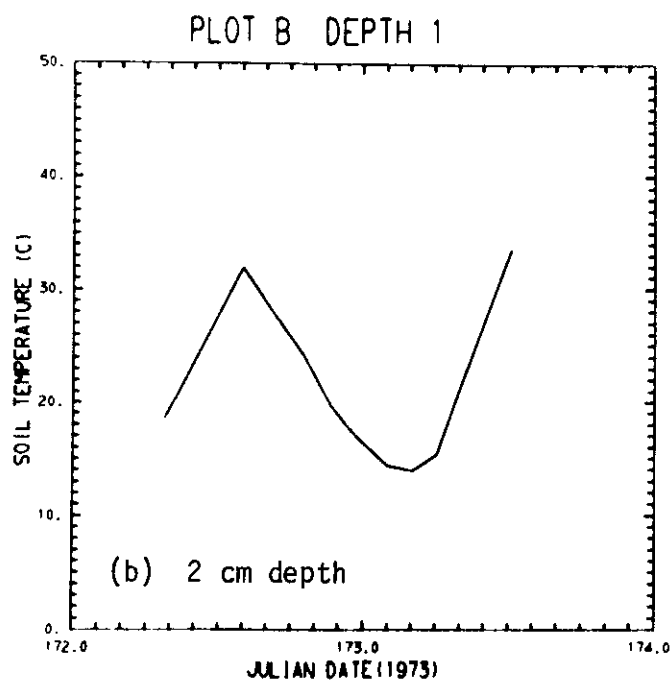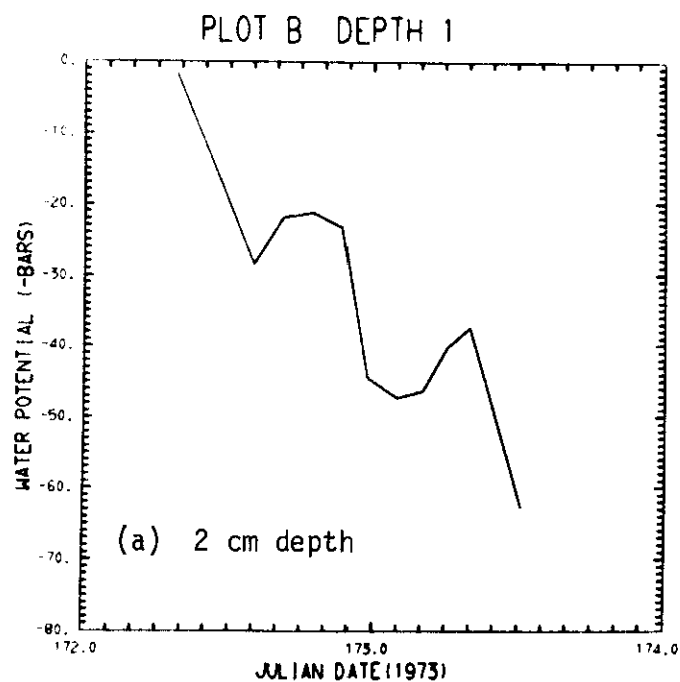
Figure 5.3a. Diurnal variation in (a) soil water potential
(2 cm, plot B) and (b) soil temperature.

evening the soil water potential increased (towards 0) and then began to decrease. No direct explanation can be given for this phenomenon. However, it is possible that at this shallow depth the psychrometer measurements may be influenced by an interchange of the atmosphere and the soil air.

At the 7 cm depth the diurnal temperature effect on the water potential is present but is not as pronounced as at the 2 cm depth (Figure 5.3b). At depths greater than 7 cm there is little diurnal temperature effect. The 2 cm gypsum and Colman resistance units show no significant temperature effect during this same time interval (Figure 5.3c). The 2 cm gypsum unit data have a gradual but continuous increase as a result of the soil water depletion by evapotranspiration. However, the 2 cm Colman unit readings show a very slight diurnal temperature effect but not as pronounced as that measured with the thermocouple psychrometer.

The second 30-hour measurement sequence was on calibration plot D. During this sequence, artificial water applications were made in the first 8-hour period of these observations. These applications of water mask out the effects of temperature on the water potential during the period of treatment (Figures 5.4a, 5.4b, 5.4c). The following day, the diurnal temperature influence on water potential is again visible at the 2 and 7 cm depths but the magnitude of the effect is greatly reduced in comparison to the plot B observations.

The response times of the different sensors are a function of their construction and mass. The thermocouple psychrometer, which
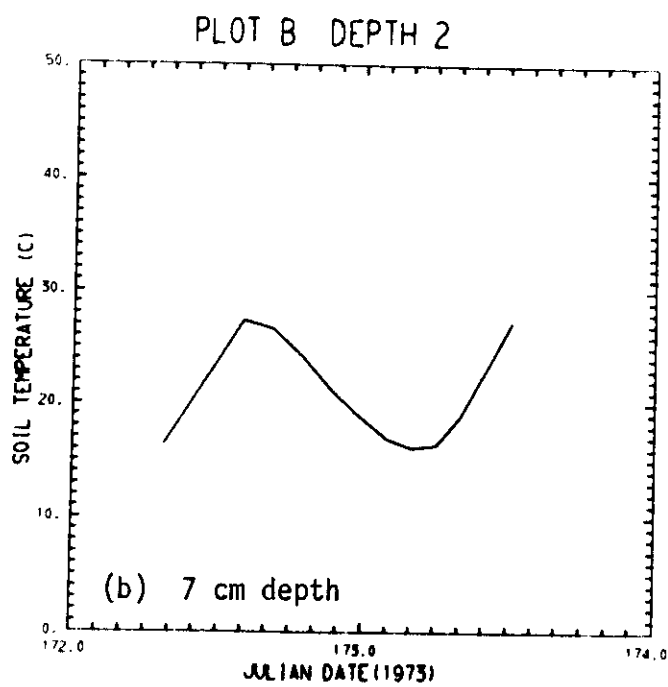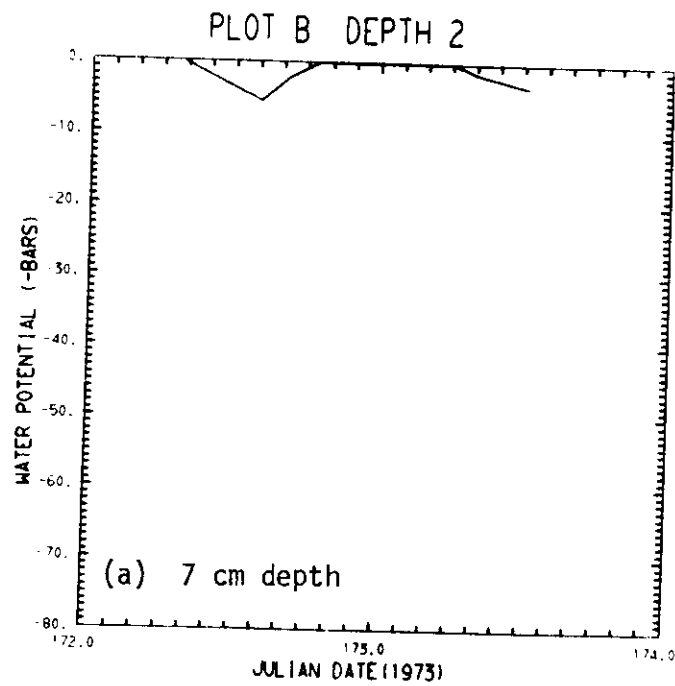
Figure 5.3b. Diurnal variation in (a) soil water potential (7 cm, plot B) and (b) soil temperature.

PLOT B DEPTH 1

(a) 2 cm depth

LOG10 RESISTANCE (OHMS) GYPSUM

JULIAN DATE (1973)

PLOT B DEPTH 1

(b) 2 cm depth

LOG10 RESISTANCE (OHMS) COLMAN

JULIAN DATE (1973)
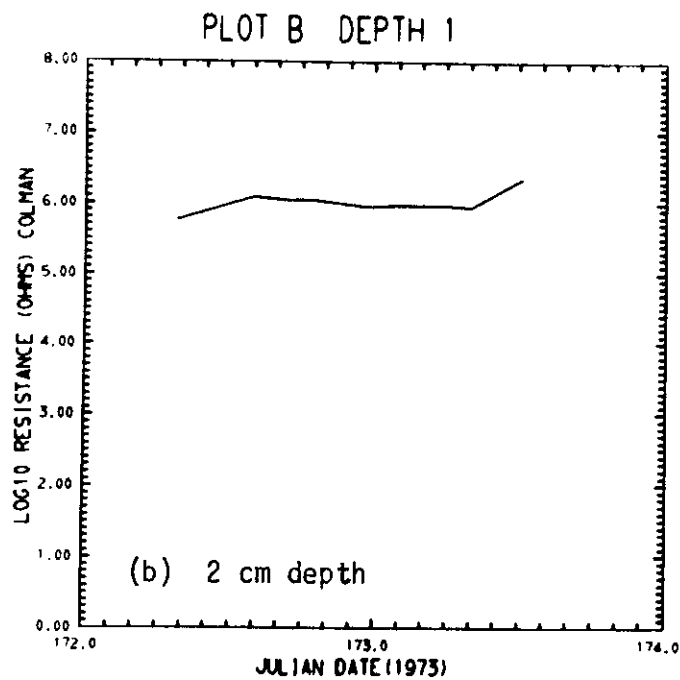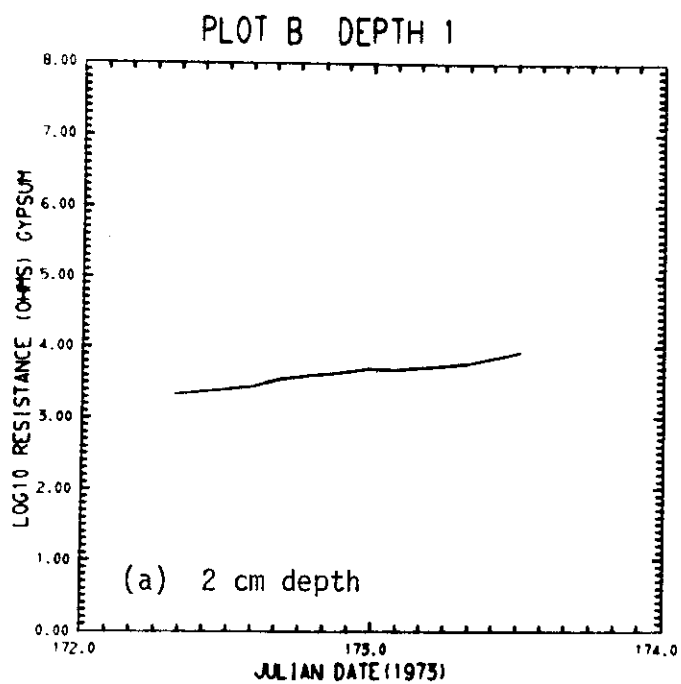
Figure 5.3c.   Diurnal variation in (a) gypsum unit resistance
and (b) Colman unit resistance (2 cm, plot B).

PLOT D   DEPTH 1

(a)   2 cm depth

PLOT D   DEPTH 1

(b)   2 cm depth
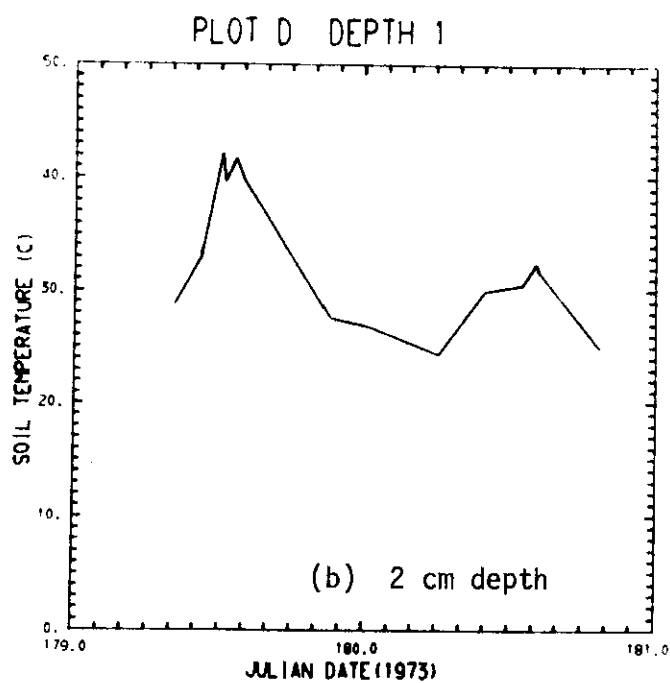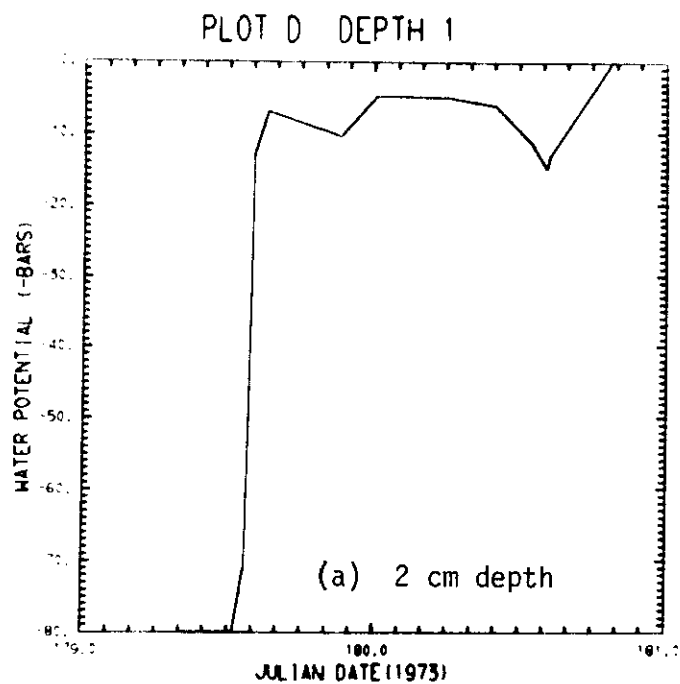
Figure 5.4a.   Diurnal variation in (a) soil water potential (plot D, 2 cm) and (b) soil temperature during a water application.

PLOT D DEPTH 1

(a) 2 cm depth

PLOT D DEPTH 1

(b) 2 cm depth
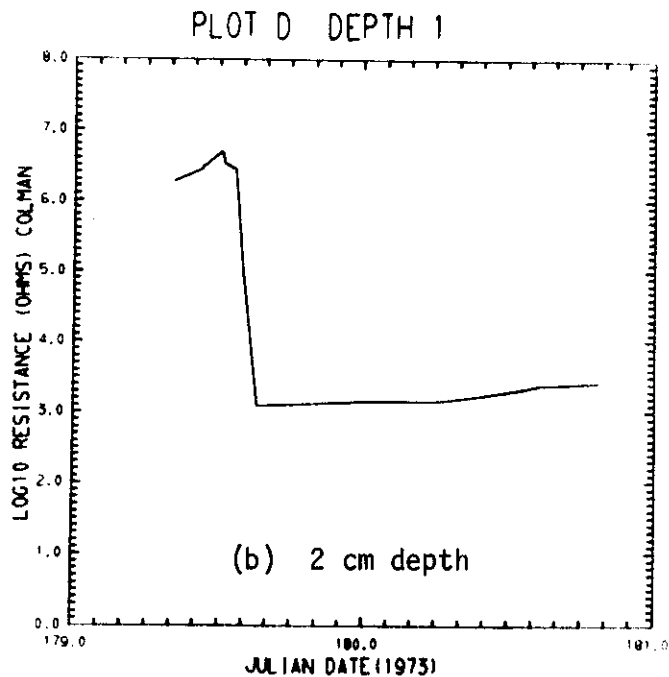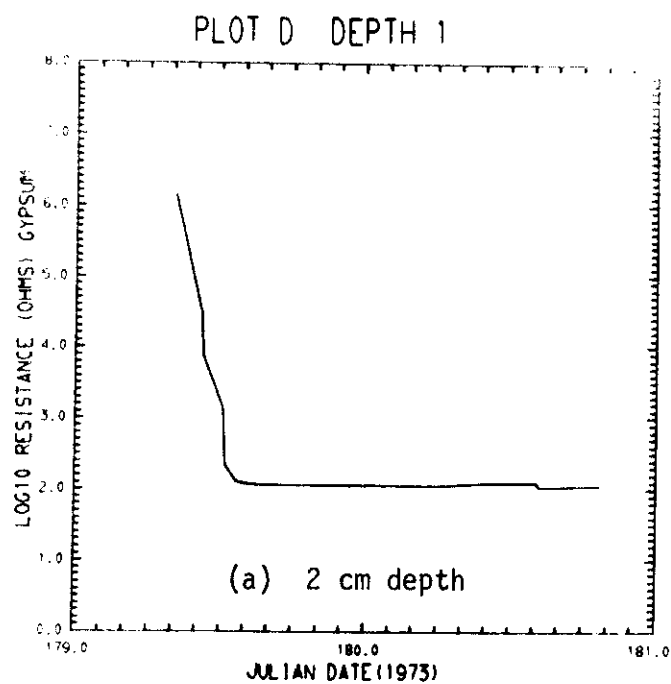
Figure 5.4b. Diurnal variation in (a) gypsum unit resistance (plot D, 2 cm) and (b) Colman unit resistance during a water application.

