1985

The Transiometer : An Alternative Method of Soil Moisture Measurement in Slowly Permeable Soils

Todd P. Trooien

Recommended Citation

Trooien, Todd P., "The Transiometer : An Alternative Method of Soil Moisture Measurement in Slowly Permeable Soils" (1985). *Electronic Theses and Dissertations*. 4315.
https://openprairie.sdstate.edu/etd/4315

THE TRANSIOMETER: AN ALTERNATIVE METHOD OF SOIL MOISTURE MEASUREMENT IN SLOWLY PERMEABLE SOILS

BY

TODD P. TROOIEN

A Thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science
Major in Agricutural Engineering
South Dakota State University
1985

THE TRANSIOMETER: AN ALTERNATIVE METHOD OF SOIL MOISTURE MEASUREMENT IN SLOWLY PERMEABLE SOILS

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

A. R. Bender Date
Thesis Adviser

Dr. M. A. Hellickson Date
Head, Agricultural Engineering

Dr. D. W. DeBoer Date
Major Adviser

ABSTRACT

The union of pressure transducer and tensiometer ceramic cup was termed "transiometer". Construction and installation procedures for a transiometer were presented.

The transiometer can be used in both saturated and unsaturated conditions. In saturated conditions, it has a faster response than a piezometer, making it very useful in fine-textured, slowly permeable soils.

The primary transiometer study site, at the RCWP Master Site, consisted of four replications each of transiometers installed at depths of 1.22 m, 1.83 m, 3.66 m, and 6.10 m, along with a sensor without the ceramic cup installed at a depth of 3.66 m. The sensors placed within 2 m of the ground surface were in the unsaturated zone. A piezometer, placed at a depth of 6.10 m, and neutron probe access tubes, for soil moisture monitoring to a depth of 5.18 m, were also installed in each of the four plots. Thermistors were installed in one plot at depths of 15, 30, 61, and 91 cm. An auxiliary site was established with a transiometer placed at a depth of 5.03 m, piezometers placed at depths of 2.26 m and 3.76 m, and a neutron probe access tube to monitor soil moisture to a depth of 3.35 m.

Random error of the measuring system of transiometer, digital voltmeter, and scanner was typically 2.8 cm with a maximum of 11.5 cm. The two most significant components of measuring system random error were the potential created at the connection terminals of the scanner and the imprecision of the transducer calibrations. The transiometer was very sensitive to atmospheric pressure fluctuations, with the response to atmospheric pressure changes increasing with depth of installation. Saturated hydraulic conductivity of the glacial till monitored was 10^{-7} to 10^{-8} m s^{-1}, while the drainable porosity was .025-.035.

ACKNOWLEDGEMENTS

I would like to thank John Bischoff, originator of the transiometer, a. k. a. bischometer. Thank you for all the help and encouragement you offered a wayfaring student. Your words of wisdom have been greatly appreciated. By the way, Lemmon isn't really all that bad if you have Pepsi for breakfast!

Special thanks also to Alan Bender, thesis and otherwise advisor, for all your help. I really appreciate all the time and effort you have put forth to help me with this project.

Also, I wish to thank Dr. D. W. DeBoer, major advisor, for words of wisdom, encouragement, and motivation in preparing this report. Additional thanks are due Dr. C. G. Carlson and Greg Kimball, members of the CM+E braintrust, for help and advice given throughout the project.

To Jolene, thank you for all your tutoring on the operation of the powerful tool known as the IBM PC. Thanks also for cranking out plots on short notice.

A special word of thanks to the family English professor, alias Mom, for all of your proofreading and suggestions.

For help in constructon, installation, and monitoring of transiometers, I extend my thanks to Sam and Mark. Your help in the establishment of the study site was invaluable. Next year's harvest of drill stems should be a bumper crop, thanks to your conscientious planting efforts!

Last, but certainly not least, I wish to thank Ken Stange, Instructor of Agricultural Engineering, for all his help in the preparation of this thesis.

This project was made possible by funds provided by the United States Geological Survey, U. S. Department of the Interior, and the Plant Science Department, South Dakota State University.