PLOT D DEPTH 2

(a) 7 cm depth

HATER POTENTIAL (-BARS)

JULIAN DATE (1973)

PLOT D DEPTH 2

(b) 7 cm depth

SOIL TEMPERATURE (C)

JULIAN DATE (1973)
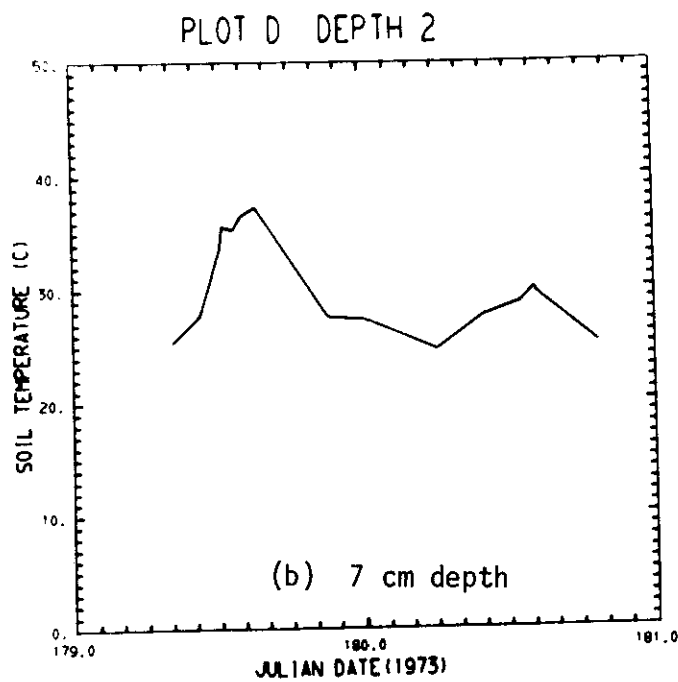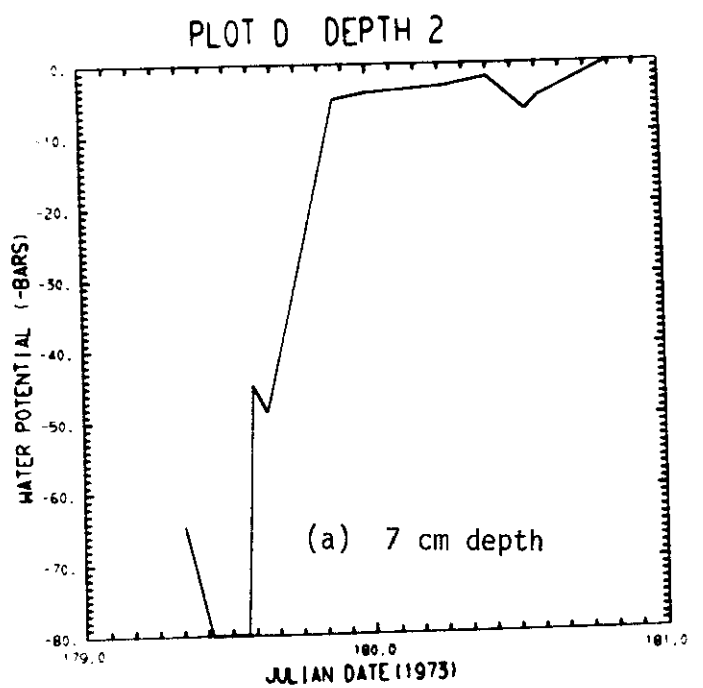
Figure 5.4c. Diurnal variation in (a) soil water potential (plot D, 7 cm) and (b) soil temperature during a water application.

samples the soil atmosphere vapor pressure, has a very small mass and a quick response to any changes in the soil water potential.

The gypsum resistance unit has a very rapid response when soil water is near saturation but a very gradual response when the soil is unsaturated. The relatively large volume of this sensor causes a significant time lag due to its water holding capacity.

Colman unit response to saturated conditions was relatively slower than the gypsum units. This is probably due to a loss of sensor-soil contact caused by soil shrinkage during the previous drying cycle. However, the Colman units were much more responsive to unsaturated movements of the soil water than the gypsum units. This is probably due to their smaller volume.

During artificial water applications, it was possible to observe a change in the resistance of the gypsum unit within 10 minutes after the application. At the same 2 cm depth, thermocouple psychrometer responses occurred in approximately 20 to 25 minutes. The Colman unit in these instances began to respond to the wetting conditions in about 30 minutes.

Graphical comparisons of the three sensor types were made. The first was a comparison of sensor readings to the corresponding volumetric water content measured with the neutron probe. The second comparison was between the resistance units and the soil water potential measured with the thermocouple psychrometer.

The variation shown by the points within the envelope curves surrounding the water potential versus the soil water content data are primarily due to hysteresis effect for Ascalon soils (Figure 5.5a).
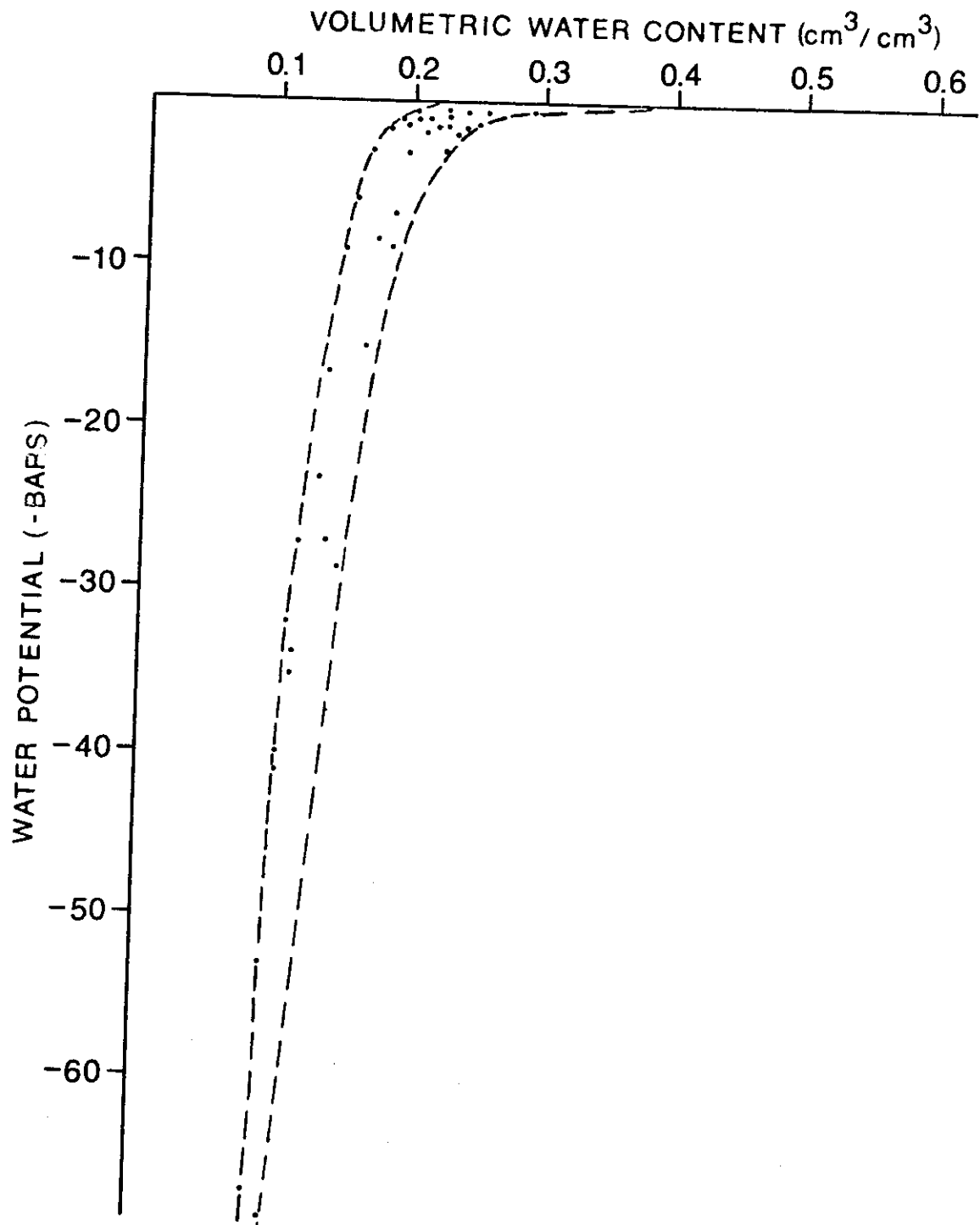
Figure 5.5a. A relationship between thermocouple psychrometer soil water potential and the volumetric soil water content measured with the neutron probe. Data is from all plots at a 15 cm soil depth.

The data points for the higher water content envelope curve correspond to the soil water characteristic curve measured with the pressure plate apparatus by Van Haveren (1974).

The comparison of the gypsum resistance unit data and volumetric water content data show much more scatter (Figure 5.5b). This is due to the compound effects of soil hysteresis, the internal water storage of the gypsum block, and sensor variability. The lag in response of the gypsum block to changes in soil water conditions creates a large variation in resistance measurements at a specific soil water content.

In the comparison of Colman unit data and the corresponding soil water contents a relationship is more apparent than in the gypsum unit graph (Figure 5.5c). However, the variation of the data is still fairly broad. This is due to the smaller water capacity effect of the fiberglass unit. During these same observations, the majority of the gypsum unit readings were in the low resistances while the associated Colman unit resistances are almost uniformly distributed over the measurement range. The broader range gives the Colman unit more resolution for measurement of changes in the soil water.

Comparisons between resistance readings of the two units and the soil water potential are shown in the second set of graphs. These graphs show the relation between the resistance values and the water potentials measured with the thermocouple psychrometer. They also give an indication of the measurement rages for the two types of resistance units.

The gypsum unit resistances plotted against water potential indicate a wide variation for a given potential (Figure 5.6a). This
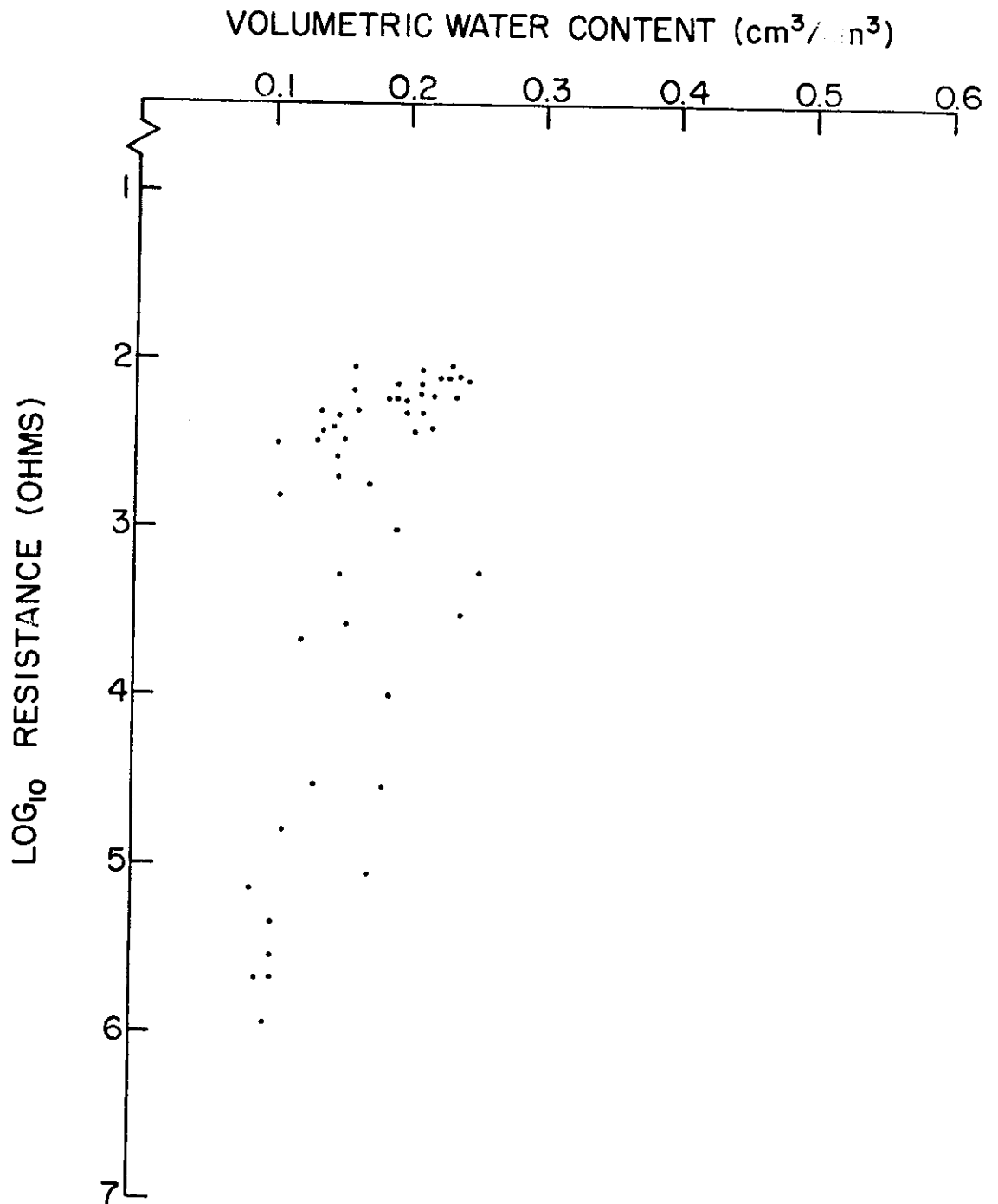
Figure 5.5b. A comparison of gypsum unit resistances and soil water content as measured in the field with the neutron probe. Values are from all plots at the 15 cm depth.

Figure 5.5c. A comparison of Colman unit resistances and soil water content as measured in the field with the neutron probe. Values are from all plots at the 15 cm depth.
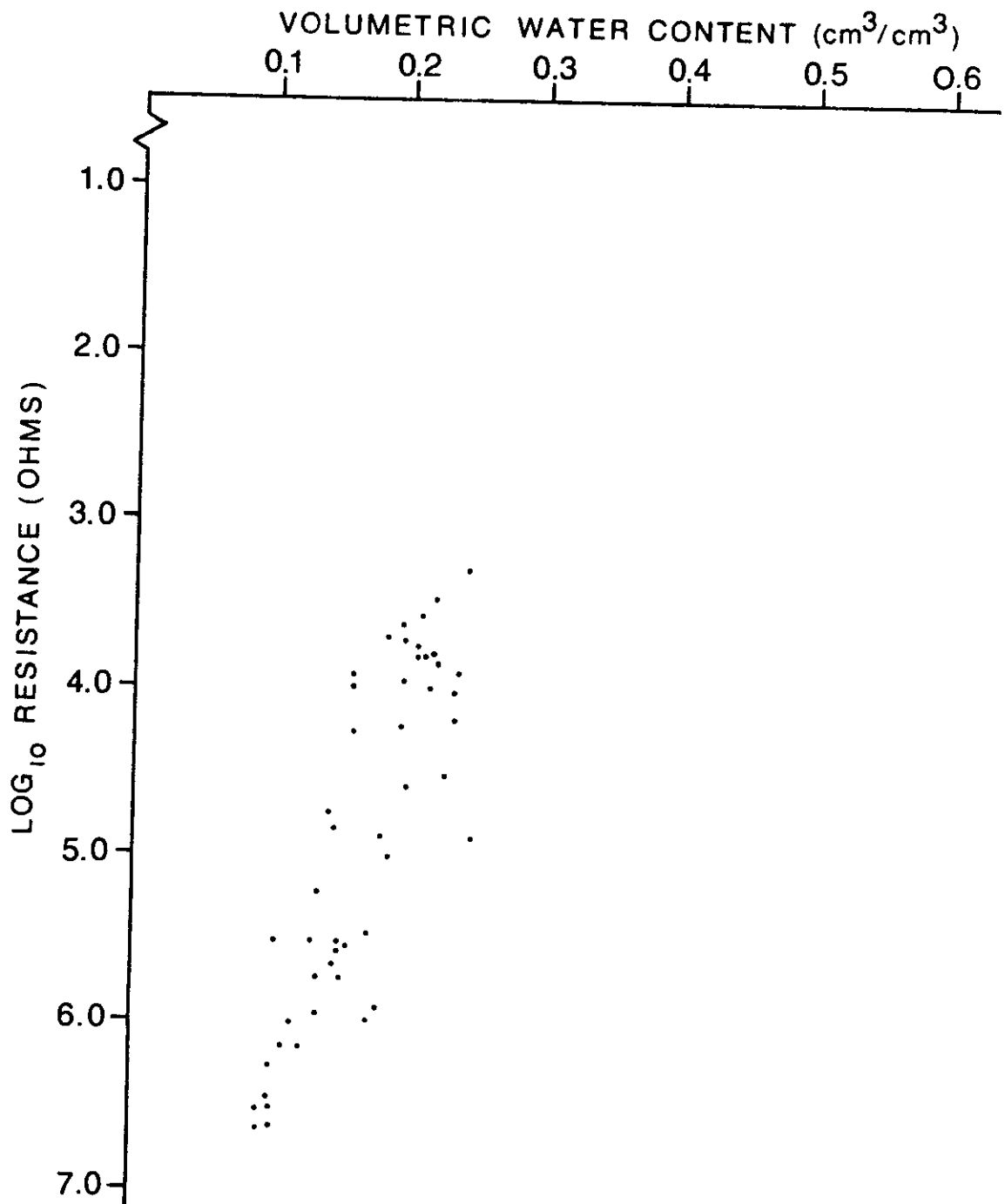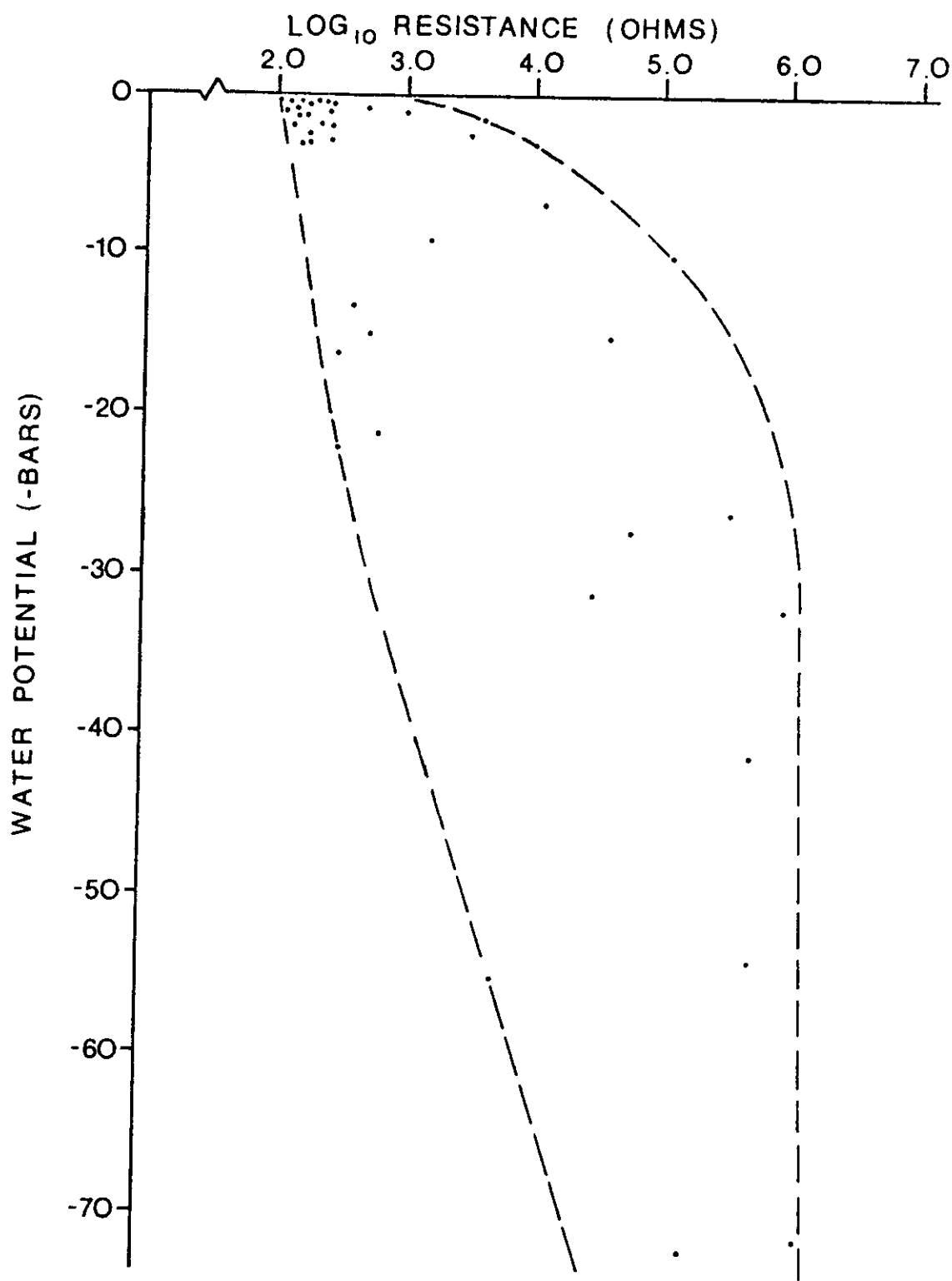
Figure 5.6a. A comparison of gypsum unit resistances and soil water potential as measured in the field with the thermocouple psychrometer. Values are from all plots at the 15 cm depth.

implies that the resistance unit was not at equilibrium with the soil water potential at the time that most of these readings were taken. The figure indicates that the gypsum units are only accurate at high water potentials where water movement primarily occurs in the liquid phase.

The distribution of Colman readings versus water potential suggests that this type of sensor has a much more sensitive response to changes in the soil water potential between 0 and -10 bars (Figure 5.6b). Therefore, the unit has a fairly reasonable response to un-saturated movements of the soil water in a limited range. At water potentials less than -10 bars this unit shows little resistance change for a wide range of potentials (-10 to -70 bars).

Based on the information in these graphs, it appeared that a better relationship between soil water potential and resistance might be possible for the individual sensors in the 0 to -15 bar range. However, plots of Colman and gypsum block resistances versus corresponding soil water potential measurements showed variations nearly as great as those in Figures 5.6a and 5.6b. Plots of individual resistance sensors against the soil water potentials showed very poor relation-ships (Appendix C).

A pairwise correlation program (Cormid) was used to test the possibility of an in situ calibration of the two types of resistance sensors with thermocouple psychrometers. This statistical program produced a simple correlation coefficient, r, which was squared to obtain the coefficient of determination (r^2).
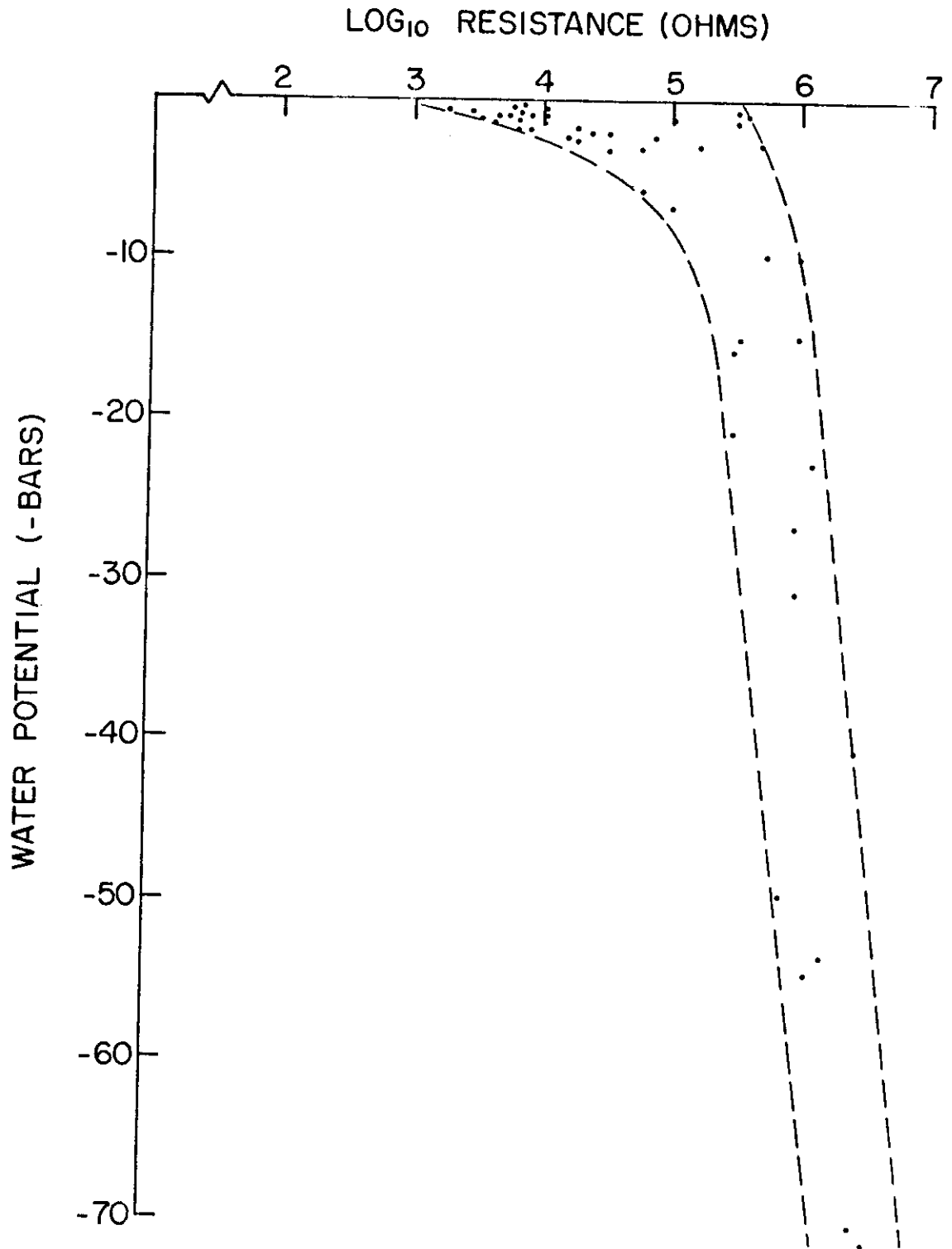
Figure 5.6b. A comparison of Colman unit resistances and soil water potential as measured in the field with the thermo-couple psychrometer. Values are from all plots at the 15 cm depth.

In the first comparison all field data for the three sensor types were tested against each other (Table 5.1). The r^2 values produced in these trials was 0.40 between psychrometer and gypsum unit data and 0.39 between the psychrometer and Colman unit readings. The correlation between the Colman and gypsum units produced an r^2 value of 0.46. These results indicate that the resistance type units cannot accurately predict the soil water potential.

The second test was a correlation of the three sensor types within the individual calibration plots (Table 5.2). The r^2 values produced in this comparison indicate that the control calibration plot (plot C) had the highest correlations among the three types of sensors. The reason for this is probably due to the smaller number of drying cycles that the sensors in this plot underwent. There was less variation in sensor readings due to the lower number of fluctuations in the soil water status.

The final sensor to sensor correlation was a comparison of all sensor data at the individual depths within each plot (Table 5.3). The effect of wetting and drying cycles is also present in these sensor correlations by depth. As the sensor depth increases the r^2 values also tend to increase in most cases. The fluxes in soil water are more gradual at greater depths and the changes in sensor readings are more uniform, producing higher correlation coefficients.

The poor correlation coefficients produced in most of these tests are probably a result of three factors. The primary factor is the basic differences in the design of the sensors and how they measure the soil water. The thermocouple psychrometer measures the total soil

83

Table 5.1. Correlation matrix of the coefficients of determination
(r^2) for all calibration plot data.

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.40	0.39
Gypsum		1.00	0.46
Colman			1.00

Table 5.2. Correlation matrices of the coefficients of determination (r^2) for all data in each calibration plot.

PLOT A

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.12	0.24
Gypsum		1.00	0.43
Colman			1.00

PLOT B

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.53	0.40
Gypsum		1.00	0.42
Colman			1.00

PLOT C

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.78	0.61
Gypsum		1.00	0.80
Colman			1.00

PLOT D

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.35	0.43
Gypsum		1.00	0.55
Colman			1.00

Table 5.3. Correlation matrices of the coefficients of determination (r^2) for calibration plot A by sampling depth.

PLOT A (2 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.41	0.24
Gypsum		1.00	0.65
Colman			1.00

PLOT A (7 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.29	0.24
Gypsum		1.00	0.48
Colman			1.00

PLOT A (15 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.12	0.38
Gypsum		1.00	0.34
Colman			1.00

PLOT A (30 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.30	0.66
Gypsum		1.00	0.33
Colman			1.00

PLOT A (45 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.23	0.53
Gypsum		1.00	0.62
Colman			1.00

Table 5.3. (continued)

PLOT B (2 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.60	0.56
Gypsum		1.00	0.66
Colman			1.00

PLOT B (7 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.59	0.36
Gypsum		1.00	0.64
Colman			1.00

PLOT B (15 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.54	0.35
Gypsum		1.00	0.39
Colman			1.00

PLOT B (30 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.59	0.44
Gypsum		1.00	0.26
Colman			1.00

PLOT B (45 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.67	0.54
Gypsum		1.00	0.63
Colman			1.00

Table 5.3. (continued)

	PLOT C (2 cm)		
	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.55	0.55
Gypsum		1.00	0.80
Colman			1.00

	PLOT C (7 cm)		
	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.85	0.50
Gypsum		1.00	0.76
Colman			1.00

	PLOT C (15 cm)		
	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.79	0.68
Gypsum		1.00	0.87
Colman			1.00

	PLOT C (30 cm)		
	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.89	0.69
Gypsum		1.00	0.89
Colman			1.00

	PLOT C (45 cm)		
	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.91	0.85
Gypsum		1.00	0.87
Colman			1.00

Table 5.3. (continued)

PLOT D (2 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.42	0.45
Gypsum		1.00	0.71
Colman			1.00

PLOT D (7 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.39	0.41
Gypsum		1.00	0.70
Colman			1.00

PLOT D (15 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.18	0.47
Gypsum		1.00	0.49
Colman			1.00

PLOT D (30 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.71	0.66
Gypsum		1.00	0.61
Colman			1.00

PLOT D (45 cm)

	Psychrometer	Gypsum	Colman
Psychrometer	1.00	0.38	0.36
Gypsum		1.00	0.42
Colman			1.00

water potential while the resistance units produce a logrithmic
resistance value which is related to the soil matrix potential. It
is not very realistic to correlate these two different scales of
measurement. Even though the resistance readings are transformed to
logrithms they have a nonlinear relationship to the soil water potential.
A second factor is the difference in the hysteresis effects of the
two types of resistance sensors. In addition, there is the effect of
the varying soil characteristics on the individual sensors. Each sensor
has its own unique association with the soil to which it is exposed.
A third factor is the varying response times of the different sensors
to the same changes in the soil water status. This effect is a combi-
nation of the sensor water capacity and the soil properties.

CHAPTER VI

SUMMARY AND CONCLUSIONS

One of the objectives of this study was to compare sensors and define their limitations. The results obtained point out that no one sensor can fulfill all of the requirements necessary to obtain a complete picutre of the soil water status. The thermocouple psychrometer directly measures the total soil water potential not the soil water content. The gypsum and Colman resistance units give only a rough measurement of the soil matric potential. The neutron probe is very accurate for the measurement of soil water content at soil depths of 15 cm or greater, but its readings cannot be interpreted in terms of water potential.

A person who needs information about the soil water should make several considerations before choosing the types of sensors needed. The primary consideration is the type of soil water information required. If the investigator is interested in hydrologic balance, then soil water content will probably be the most useful data to him. Soil water contents can be used to establish the water balance for a particular study area. Water content data can also be used to determine the consumptive use by plants and evaporation. If soil water stress is of interest, then the sensors chosen must be capable of measuring the soil water potential. These data will be very useful in the study of plant-soil-water relationships.