TPT

CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

A large portion of lands that are potentially very productive in the northern Great Plains involve glacial till soils. Glacial tills are generally heterogeneous, fine-textured, and slowly permeable. The predominant handicap of glacial tills is their low hydraulic conductivity: the slow movement of water through the soil.

Low hydraulic conductivity can be translated to low drainage capacity, which can cause two general problems. If the total water input is greater than the sum of the soil's drainage capability plus the crop's water use, an elevated water table may develop. If an artificial water table is elevated into the root zone, crop damage can occur. The second problem inherent in slowly permeable soils is the lack of proper leaching of salts from the soil profile. This is a major concern when the water input contains a greater salt load than normal precipitation, as in the application of irrigation water.

When water is applied in excess of the soil's field capacity, the soil must drain adequately to remove the free water. Because salts can be effectively removed from the soil profile only by leaching, drainage also is the single most important factor in salinity control (Bernstein, 1974). In spite of low hydraulic conductivity, scattered irrigation is currently being conducted on glacial tills. Soils developed on shallow tills in some areas of southern Alberta have been irrigated for over 60 years with no damage to the soil (Hendry, 1982). In South Dakota, even though the water supply currently used for irrigation of tills is groundwater of questionable chemical quality, soil profile data there indicate the development of very few salinity problems. Although water level data have not been recorded, the lack of salt accumulation indicates adequate internal drainage, with no water table buildup problems (Bender et al., 1983).

How are excess water and salts removed from the slowly permeable soils presently being irrigated? To answer this and many other questions being raised about the movement of water through slowly permeable soils, glacial tills specifically, the researcher must know the hydraulic properties of the soil. Among the hydraulic properties of interest are: presence and location of a water table, hydraulic conductivity, drainable porosity, and any gradients and fluxes normally occurring in the soil profile.

These hydraulic properties have not been sufficiently quantified for glacial till soils. Resulting from the lack of knowledge of these properties, especially quantified hydraulic conductivity and located water table, is a failure to adequately characterize the movement of water through tills.

Recent studies performed on glacial tills have hypothesized that the water movement regimes through till are dominated by flow through macropores, or fractures (Grisak et al., 1976; Grisak et al., 1980; Hendry, 1982, 1983; Hendry et al., 1984; Mawson, 1964). Therefore, accurate quantifications of till hydraulic properties must be based on tests of samples large enough to contain a representative macropore volume and configuration. Failure to include a representative fracture volume in the tested sample will underestimate the hydraulic conductivity of the till bulk.

To ensure a proper macropore volume in the tested sample, the test may be performed _in situ_. Barring human errors during site preparation, tests performed _in situ_ should result in experimental conditions that are more nearly natural than standard laboratory procedures. Hydraulic conductivity tests conducted on a soil with a slowly permeable substratum have produced much faster conductivities when conducted _in situ_ than the standard laboratory tests of cores (Doering et al., 1984).

The piezometer is a conventional tool in the monitoring of saturated soil conditions _in situ_ and works well in soils of sufficient permeability to allow water to enter and exit the piezometer freely. However, reported hydraulic conductivity values of the till bulk as measured in situ range from 10^{-6} m s^{-1} (0.14 iph) (Mawson, 1964) to 10^{-11} m s^{-1} (1.4×10^{-6} iph) (Grisak et al., 1976). With the permeability of the soil very low, water movement into and out of the piezometer is very slow. The resulting time lag was not only undesirable because it caused a long waiting period from event to measurable instrument response, but could also cause difficulties or inaccuracies in analyses of piezometer data.

The response time of conventional piezometers was unacceptably long when used to measure soil moisture in slowly permeable soils. To decrease the response time of an instrument measuring a pressure head in a soil of given permeability, two parameters can be adjusted: the intake of the instrument can be enlarged, or the volume of flow required to equilibrate the instrument with soil conditions can be decreased. A very large increase of intake area is required to significantly decrease the response time. This often extends the intake of the instrument beyond the boundaries of the monitored stratum, introducing a significant systematic error.