Thermocouple psychrometers are not recommended for use in data acquisition systems. Exceptions can be made if the investigator is willing to make equipment checks on a very regular basis. The small microvolt output of this sensor demands a very precise and complex system. If these standards are not met erroneous data may result, and much time and expense wasted. The thermocouple psychrometer is, however, the most reliable in situ sensor for the direct measurement of a wide range of soil water potentials. Double-junction psychrometers have the added advantage of higher thermal stability as compared to single junction units, and are recommended for field use. The water potential data from the shallow sampling depths indicates that thermocouple psychrometers should not be installed at soil depths less than 5 cm. The 2 cm psychrometer time traces are highly discontinuous due to water potentials greater than the psychrometer measurement range. Other problems are the large temperature changes during measurement periods and the apparent atmosphere-soil interface effect at these shallow depths.

If the researcher needs information on the relative soil "wetness" or "dryness", then either of the resistance type sensors may be the most beneficial. These units can be monitored with data acquisition equipment at a very low cost and can also give an indication of soil water movement if placed in a stack at different soil depths. The choice of resistance sensor type can be based on the properties of the soils present in the study area. In saline conditions, the gypsum resistance unit will give the most reliable data due to the $CaSO_4$ buffer effect. However, in acid soils the $CaSO_4$ will dissolve very rapidly and may last less than one year under such conditions. At the Pawnee Site,

the ARS has used the same gypsum blocks for up to 6 years in Ascalon soils without replacement. If the soil salinity permits the use of the Colman units, they are the more responsive resistance sensor to the actual soil water conditions.

The neutron scattering method is a proven technique for measurement of the soil water content. However, it is most useful when manual measurement applications are appropriate and when shallow measurements are not required.

For plant soil water relations research, a combination of the neutron scattering method and thermocouple psychrometers can provide the most useful information. The sampling schedule does not have to be too intense. Instead, a routine schedule can be used except during periods of major precipitation inputs to the soil.

Based on observations made during this study, plant phenology appeared to be useful as a direct indication of the soil water status. For blue grama, a change in phenological stage appears to be a direct indication of a change in the soil water potential. Artificial water application on three of the calibration plots modified the timing of plant phenology. Unfortunately, no record of plant development was kept on these plots for comparison with the control plot. This information could have been useful in obtaining a more exact picture of the relationships between the soil water potential and plant development in the shortgrass prairie ecosystem.

LITERATURE CITED

Aitchison, G. D., P. F. Butler, and C. G. Gurr. 1951. Techniques associated with the use of gypsum block soil moisture meters. Australian Journal of Applied Science 2:56-75.

Bartos, D. L. and P. L. Sims. 1974. Root dynamics of a shortgrass ecosystem. Journal of Range Management. 27:33-36.

Belcher, D. J., T. R. Cuykendall, and H. S. Sack. 1950. The measurement of soil moisture and density by neutron and gamma ray scattering. Civil Aeronautics Admin. Tech. Devel. Report 127.

Bertolin, G. and J. Rasmussen. 1969. Preliminary report on the study of the precipitation on the Pawnee National Grassland. USIBP Grasslands Biome. Tech. Report No. 17. Colorado State Univ., Ft. Collins. 34 p.

Bourget, S. J., D. E. Elrick, and C. B. Tanner. 1958. Electrical resistance units for moisture measurements; their moisture hysteresis, uniformity and sensitivity. Soil Science 86:298.

Bouyoucos, G. J. 1956. Improved soil moisture meter. Agr. Engineering 37:261.

Bouyoucos, G. J. 1973. A new electrical soil-moisture measuring unit. Soil Science 114 (6):493.

Bouyoucos, G. J. and A. H. Mick. 1940. An electrical resistance method for the continuous measurement of soil moisture under field conditions. Mich Agr. Expt. Station. Tech. Bulletin 172.

Briggs, L. J. and H. L. Shantz. 1912. The relative wilting coefficients for different plants. Botanical Gazette 53:229-235.

Brown, R. W. and B. P. Van Haveren eds. 1972. Psychrometry in water relations research. Utah Agr. Expt. Station, Logan, Utah. 342 p.

Campbell, G. S. and W. H. Gardner. 1971. Psychrometric measurement of soil water potential: temperature and bulk density effects. Soil Science Society of America Proceedings. 36:8-12.

Cary, T. W. and S. A. Taylor. 1967. The dynamics of soil water II: temperature and solute effects in Chapter 13 Irrigation of Agricultural Lands. Havan, R. M., H. R. Haise and T. W. Edminster. eds. Monograph No. 11. American Society of Agronomy.

Chemical Rubber Company. 1965. Handbook of chemistry and physics. 45th edition. The Chemical Rubber Co., Cleveland, Ohio.

Chow, T. L. and J. De Vries. 1973. Dynamic measurement of soil and leaf with a double loop Peltier type thermocouple pshychrometer. Soil Science Society of America Proceedings. Vol. 37, No. 2.

Colman, E. A. 1946. The place of electrical soil moisture meters in hydrologic research. Trans. Amer. Geophys. Union 27(Vl): 847-853.

Colman, E. A. and T. M. Hendrix. 1949. The fiberglass electrical soil-moisture instrument. Soil Science 67:425-438.

Ewart, G. Y. and L. D. Baver. 1950. Salinity effects on soil moisture electrical resistance relationships. Soil Science Society of America Proceedings. Vol. 15, Sec. 1:56-63.

Galbraith, A. F. 1971. The soil water regime of a shortgrass prairie ecosystem. PhD dissertation, Colo. State Univ. Fort Collins. 127 p.

Hendrix, T. M. and E. A. Colman. 1951. Calibration of soil moisture units. Soil Science 71:419-427.

Hillel, D. 1971. Soil water: physical principles and processes. Academic Press, New York. 288 p.

Hoffman, G. J. and W. N. Herkelrath. 1968. Design features of intact leaf thermocouple psychrometers for measuring water potential. American Society of Agr. Engineers. 11:631-634.

Hyder, D. N. 1969. The impact of domestic animals on the function and structure of grassland ecosystems. p. 243-260. In Dix, R. L. and R. G. Beidleman. eds. The grassland ecosystem: a preliminary synthesis. Range Science Dept. Science Series No. 2. Colo. State Univ. Fort Collins.

Hyder, D. N. 1974. Ecological responses of native plants and guidelines for management of shortgrass range. USDA Technical Bulletin (In press).

Johnson, A. I. 1962. Methods of measuring soil moisture in the field. U.S. Dept. of the Interior, Geological Survey Water Supply Paper Vol. 1619.

Klute, A. 1969. The movement of water in unsaturated soils. In The Progress of Hydrology, Proceedings of the First International Seminar for Hydrology Professors. Vol. II, Specialized Hydrologic Subjects. p. 821-888.

Kohnke, H. 1968. Soil physics. McGraw Hill, Inc. New York, 224 p.

Kramer, P. J. 1969. Plant and soil water relationships: a modern synthesis. McGraw Hill, Inc. New York. 482 p.

Lang, A. R. G. and E. S. Trickett. 1965. Automatic scanning of spanner and droplet psychrometers having outputs up to 30 microvolts. Journal of Scientific Instruments. 42:777-782.

Lawless, G. P., N. A. MacGillivray and P. R. Nixon. 1963. Soil moisture interface effects upon readings of neutron moisture probes. Soil Science Society of America Proceedings. 27(5):502-507.

Lull, H. W. and K. G. Reinhart. 1955. Soil moisture measurement. U.S. Dept. of Agriculture. Southern Forest Experiment Station. Occasional paper 140. 56 p.

McQueen, I. S. and R. F. Miller. 1968. Calibration and evaluation of a wide-range gravimetric method for measuring moisture stress. Soil Science. 106(3):225-231.

Millar, C. E., L. M. Turk and H. D. Foth. 1965. Fundamentals of soil science. John Wiley and Sons, Inc., New York, 486 p.

Rasmussen, J. L., G. Bertolin and G. F. Almeyda. 1971. Grassland climatology of the Pawnee grassland. USIBP Grasslands Biome. Tech. Report. No. 127. Colorado State Univ., Fort Collins. 79 p.

Rauzi, F. and F. M. Smith. 1973. Infiltration rates: three soils with three grazing levels in northeastern Colorado. J. Range Manage. 26(2):126-129.

Rawlins, S. L. 1965. Theory for thermocouple psychrometers used to measure water potential in soil and plant smaples. Agric. Meteorology. 3(1966):293-310.

Rose, C. W. 1966. Agricultural physics. Pergamon Press Ltd. Oxford. 230 p.

Russell, Sir E. J. 1950. Soil conditions and plant growth. Longmans, Green and Co., Inc., London. 688 p.

Salisbury, F. B. and C. Ross. 1969. Plant physiology. Wadsworth Publishing Co., Inc. Belmont, Calif. 747 p.

Slayter, R. O. 1967. Plant-water relationships. Academic Press. New York. 366 p.

Spanner, D. C. 1951. The Peltier effect and its use in the measurement of suction pressure. Journal of Exper. Botany. p. 145-168.

Striffler, W. D. 1969. The grassland hydrologic cycle. p. 101-116. In R. L. Dix and R. G. Beidleman eds. The grassland ecosystem: a preliminary synthesis. Range Science Dept. Science Series. No. 2. Colo. State Univ. Fort Collins.

Taylor, S. A., D. D. Evans and W. D. Kemper. 1961. Evaluating soil water. Utah Agricultural Experiment Station, Logan, Utah, Bulletin 426. 67 p.

Van Bavel, C. H.M., N. Underwood, and R. W. Swanson. 1956. Soil moisture measurement by neutron moderation. Soil Science. 82:29-41.

Van Dyne, G. M. 1969. Analysis of structure and function of grass-land ecosystems. USIBP Grasslands Biome Continuation Proposal. Colo. State Univ. Fort Collins.

Van Haveren, B. P. 1974. Soil water phenomena of a shortgrass prairie site. M.S. Thesis, Colo. State Univ., Fort Collins. 164 p.

Van Haveren, B. P. and A. F. Galbraith. 1971. Some hydrologic and physical properties of the major soil types on the Pawnee Intensive Site. USIBP Grasslands Biome Tech. Report No. 115. Colo. State Univ. Fort Collins. 46 p.

Weaver, J. E. and F. E. Clements. 1938. Plant ecology. 2nd edition. McGraw-Hill Book Co., New York.

Weinberg, A. M. and E. P. Wigner. 1958. The physical theory of neutron chain reactors. Univ. of Chicago Press. Chicago, Ill.

Whitney, M. A. 1896-1899. Report of the chief of the division of agricultural soils. From annual reports of the Secretary of Agriculture.

Wiebe, H. H., R. W. Brown, T. W. Daniel and E. Campbell. 1970. Water potential measurements in trees. Bio Science 20: p 225-226.

Wiebe, H. H., G. S. Campbell, W. H. Gardner, S. L. Rawlins, J. W. Cary, and R. W. Brown. 1971. Measurement of plant and soil water status. Utah Agric. Exp. Sta. Bull. 484. 71 p.

APPENDIX A

Double-Junction Thermocouple Psychrometer Switching Unit:

Circuit Diagram and Materials
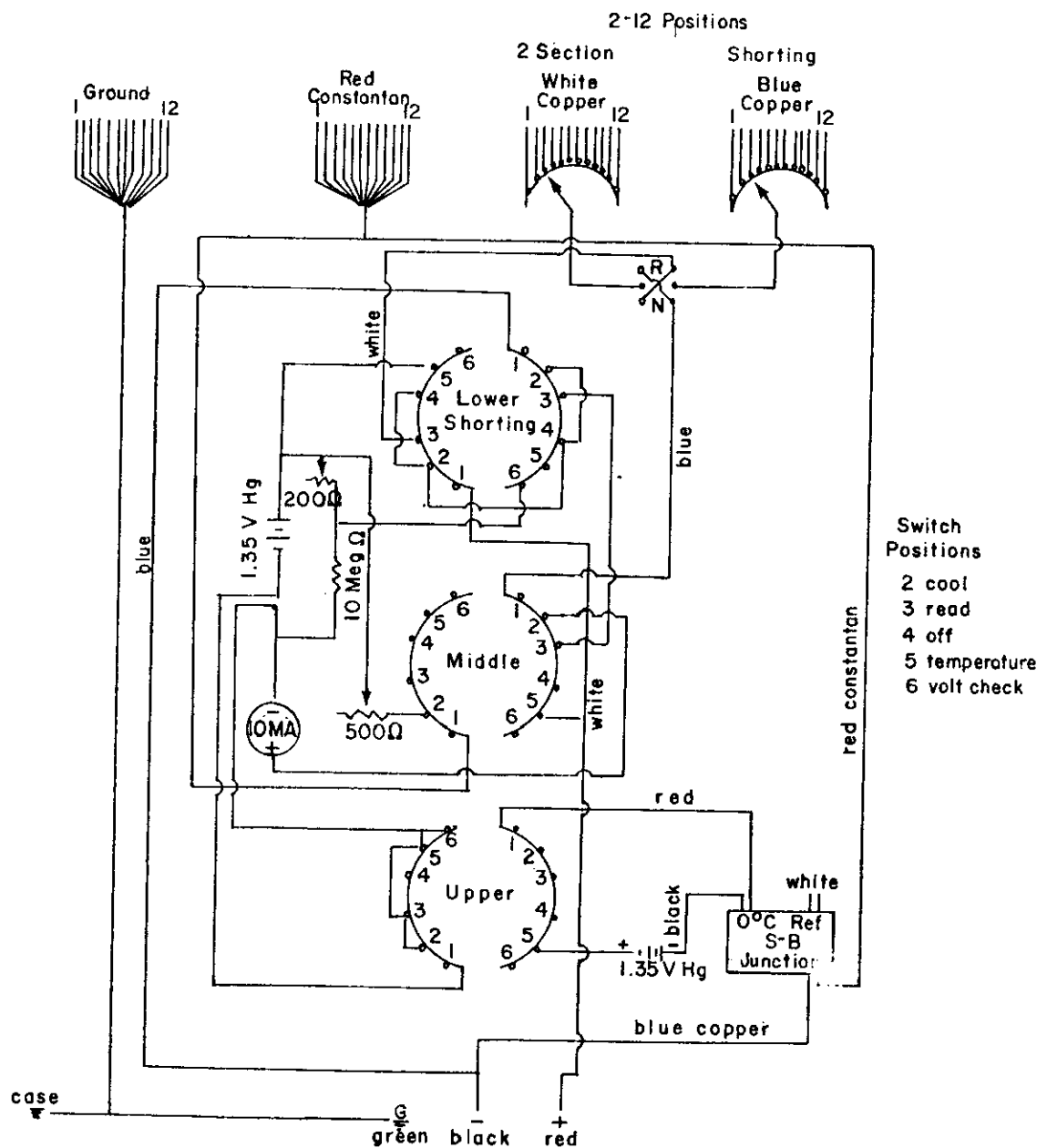
Double-junction thermocouple psychrometer switching unit circuit diagram by Brown (unpublished).

DOUBLE-JUNCTION THERMOCOUPLE PSYCHROMETER SWITCHING UNIT MATERIALS LIST

Allied Electronics
2400 Washington Blvd.
Chicago, Illinois 60612

Quantity	Description	Price
1	Bud Metal Utility Cabinet #CU-729	2.40
3	Miniature fluted binding posts	
	1-green #930-0511	.69
	1-red #930-0513	.69
	1-black #930-0507	.69
1	Miniature ceramic switch, shorting, 6 poles, 2-6 positions, 3 sections Allied #747-2022 (Centralab #PA-2022)	5.48
1	Miniature potentiometer, 500 ohm, 1/2 watt #875-0303	5.10
2	Mercury batteries, 1.35 V #853-0008 (Mallory #RM12R)	3.90
2	Battery holders #839-3239 (Keystone #139)	.70
1	DC milliammeter, Simpson 0-10 MA #918-4554 (Simpson #2121)	21.00
1	Miniature ceramic switch, shorting, 2 poles, 2-12 position, 2 sections, Allied #747-2004 (Centralab #PA-2004)	4.29
1	Alco #MST-205N, DPDT toggle switch Allied #700-5795	2.44

Quantity	Description	Price
1	Bourns #3009Y trimpot 0-200 ohms #528-75RC	3.02
1	Resistor, 10 megohm, 1/4 watt, 5% #824-1924	.09

Cramer/Denver
5465 E. Evans Pl.
Denver, Colorado 80222

12	Augat TO-5 sockets #8092-1G9 (@1.44)	17.28

or

1	Amphenol micro-ribbon miniature	4.00
	50 contact receptacle #20500	
1	Amphenol micro-ribbon miniature	5.54
	50 contact plug w/cable clamp #30500	

S-B Systems
2130 Prairie Glen
Manhattan, Kansas 66502

1	Programmable $0^{o}C$ Cu-Constantan temperature	43.00
	reference junction	

APPENDIX B

Field Data Forms and Program Calplot (program will be microfeisch)

GRASSLAND BIOME

U.S. INTERNATIONAL BIOLOGICAL PROGRAM

FIELD DATA SHEET--SOIL MOISTURE-MICROWATERSHEDS

IBP

Month	Day	Year	Watershed	Maximum Depth	Number Tubes Not Read	Counting Time (min.)	Treatment	Data Type	Site
2-3	4	5-6	7	8-9	11	13-15	17	19-22	24
-		-							

26-27	28-29
54	

Site

11 Pawnee

Data Type

54 Soil moisture - microwatersheds

Treatment

1 Ungrazed
2 Lightly grazed
3 Moderately grazed
4 Heavily grazed
5 Grazed 69, Ungrazed 70
A Diet light
B Diet moderate

C Field study
D ESA - O
E ESA - W
F ESA - N
G ESA - WN
H Lynn Lake
I Winter grazed

Tube	Probe	Tube	Probe	Tube	Probe	Tube	Probe	Tube	Probe	Tube	Probe	Tube	Probe	Tube	Probe	Tube	Probe	Tube	Probe
4-5	6-8	10-11	12-14	16-17	18-20	22-23	24-26	28-29	30-32	34-35	36-38	40-41	42-44	46-47	48-50	52-53	54-56	58-59	60-62

Depth	Counts	Counts	Counts	Counts	Counts	Counts	Counts	Counts	Counts	Counts	Counts	Date			Watershed
												Day	Month	Year	
1-3	4-9	10-15	16-21	22-27	28-33	34-39	40-45	46-51	52-57	58-63		65-66	67-68	69-70	72

GRASSLAND BIOME

DATA SHEET - CALIBRATION PLOT - SOIL WATER POTENTIAL

SITE	TREATMENT	DATE			TIME	PLOT	DEPTH		NORMAL PSYCHROMETER	REVERSE PSYCHROMETER	THERMOCOUPLE	THERMISTER	HI BOUYOUCUS	LO BOUYOUCUS	HI COLEMAN	LO COLEMAN
		MO.	DAY	YEAR												
1-2	3	4-5	6-7	8-9	11-14	16	17		21-25	31-35	41-45	51-54	61-63	66-68	71-73	76-78

```
      PROGRAM CALPLOT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,PUNCH,
     ATAPE7=PUNCH,TAPE8)
C
C     ************************************************************************
C     PROGRAM CALPLOT CONVERTS TWO SETS OF READINGS FROM EACH OF THREE
C     SOIL-WATER SENSORS(PSYCHROMETER-NORMAL AND REVERSE, BOUYOUCUS-
C     HIGH AND LOW, AND COLMAN-HIGH AND LOW) INTO STANDARD UNITS FOR
C     COMPARISON OF THE DIFFERENT SENSORS.
C
C     TEMPERATURE READINGS FROM A THEMOCOUPLE SENSOR ARE CONVERTED
C     TO STANDARD CENTIGRADE AND USED TO DETERMINE COEFFICIENTS IN
C     THE CONVERSION EQUATIONS FOR THE PSYCHROMETER READINGS.
C
C     TEMPERATURES FROM A THERMISTER ARE CONVERTED TO FAHRENHEIT FOR
C     USE IN THE BOUYOUCUS AND COLMAN CONVERSION EQUATIONS.
C     ************************************************************************
C
      COMMON N,SITE(200),TREAT(200),DATE(200),TIME(200),PLOT(200),
     ADEPTH(200),NPSYCH(200),RPSYCH(200),THRMCP(200),THRMIS(200),
     BHBOUY(200),LBOUY(200),HCOLE(200),LCOLE(200),PUPAR,TAPAR,PRPAR
      INTEGER SITE,TREAT,DATE,TIME,PLOT,DEPTH,PRPAR,PUPAR,TAPAR,PAR
      REAL LBOUY,LCOLE,NPSYCH
C.....READ THE PARAMETER CARD - IT MUST HAVE AN * IN COL. 1
C.....A 1 IN COL. 10 MEANS PRINTED OUTPUT IS DESIRED
C.....A 1 IN COL. 20 MEANS PUNCHED OUTPUT IS DESIRED
C.....A 1 IN COL. 30 MEANS MAGNETIC TAPE OR DISK FILE OUTPUT IS DESIRED
      READ(5,1)PAR,PRPAR,PUPAR,TAPAR
1     FORMAT(A1,8X,3(I1,9X))
      IF(PAR.EQ.1H*)GO TO 10
      PRINT 100
100   FORMAT(20X,*PARAMETER CARD IS MISSING OR INCORRECT*)
      STOP
10    CALL OVERLAY(4HCONV,1,0)
      CALL OVERLAY(4HCONV,2,0)
      CALL OVERLAY(4HCONV,3,0)
      CALL OVERLAY(4HCONV,4,0)
      CALL OVERLAY(4HCONV,5,0)
      CALL OVERLAY(4HCONV,6,0)
      END
```

```
      PROGRAM READ
C
C
C     ********************************************************************
C        THE READ SECTION PLACES INPUT DATA INTO ARRAYS AND COUNTS THE NUMBER
C     OF RECORDS READ.
C     ********************************************************************
C
      COMMON N,SITE(200),TREAT(200),DATE(200),TIME(200),PLOT(200),
     ADEPTH(200),NPSYCH(200),PPSYCH(200),THRMCP(200),THRMIS(200),
     BHBODY(200),LBODY(200),HCOLE(200),LCOLE(200),PUPAR,TAPAR,PRPAR
      INTEGER SITE,TREAT,DATE,TIME,PLOT,DEPTH,PRPAR,PUPAR,TAPAR
      REAL LBODY,LCOLE,NPSYCH
      N=1
1     READ(5,2)SITE(N),TREAT(N),DATE(N),TIME(N),PLOT(N),DEPTH(N),
     ANPSYCH(N),PPSYCH(N),THRMCP(N),THRMIS(N),HBODY(N),LBODY(N),
     BHCOLE(N),LCOLE(N)
2     FORMAT(I2,A1,I6,1X,I4,1X,A1,I1,3X,F5.2,5X,F5.2,5X,F5.3,5X,F4.1,
     A6X,F3.0,3(2X,F3.0))
      IF(EOF(5),NE.0.0)GO TO 5
      N=N+1
      GO TO 1
5     N = N-1
      END
```

```
      PROGRAM TEMP
C
C     ***************************************************************************
C     TEMP CONVERTS THE THERMISTER READINGS TO DEGREES FAHRENHEIT AND
C     THE THERMOCOUPLE READINGS TO DEGREES CENTIGRADE.
C     ***************************************************************************
C
      COMMON N,SITE(200),TREAT(200),DATE(200),TIME(200),PLOT(200),
     ADEPTH(200),NPSYCH(200),RPSYCH(200),THRMCP(200),THRMIS(200),
     BHBOUY(200),LBOUY(200),HCOLE(200),LCOLE(200),PUPAR,TAPAR,PRPAR
      INTEGER SITE,TREAT,DATE,TIME,PLOT,DEPTH,PRPAR,PUPAR,TAPAR
      REAL LBOUY,LCOLE,NPSYCH
      DO 10 I=1,N
        THRMIS(I) = 9.0*THRMIS(I)/5.0 + 32.0
        THRMCP(I) = 0.8222 + 24.3*THRMCP(I)
10    CONTINUE
      END
```

```
       PROGRAM PSYCH
C
C
C      ****************************************************************************
C      PROGRAM PSYCH CONVERTS BOTH NORMAL AND REVERSE PSYCHROMETER READINGS BY
C      A SECOND DEGREE POLYNOMIAL EQUATION. THE COEFFICIENTS FOR THE EQUATION
C      ARE DETERMINED ACCORDING TO THE PLOT AND DEPTH OF THE SENSOR. THE
C      FINAL EQUATION IS MULTIPLIED BY A TEMPERATURE CORRECTION FACTOR WHICH
C      IS DETERMINED FROM THE THERMOCOUPLE VALUE.
C      ****************************************************************************
C
       COMMON N,SITE(200),TREAT(200),DATE(200),TIME(200),PLOT(200),
      ADEPTH(200),NPSYCH(200),RPSYCH(200),THRMCP(200),THRMIS(200),
      BHBUUY(200),LBOUY(200),HCOLE(200),LCOLE(200),PUPAR,TAPAR,PRPAR
       DIMENSION PCOEF(3,20),TCORR(5),P(4)
       INTEGER SITE,TREAT,DATE,TIME,PLOT,DEPTH,PRPAR,PUPAR,TAPAR,P
       REAL LBOUY,LCOLE,NPSYCH
       DATA P,TCORR,PCOEF/1HA,1HB,1HC,1HD,1.257,1.0,0.832,0.712,0.629,
      A-1.11219,2.400002,0.001286,-0.839332,2.254006,0.002764,
      B-1.230775,2.078532,0.018152,-0.931377,2.187733,0.022609,
      C-0.366755,2.1256B7,0.028503,-0.941358,2.327063,0.007900,
      D-1.358770,2.634500,-0.005660,0.039481,1.790124,0.043203,
      E-0.176570,1.961743,0.027972,-0.015242,2.243775,0.015937,
      F-0.725952,2.404286,0.001761,-0.794595,2.351798,0.006059,
      G-0.481818,2.027229,0.026051,-0.178192,2.06160H,0.018244,
      H-0.252562,1.939059,0.031771,-0.568746,1.892956,0.034922,
      I-0.814816,2.143412,0.021110,-1.795082,2.2526424,0.000039,
      J-0.184209,1.920146,0.036362,-0.677931,2.100918,0.020183/
       DO 25 J=1,N
C.....DETERMINE THE PLOT VALUE
       DO 15 K=1,4
          IF(PLOT(J).EQ.P(K))GO TO 16
15     CONTINUE
C.....DETERMINE, FROM THE PLOT AND DEPTH, WHICH SET OF THREE COEFFICIENTS TO USE
16     I = 5*(K-1) + DEPTH(J)
C.....THE TEMPERATURE CORRECTION FACTORS ARE FOR 10, 20, 30, 40,
C.....AND 50 DEGREES CENTIGRADE
C.....FIND THE RANGE OF THE THERMOCOUPLE VALUE(10-20, 20-30, 30-40, 40-50)
       DO 17 MAXT=20,50,10
          IF(THRMCP(J).LT.MAXT)GO TO 18
17     CONTINUE
C.....IF THE THERMOCOUPLE VALUE IS GREATER THAN 50, THE CORRECTION FACTOR
C.....IS THE SAME AS FOR A 50 DEGREE VALUE
       CORR=TCORR(5)
       GO TO 19
18     MINT = MAXT-10
C.....INTERPOLATE THE CORRECTION FACTOR WITHIN THE RANGE GIVEN BY THE
C.....THERMOCOUPLE VALUE
       CORR = TCORR(MINT/10) + (THRMCP(J)-MINT)/10*(TCORR(MAXT/10) -
      A TCORR(MINT/10))
C.....IF THE PSYCHROMETER VALUE IS ZERO, NO CORRECTION IS NECESSARY
19     IF(NPSYCH(J).EQ.0.0)GO TO 20
C.....CALCULATE THE CORRECTED PSYCHROMETER(NORMAL) VALUE
       NPSYCH(J) = -CORR*(PCOEF(1,I) + NPSYCH(J)*(PCOEF(2,I) +
      A NPSYCH(J)*PCOEF(3,I)))
```

```
C.....IF THE PSYCHROMETER VALUE IS ZERU, NO CORRECTION IS NECESSARY
20      IF(RPSYCH(J).EQ.0.0)GO TO 21
C.....CALCULATE THE CORRECTED PSYCHROMETER(REVERSE) VALUE
        RPSYCH(J) = -CORR*(PCOEF(1,I) + RPSYCH(J)*(PCOEF(2,I) +
     A  RPSYCH(J)*PCOEF(3,I)))
C.....IF THE PSYCHROMTER VALUE IS POSITIVE, SET IT TO ZERO
21      IF(NPSYCH(J).GT.0.0)NPSYCH(J)=0.0
        IF(RPSYCH(J).GT.0.0)RPSYCH(J)=0.0
25      CONTINUE
        END
```

```
      PROGRAM RESHI
C
C     ***********************************************************************
C     PROGRAM RESHI CONVERTS HIGH BOUYOUCUS AND COLMAN READINGS ACCORDING
C     TO A TEN DEGREE POLYNOMIAL EQUATION. THE COEFFICIENTS FOR THE EQUATION
C     ARE DEPENDENT ON THE TEMPERATURE VALUE FROM THE THERMISTER.
C     ***********************************************************************
C
      COMMON N,SITE(200),TREAT(200),DATE(200),TIME(200),PLOT(200),
     ADEPTH(200),NPSYCH(200),RPSYCH(200),THRMCP(200),THRMIS(200),
     BHBOUY(200),LBOUY(200),HCOLE(200),LCOLE(200),PUPAR,TAPAR,PRPAR
      DIMENSION RHCOEF(11,16)
      INTEGER SITE,TREAT,DATE,TIME,PLOT,DEPTH,PRPAR,PUPAR,TAPAR
      REAL LBOUY,LCOLE,NPSYCH
      DATA ((RHCOEF(I,J),I=1,11),J=1,4)/6.37859,-0.1126682855,
     A0.6092886264E-02,
     A-0.22462513525-03,0.5211402953E-05,-0.1766236418E-07,
     B0.1543760405E-09,-0.4748167828E-11,0.1665969062E-13,
     C-0.4158794672E-16,0.4011753824E-19,6.43167,-0.1137599101,
     D0.5067753762E-02,-0.2211741777E-03,0.5101334159E-05,
     E-0.7591271489E-07,0.7165141179E-09,-0.4663999924E-11,
     F0.1840926826E-13,-0.4122943449E-16,0.3996993543E-19,
     G6.48516,-0.1148515374,0.6042621545E-02,-0.2177232324E-03,
     H0.4991265677E-05,-0.7416307004E-07,0.7226532355BE-09,
     I-0.4579812218E-11,0.1615884647E-13,-0.4087092307E-16,
     J0.3982233293E-19,6.52952,-0.114233309,0.5918574244E-02,
     K-0.2105930049E-03,0.4765764755E-05,-0.7072621656E-07,
     L0.6872521625E-09,-0.4353465244E-11,0.1728438576E-13,
     M-0.3900759342E-16,0.3814740515E-19/
      DATA ((RHCOEF(I,J),I=1,11),J=5,8)/6.57938,-0.1146892354,
     N0.6076503224E-02,-0.2243353960E-03,0.5280253833E-05,
     O-0.8033303968E-07,0.7967640478E-09,-0.5150107656E-11,
     P0.2072425259E-13,-0.4724882949E-16,0.4656238719E-19,
     Q6.63847,-0.1177177661,0.6263134207E-02,-0.2300659726E-03,
     R0.5373392238E-05,-0.8106473107E-07,0.7994468547E-09,
     S-0.5115852349E-11,0.2045067113E-13,-0.4630397433E-16,
     T0.4547986278E-19,6.69746,-0.1202192851,0.6452153397E-02,
     U-0.2388475641E-03,0.5616040624E-05,-0.8517912653E-07,
     V0.8432664949E-09,-0.5409564323E-11,0.2165629495E-13,
     W-0.4910948972E-16,0.4816043716E-19,6.75642,-0.122720B139,
     X0.6641169942E-02,-0.2476291946E-03,0.5858691623E-05,
     Y-0.6929357504E-07,0.8670847057E-09,-0.5703280443E-11,
     Z0.2285532554E-13,-0.5165505009E-16,0.5084105862E-19/
      DATA ((RHCOEF(I,J),I=1,11),J=9,12)/6.81836,-0.1275577204,
     A0.7118598523E-02,-0.2700785658E-03,
     B0.64443197E-05,-0.9852692925E-07,0.9786143421E-09,
     C-0.6276835745E-11,0.2505786092E-13,-0.5658069617E-16,
     D0.5517544736E-19,6.87314,-0.1292281265,0.7305352729E-02,
     E-0.2802859116E-03,0.6755551111E-05,-0.1041557374E-06,
     F0.1040912377E-08,-0.6702559696E-11,0.2680967276E-13,
     G-0.6055964925E-16,0.5900802765E-19,6.93174,-0.1313456989,
     H0.7436615889E-02,-0.2831348679E-03,0.6748690301E-05,
     I-0.1028675494E-06,0.1016996255E-08,-0.6483421572E-11,
     J0.2569304168E-13,-0.5753214885E-16,0.5559462914E-19,
```

```
      K6.99572,-0.13728H4486,0.821083688E-02,-0.3285092849E-03,
      L0.8140905457E-05,-0.1278751532E-06,0.1295027889E-08,
      M-0.8422900081E-11,0.3395895010E-13,-0.7720416605E-16,
      N0.7562506428E-19/
       DATA ((RHCOEF(I,J),I=1,11),J=13,16)/7.05569,-0.1407359318,
      O0.8592029563E-02,
      O-0.3493236378E-03,0.8754042002E-05,-0.1386487238E-06,
      P0.1413767696E-08,-0.9251795027E-11,0.3751504103E-13,
      Q-0.857559185E-16,0.8443712625E-19,7.11096,-0.1374349732,
      R0.7991993123E-02,-0.315050408E-03,0.7795345155E-05,
      S-0.1234624556E-06,0.1268590338E-08,-0.8400178608E-11,
      T0.3453182877E-13,-0.8007023107E-16,0.799610702E-19,
      U7.18719,-0.140417935,0.791700695E-02,-0.29958486E-03,
      V0.7144121352E-05,-0.1096379619E-06,0.1096932175E-08,
      W-0.7103441096E-11,0.286679784E-13,-0.6547984369E-16,
      X0.6459925619E-19,7.22669,-0.1366368399,0.7281982773E-02,
      Y-0.2621107157E-03,0.6020729154E-05,-0.9007904736E-07,
      Z0.8870438489E-09,-0.5693185262E-11,0.2288221274E-13,
      A-0.5221807026E-16,0.515766264/E-19/
       DO 30 K=1,N
C.....FIND THE TEMPERATUE RANGE FOR THE THERMISTER
       DO 10 I=50,110,4
          IF(THRMIS(K).LT.(I+3))GO TO 15
10     CONTINUE
C.....FIND THE SET OF ELEVEN COEFFICIENTS TO BE USED IN THE CONVERSION EQUATION
15     J = (I-50)/4 + 1
C.....ASSIGN A LARGE BOUYOUCUS VALUE IF THE ORIGINAL VALUE IS GREATER THAN 190
       IF(HBOUY(K).GT.190.0)GO TO 16
C.....IF THE BOUYOUCUS VALUE IS ZERO, NO CORRECTION IS NECESSARY
       IF(HBOUY(K).EQ.0.0)GO TO 21
C.....CALCULATE THE CORRECTED BOUYOUCUS(HIGH) VALUE
       HBOUY(K) = RHCOEF(1,J) + HBOUY(K)*(RHCOEF(2,J) + HBOUY(K)*
      A  (RHCOEF(3,J) + HBOUY(K)*(RHCOEF(4,J) + HBOUY(K)*(RHCOEF(5,J) +
      B   HBOUY(K)*(RHCOEF(6,J) + HBOUY(K)*(RHCOEF(7,J) + HBOUY(K)*
      C   (RHCOEF(8,J) + HBOUY(K)*(RHCOEF(9,J) + HBOUY(K)*(RHCOEF(10,J) +
      D   HBOUY(K)*RHCOEF(11,J))))))))))
       GO TO 21
16     HBOUY(K) = 117.0
C.....ASSIGN A LARGE COLMAN VALUE, IF THE ORIGINAL VALUE IS GREATER THAN 190
21     IF(HCOLE(K).GT.190.0)GO TO 22
C.....IF THE COLMAN VALUE IS ZERO, NO CORRECTION IS NECESSARY
       IF(HCOLE(K).EQ.0.0)GO TO 30
C.....CALCULATE THE CORRECTED COLMAN(HIGH) VALUE
       HCOLE(K) = RHCOEF(1,J) + HCOLE(K)*(RHCOEF(2,J) + HCOLE(K)*
      A  (RHCOEF(3,J) + HCOLE(K)*(RHCOEF(4,J) + HCOLE(K)*(RHCOEF(5,J) +
      B   HCOLE(K)*(RHCOEF(6,J) + HCOLE(K)*(RHCOEF(7,J) + HCOLE(K)*
      C   (RHCOEF(8,J) + HCOLE(K)*(RHCOEF(9,J) + HCOLE(K)*(RHCOEF(10,J) +
      D   HCOLE(K)*RHCOEF(11,J))))))))))
       GO TO 30
22     HCOLE(K) = 117.0
30     CONTINUE
       END
```

```
      PROGRAM RESLO
C
C
C     *****************************************************************
C     PROGRAM RESLO CONVERTS LOW BOUYOUCUS AND COLMAN READINGS ACCORDING TO
C     A TEN DEGREE POLYNOMIAL EQUATION. THE COEFFICIENTS FOR THE EQUATION ARE
C     DEPENDENT ON THE TEMPERATURE VALUE FROM THE THERMISTER.
C     *****************************************************************
C
      COMMON N,SITE(200),TREAT(200),DATE(200),TIME(200),PLOT(200),
     ADEPTH(200),NPSYCH(200),RPSYCH(200),THRMCP(200),THRMIS(200),
     BHBOUY(200),LBOUY(200),HCOLE(200),LCOLE(200),PUPAR,TAPAR,PRPAR
      DIMENSION RLCOEF(9,16)
      INTEGER SITE,TREAT,DATE,TIME,PLOT,DEPTH,PRPAR,PUPAR,TAPAR
      REAL LBOUY,LCOLE,NPSYCH
      DATA ((RLCOEF(I,J),I=1,9),J=1,6)/-6.68064,0.947879207,
     A-0.3448588481E-01,
     A0.6821036341E-03,-0.81455496801E-05,0.6037911212E-07,
     B-0.272066331E-09,0.6828803397E-12,-0.7326425174E-15,
     C-3.80046,0.7291109517,-0.27359929969E-01,0.552945682E-03,
     D-0.6716554294E-05,0.5047146317E-07,-0.229696169E-09,
     E0.5825090191E-12,-0.6297931724E-15,-2.41034,0.6297699603,
     F-0.2426194267E-01,0.4964406434E-03,-0.61199304086E-05,
     G0.4629386002E-07,-0.2116914723E-09,0.53702711886E-12,
     H-0.5807221393E-15,-1.95831,0.5845238634,-0.22353343E-01,
     I0.455992096RE-03,-0.55086880482E-05,0.4196554933E-07,
     J-0.1914420004E-09,0.48505475194E-12,-0.5243805836E-15,
     K-5.13012,0.8416832013,-0.3103282776E-01,0.516763426RE-03,
     L-0.7357669343E-05,0.542312138E-07,-0.24215731716E-09,
     M0.6009437608E-12,-0.6356825051E-15,-3.80859,0.7399126722,
     N-0.2761242766E-01,0.5528236591E-03,-0.6632981991E-05,
     O0.491326769RE-07,-0.2203796049E-09,0.5491997346E-12,
     P-0.5841992653E-15/
      DATA ((RLCOEF(I,J),I=1,9),J=7,12)/1.49851,0.3100154973,
     Q-0.1283753832E-01,
     Q0.272307791E-03,-0.34235746E-05,0.2631859953E-07,
     R-0.1219040624E-09,0.3127166445E-12,-0.3418447385E-15,
     S3.84409,0.12235004R,-0.6389553234E-02,0.1498098241E-03,
     T-0.199851863E-05,0.1601219059E-07,-0.7644255888E-10,
     U0.2008120269E-12,-0.2240867467E-15,4.47874,0.7529129162E-01,
     V-0.4777127793E-02,0.1186200888E-03,-0.1632195509E-05,
     W0.1336065301E-07,-0.6493500954E-10,0.1734488071E-12,
     X-0.1967610637E-15,6.50472,-0.8110024175E-01,0.3663917516E-03,
     Y0.25R6429454E-04,-0.626191c474E-06,0.6671286617E-08,
     Z-0.38089396l5E-10,0.1139731086E-12,-0.1409304696E-15,
     A-10.5100,0.133204465E01,-0.4926766163E-01,0.9911269658E-03,
     B-0.1200400143E-04,0.6992206221E-07,-0.4078503969E-09,
     C0.1026235137E-11,-0.1950169236E-14,-2.9989,0.7075327495,
     D-0.2721315767E-01,0.5606074639E-03,-0.6919118005E-05,
     E0.5267201243E-07,-0.2423703363E-09,0.6180603918E-12,
     F-0.6706390305E-15/
      DATA ((RLCOEF(I,J),I=1,9),J=13,16)/4.51221,0.8302062056E-01,
     G-0.5158422763E-02,
     G0.1300877603E-03,-0.1834232327E-05,0.1542138721E-07,
     H-0.7688021038E-10,0.2098854942E-12,-0.2421086795E-15,
```

```
      I3.55144.0.1529327546.-0.7156144723E-02.0.1599221476E-03.
      J-0.207981132E-05.0.1645401328E-07.-0.7818648546E-10.
      K0.205412359E-12.-0.2298482499E-15.4.30153.0.9632802123E-01.
      L-0.5290009269E-02.0.1262533712E-03.-0.1716552643E-05.
      M0.1405777937E-07.-0.6876305100E-10.0.1853114899E-12.
      N-0.2121746973E-15.2.94096.0.2114383872.-0.9274430554E-02.
      00.2015000636E-03.-0.2565941691E-05.0.1993949055E-07.
      P-0.9323648641E-10.0.2414391095E-12.-0.2666073568E-15/
      DO 30 K=1.N
C.....FIND THE TEMPERATUE RANGE FOR THE THERMISTER
         DO 10 I=50.110.4
            IF(THRMIS(K).LT.(I+3))GO TO 15
10       CONTINUE
C.....FIND THE SET OF NINE COEFFICIENTS TO BE USED IN THE CONVERSION EQUATION
15       J = (I-50)/4 + 1
C.....ASSIGN A LARGE BOUYOUCUS VALUE IF THE ORIGINAL VALUE IS GREATER THAN 200
         IF(LBOUY(K).GT.200.0)GO TO 16
C.....IF THE BOUYOUCUS VALUE IS ZERO. NO CORRECTION IS NECESSARY
         IF(LBOUY(K).EO.0.0)GO TO 21
C.....CALCULATE THE CORRECTED BOUYOUCUS(LOW) VALUE
         LBOUY(K) = RLCOEF(1.J) + LBOUY(K)*(RLCOEF(2.J) + LBOUY(K)*
     A   (RLCOEF(3.J) + LBOUY(K)*(RLCOEF(4.J) + LBOUY(K)*(RLCOEF(5.J) +
     B   LBOUY(K)*(RLCOEF(6.J) + LBOUY(K)*(RLCOEF(7.J) + LBOUY(K)*
     C   (RLCOEF(8.J) + LBOUY(K)*RLCOEF(9.J)))))))))
         GO TO 21
16       LBOUY(K) = 117.0
C.....ASSIGN A LARGE COLMAN VALUE. IF THE ORIGINAL VALUE IS GREATER THAN 200
21       IF(LCOLE(K).GT.200.0)GO TO 22
C.....IF THE COLMAN VALUE IS ZERO. NO CORRECTION IS NECESSARY
         IF(LCOLE(K).EO.0.0)GO TO 30
C.....CALCULATE THE CORRECTED COLMAN(LOW) VALUE
         LCOLE(K) = RLCOEF(1.J) + LCOLE(K)*(RLCOEF(2.J) + LCOLE(K)*
     A   (RLCOEF(3.J) + LCOLE(K)*(RLCOEF(4.J) + LCOLE(K)*(RLCOEF(5.J) +
     B   LCOLE(K)*(RLCOEF(6.J) + LCOLE(K)*(RLCOEF(7.J) + LCOLE(K)*
     C   (RLCOEF(8.J) + LCOLE(K)*RLCOEF(9.J)))))))))
         GO TO 30
22       LCOLE(K) = 117.0
30    CONTINUE
      END
```

```
      COMMON N,SITE(200),TREAT(200),DATE(200),TIME(200),PLOT(200),
     ADEPTH(200),NPSYCH(200),RPSYCH(200),THRMCP(200),THRMIS(200),
     BHBOUY(200),LBOUY(200),HCOLE(200),LCOLE(200),PUPAR,TAPAR,PRPAR
      INTEGER SITE,TREAT,DATE,TIME,PLOT,DEPTH,PRPAR,PUPAR,TAPAR
      REAL LBOUY,LCOLE,NPSYCH
      IPAGE=LINES=1
        WRITE(6,101)IPAGE
      DO 20 K=1,N
C.....PRINT 45 LINES PER PAGE
      IF(LINES.LE.45)GO TO 5
        WRITE(6,105)
      LINES=1
C.....INCREMENT PAGE NUMBER
        IPAGE=IPAGE+1 $ ITIME=1
C.....PRINT TITLE AND HEADINGS
        WRITE(6,101)IPAGE
5     LINES = LINES+1
C.....GROUP DATA BY TIME. SKIPPING A LINE BETWEEN EACH TIME INTERVAL
         IF(TIME(K).NE.ITIME)WRITE(6,104)
         ITIME = TIME(K)
         IF(PRPAR.EQ.1)WRITE(6,102)SITE(K),TREAT(K),DATE(K),TIME(K),
     A   PLOT(K),DEPTH(K),NPSYCH(K),RPSYCH(K),THRMCP(K),THRMIS(K),
     B   HBOUY(K),LBOUY(K),HCOLE(K),LCOLE(K)
         IF(PUPAR.EQ.1)WRITE(7,110)SITE(K),TREAT(K),DATE(K),TIME(K),
     A   PLOT(K),DEPTH(K),NPSYCH(K),RPSYCH(K),THRMCP(K),
     B   HBOUY(K),LBOUY(K),HCOLE(K),LCOLE(K)
         IF(TAPAR.EQ.1)WRITE(8,110)SITE(K),TREAT(K),DATE(K),TIME(K),
     A   PLOT(K),DEPTH(K),NPSYCH(K),RPSYCH(K),THRMCP(K),
     B   HBOUY(K),LBOUY(K),HCOLE(K),LCOLE(K)
20    CONTINUE
101   FORMAT(*1*,/,* *,120X,*PAGE*,I3,/,* *,46X,*CALIBRATION DATA - SOIL
     A WATER POTENTIAL*,/,*-*,55X,*PSYCHROMETER*,8X,*THERMO-*,4X,*THERM-
     B*,6X,*BOUYOUCUS*,10X,*COLMAN*,/,* *,11X,*TREAT-*,36X, *(-BARS H2O
     CPOT.)*,6X,*COUPLE*,5X,*ISTER*,7X,*( LOG R )*,9X,*( LOG R )*,/,* *,
     D4X,*SITE*,3X,*MENT*,6X,*DATE*,4X,*TIME*,3X,*PLOT*,3X,*DEPTH*,
     E4X,*NORMAL*,5X,*REVERSE*,5X,*(DEG C)*,3X,*(DEG F)*,4X,*HIGH*,
     F5X,*LOW*,6X,*HIGH*,5X,*LOW*)
102   FORMAT(* *,5X,I2,6X,A1,6X,I6,3X,I4,4X,A1,7X,I1,6X,F6.2,5X,F6.2,
     A6X,F5.2,6X,F5.1,4X,F6.3,2X,F6.3,4X,F6.3,2X,F6.3)
104   FORMAT(* *)
105   FORMAT(70H0* INDICATES THE BOUYOUCUS OR COLMAN VALUE WAS ABOVE TH
     AE NORMAL RANGE)
110   FORMAT(I2,1X,A1,1X,I6,1X,I4,1X,A1,1X,I1,1X,F6.2,1X,F6.2,1X,F5.2,
     A1X,F6.3,1X,F6.3,1X,F6.3,1X,F6.3)
      END
```

```
      PROGRAM BLANK(INPUT,OUTPUT,TAPE5=INPUT,TAPE6)
C......
C......PROGRAM BLANK IS USED TO CONSOLIDATE THE DATA FROM PROGRAM CALPLOT
C......FOR THE THREE SOIL WATER SENSORS IT ALSO USES FUNCTION JULIAN TO CHANGE
C...... THE TIME OF READING TO A JULIAN DATE
C......
      DIMENSION IA(6),IN(6)
5     READ(5,100)K,MO,MD,MY,TYM,L,IA(1),IN(1),IA(2),IN(2),ITM,(IA(I),
     2IN(I),I=3,6)
100   FORMAT(A5,3I2,F5.0,A4,2(A2,A5),A6,4(A2,A5))
      IF(EOF(5).NE.0)GO TO 30
      DO 20 I=1,6
      IF(IA(I).NE.2H *)GO TO 15
      IA(I)=1H
      IN(I)=1H
      GO TO 20
15    CONTINUE
      IF(I.GT.2)GO TO 17
      IF(IN(I).EQ.5H-0.00)IN(I)=1H
      GO TO 20
17    CONTINUE
      IF(IN(I).NE.5H0.000.OR.IA(I).NE.2H -)GO TO 20
      IA(I)=1H
      IN(I)=1H
20    CONTINUE
      IF(IN(1).EQ.1H )IA(1)=2H -
      IF(IN(2).EQ.1H )IA(2)=2H -
      IF(IN(1).EQ.1H )IN(1)=5H80.00
      IF(IN(2).EQ.1H )IN(2)=5H80.00
      IF(IN(3).EQ.1H )IN(3)=IN(4)
      IF(IN(5).EQ.1H )IN(5)=IN(6)
      AJ=JULIAN(MD,MO,MY)
      TYM=AJ+TYM/2400.
      WRITE(6,200) K,TYM,L,IA(1),IN(1),IA(2),IN(2),ITM,IN(3),IN(5)
200   FORMAT(A6,F8.3,3X,A4,2(A2,A5),A6,2X,A5,9X,A5)
      GO TO 5
30    ENDFILE 6
      STOP
      END
```

```
      FUNCTION JULIAN(IDAY,MO,IYR)
C.....GIVEN DAY, MONTH, YEAR RETURNS JULIAN DATE
      INTEGER DPM(12)
      DATA DPM/0,31,59,90,120,151,181,212,243,273,304,334/
      IF(IYR.LE.0) GO TO 2
      K=DPM(MO)+IDAY
      IF(MOD(IYR,4).NE.0.0.MO.LE.2) GO TO 1
      K=K+1
1     JULIAN=K
      RETURN
2     JULIAN=0
      RETURN
      END
```

APPENDIX C

Comparisons of Individual Resistance Sensors and the Soil
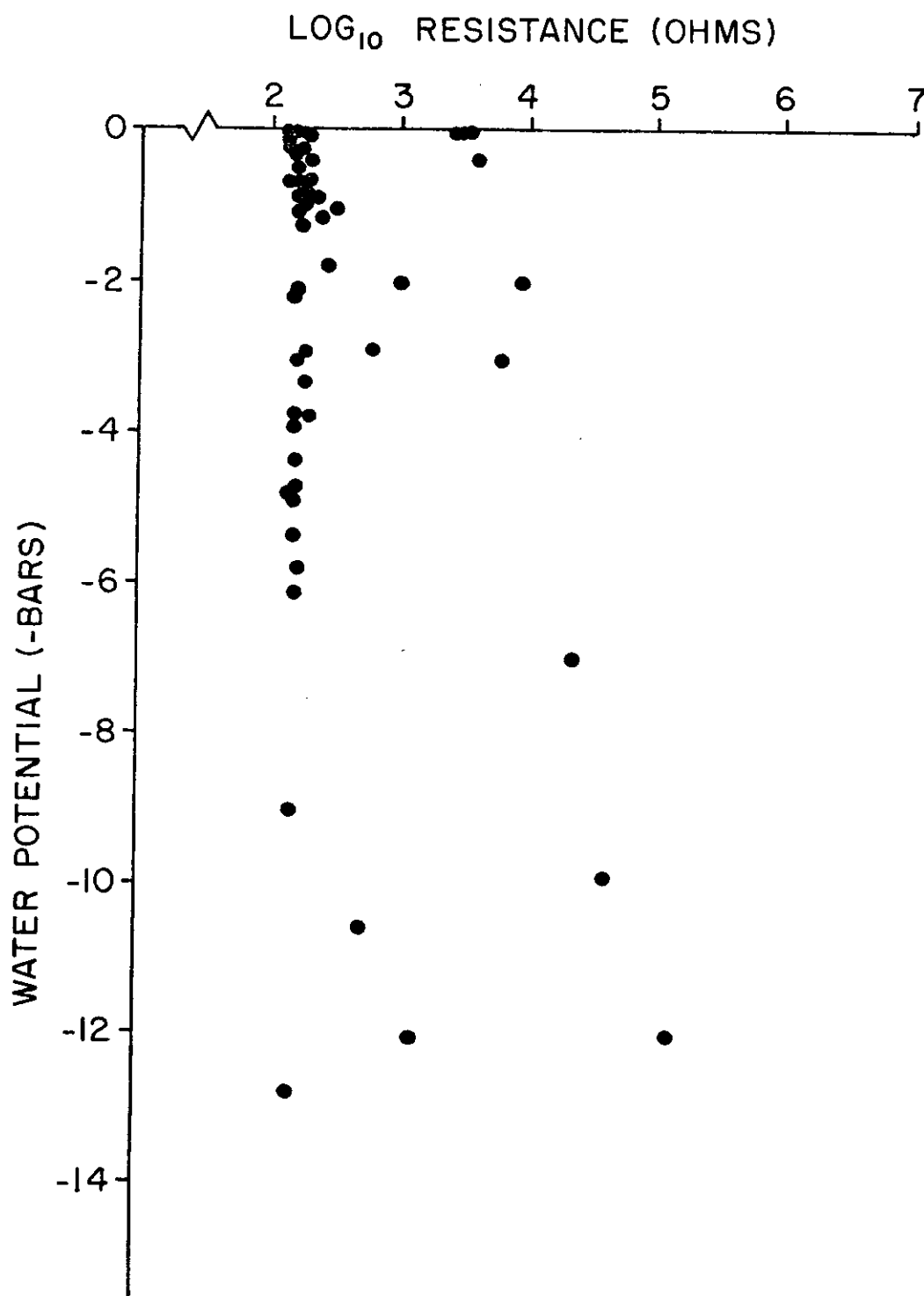Water Potential Measured with the Thermocouple Psychrometer

Figure C.1. A comparison of gypsum block resistance and the soil water potential as measured with a thermocouple psychrometer (Plot B - 2 cm depth; June 18th - August 31st 1973).
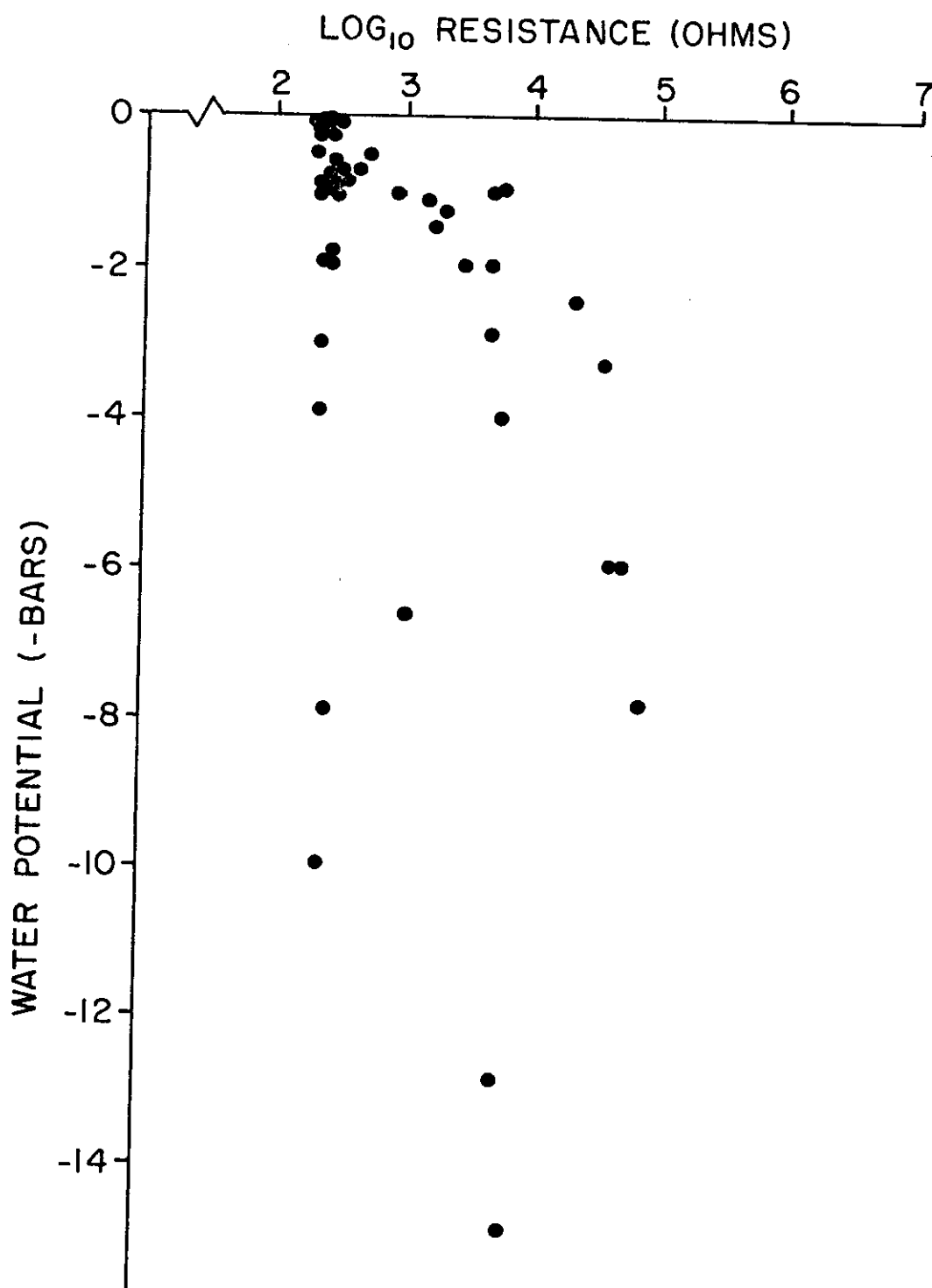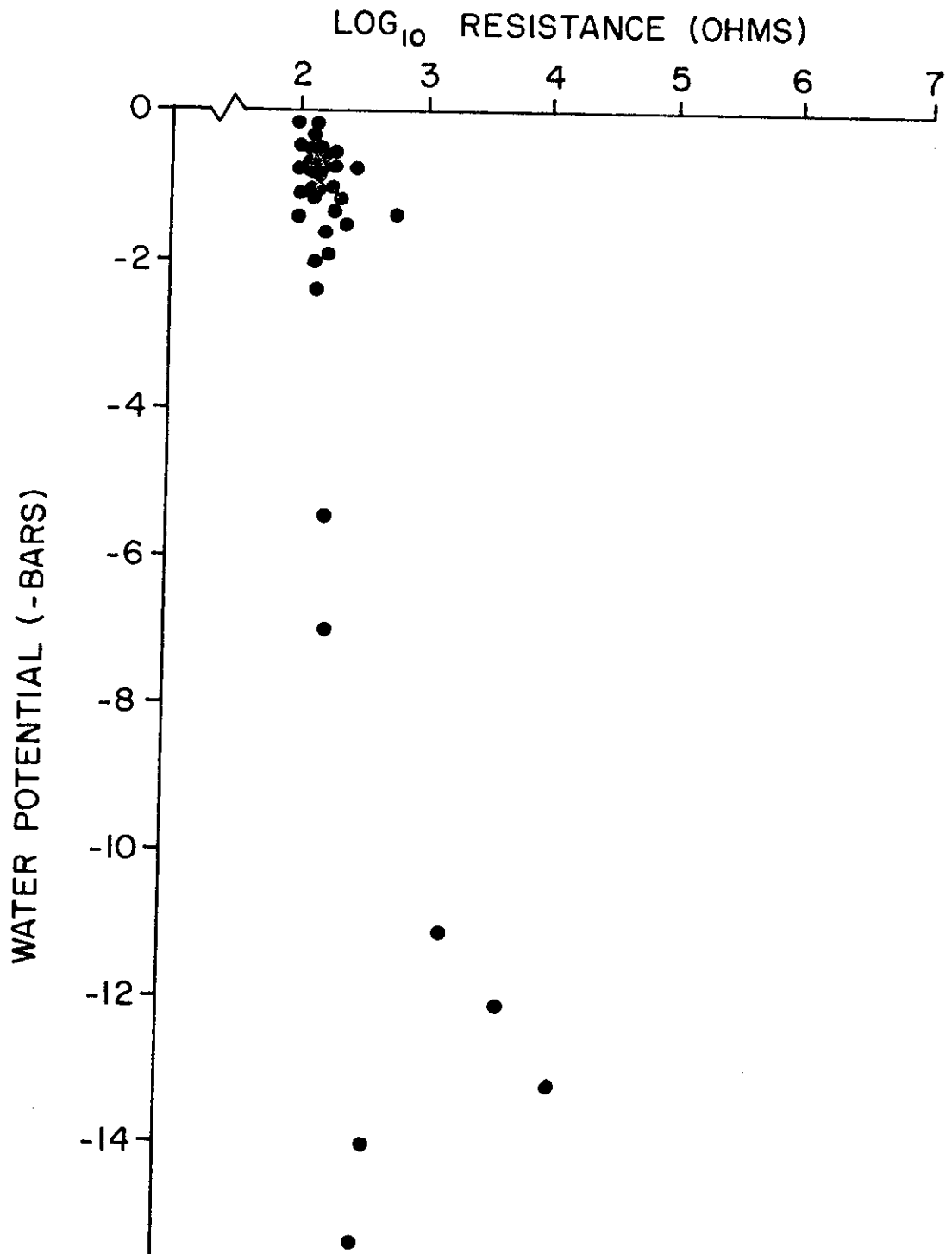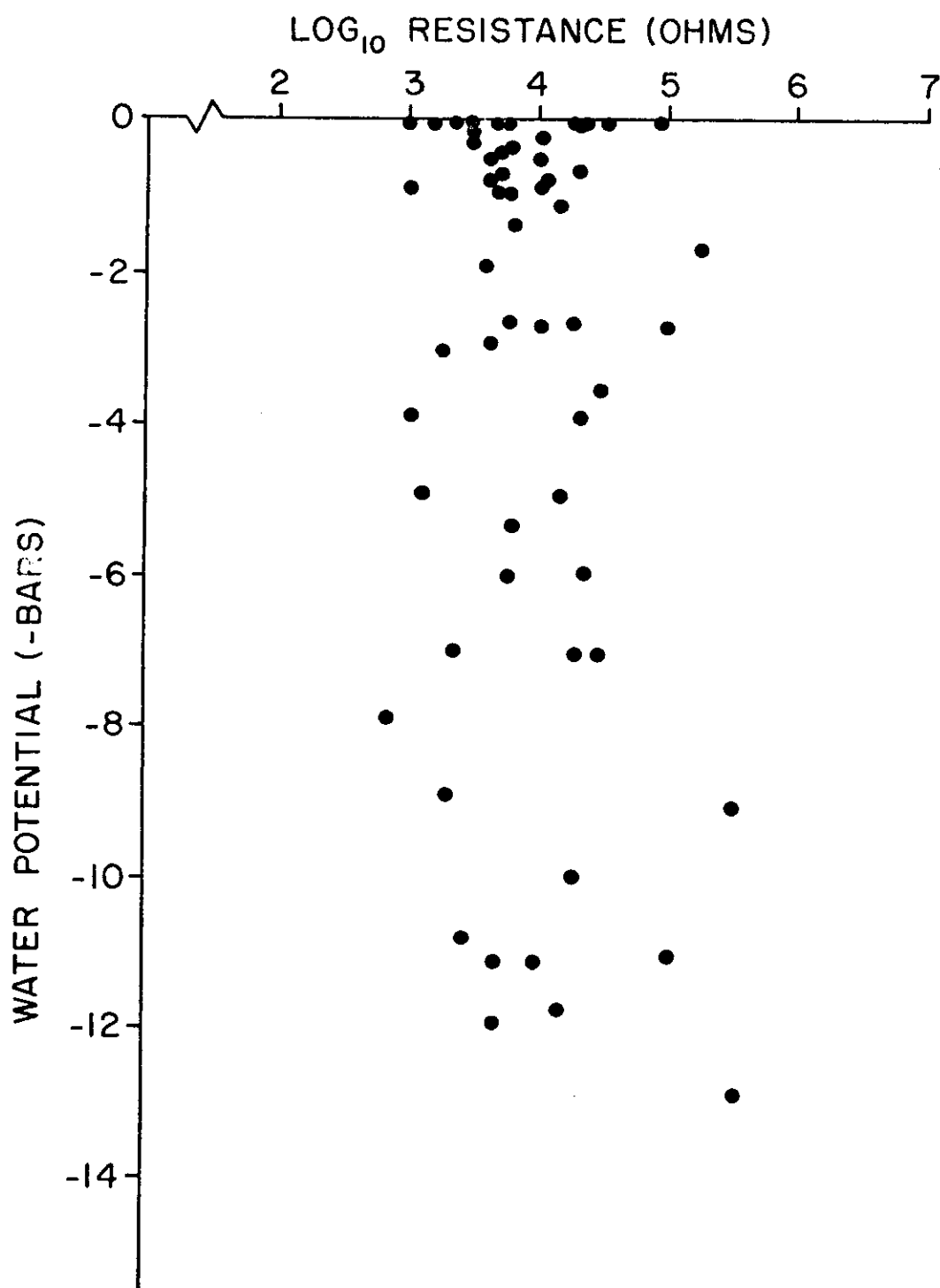
Figure C.2. A comparison of gypsum block resistance and the soil water potential as measured with a thermocouple psychrometer (Plot B - 7 cm depth; June 18th - August 31st 1973).
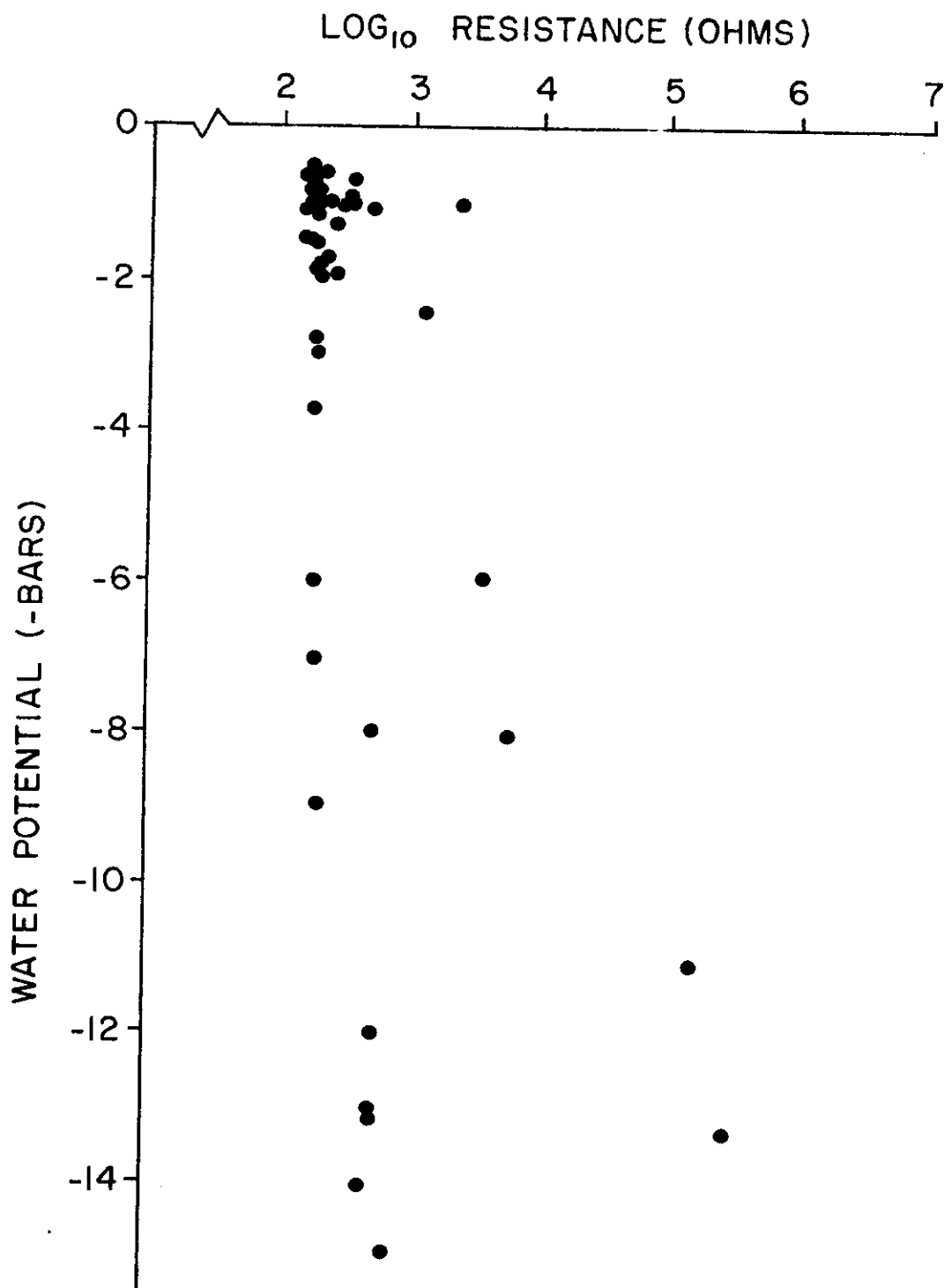
Figure C.3. A comparison of gypsum block resistance and the soil water potential as measured with a thermocouple psychrometer (Plot B - 15 cm depth; June 18th - August 31st 1973).

Figure C.4. A comparison of gypsum block resistance and the soil water
potential as measured with a thermocouple psychrometer
(Plot B - 30 cm depth; June 18th - August 31st 1973).

Figure C.5. A comparison of Colman unit resistance and the soil water potential as measured with a thermocouple psychrometer (Plot B - 2 cm depth; June 18th - August 31st 1973).
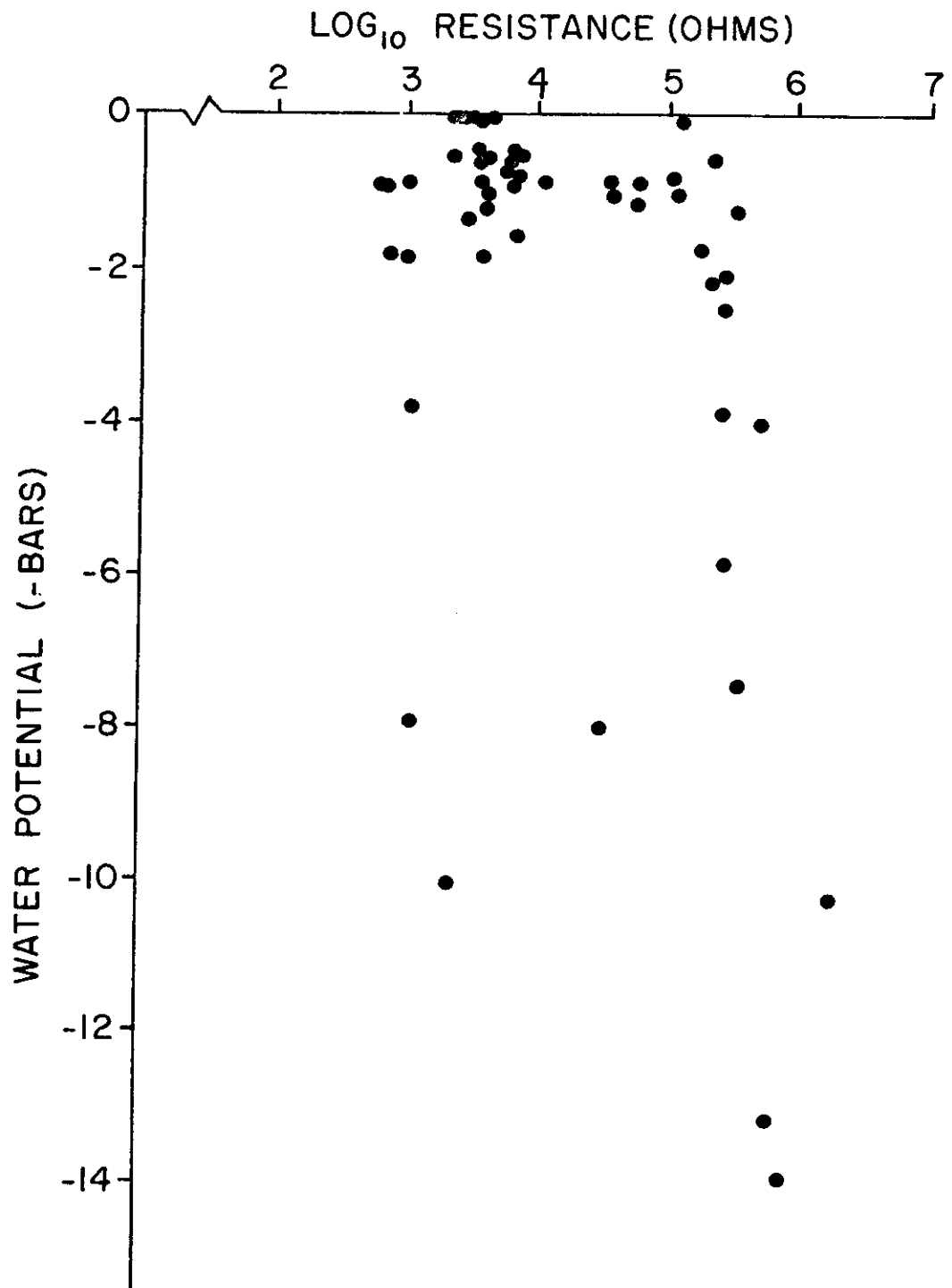
Figure C.6.   A comparison of Colman unit resistance and the soil water potential as measured with a thermocouple psychrometer (Plot B - 7 cm depth; June 18th - August 31, 1974).
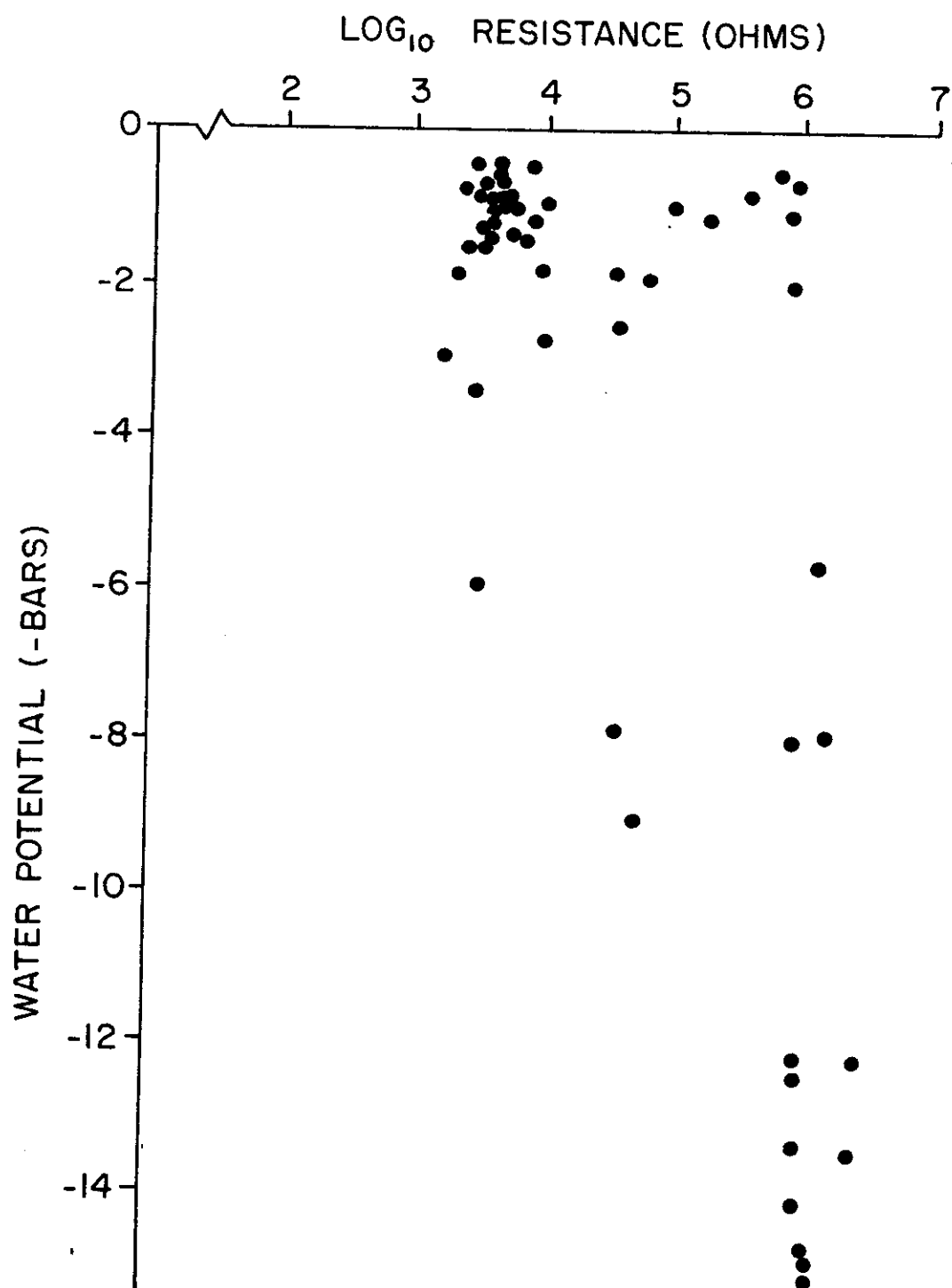
Figure C.7. A comparison of Colman unit resistance and the soil water
potential as measured with a thermocouple psychrometer
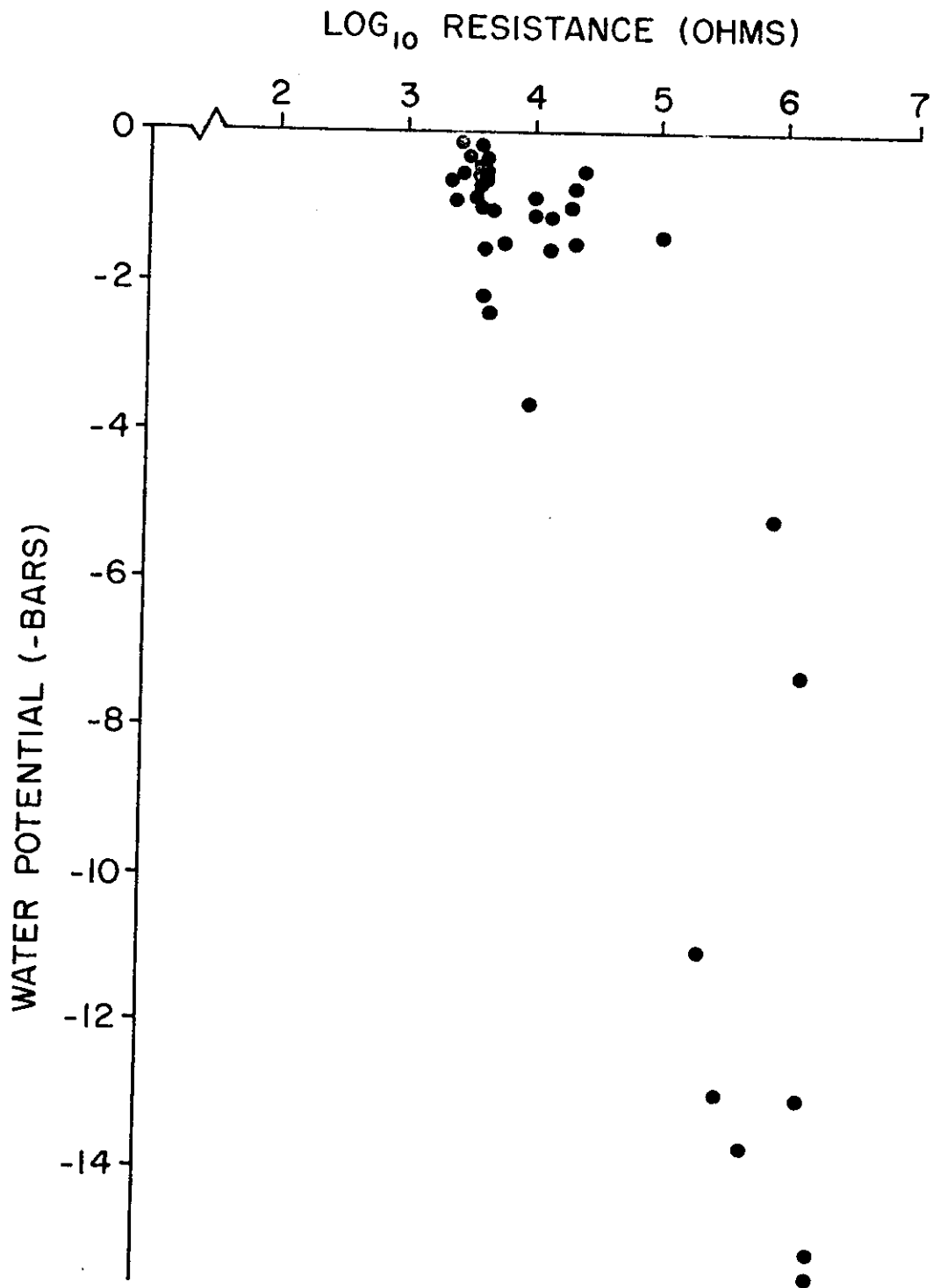(Plot B - 15 cm depth; June 18th - August 31st 1973).

Figure C.8. A comparison of Colman unit resistance and the soil water
potential as measured with a thermocouple psychrometer
(Plot B - 30 cm depth; June 18th - August 31st 1973).