A decrease in the flow volume required to equilibrate the instrument can be achieved two ways: by using a smaller diameter piezometer stem, or by creating a hydraulic connection between the soil water and a transducer/ readout device. The use of a smaller diameter stem creates monitoring difficulties, and a flux is still required for system response, making this an undesirable solution. Transducer/ readout devices such as manometers and bourdon tube gauges have been used successfully with piezometer installations, but introduce two new problems: the maintenance of a long hydraulic connection and limited installation depths. Theoretically, the hydraulic connection could be maintained for installations as deep as 10.4 m (34 feet), but in practice the maximum water column is 7.3 m to 8.5 m (24 feet to 28 feet) depending on the elevation above mean sea level.

Both of these problems with transducer/ readout devices could be alleviated by placing the transducer at the depth of monitoring. An electronic pressure transducer can be placed at the desired monitoring depth and connected with a readout device at the ground surface. The electrical conductors linking pressure transducer and readout device eliminate the need for a hydraulic connection from sensor to ground surface. Electrical conductors are easier to maintain than hydraulic connections.

Coupling the pressure transducer with a porous ceramic cup such as are used on a tensiometer, allows use of the unit to measure matric potential. Matric potential is the tension created by the soil in unsaturated conditions, and is measured as pressure less than atmospheric. Such a transducer-tensiometer can be used at any depth, in saturated or unsaturated soil conditions.

OBJECTIVES

The objectives of the study undertaken and reported here were:

1. Design an instrument to utilize a pressure transducer and porous ceramic cup to measure both positive and negative soil water pressures.

2. Construct the instrument using economical and readily available components.

3. Install the instrument in slowly permeable soil, and test the accuracy of the instrument by comparing results to piezometer and neutron probe data.

4. Determine the precision of the instrument through the use of typical and worst-case numerical simulations.

LITERATURE REVIEW

Piezometers have been widely used to measure the pressure imparted by the soil water at the depth of placement under saturated conditions, measuring both static and dynamic piezometric levels. One inherent problem in measuring a dynamic piezometric head with a piezometer is the lag time from the event until 100 per cent piezometer response .

Hvorslev (1951) presented algebraic equations to calculate the volume and flow rate for various piezometer configurations. The basic time lag is the total volume of flow required to equalize the head difference divided by the rate of flow, assuming isotropic soil conditions. The volume of flow required to equalize the head difference as defined by these equations is dependent solely upon the piezometer size and shape. It can be increased or decreased to match site conditions. However, rate of flow is a function not only of instrument size and shape, but also of soil hydraulic conductivity.

The shape factor of a piezometer is an empirical constant used in the equation of flow to a piezometer to correct for the constriction of flow due to the geometry of the intake. The equation of flow to a piezometer has

Wilkinson (1968) were other systematic errors, such as hydraulic head loss in the instrument and smearing of the borehole. Smear became especially significant in clays with a "well-defined pervious macrostructure", i. e. fractures. This disturbance causes a test to indicate a permeability lower than the actual permeability of the soil.

Gibson (1963) also analyzed the systematic errors due to system flexibility. This error had two basic origins: expandibility of the instrument itself, and entrapped air or gas in the fluid.

Yet another error in the measurement of the saturated zone is the diurnal fluctuation of the free water surface. Turk (1975) measured fluctuations in a shallow water table of 1.5- 6.0 cm (0.6- 2.4 in) per day during the summer and 0.5- 1.0 cm (0.2- 0.4 in) per day during the winter. These fluctuations were attributed to the atmospheric pressure changes related to changes in temperature. The pressure changes acted upon the capillary water, pulling it out of the water table or driving it into the saturated zone.

The barometric pressure was considered to be a series of step functions by Weeks (1979). Best results for correction for atmospheric pressure variations were obtained by Weeks (1979) when considering the step function and a pneumatic diffusivity value found by trial and error. The pneumatic diffusivity value assumes that the unsaturated zone restricts air movement and stores air during barometric pressure changes.

The effect of a ceramic piezometer intake was estimated for a spherical intake (Gibson, 1966). A spherical intake was considered because the flow equations to the tip are simpler and more accurate than for a cylindrical intake. When the permeability of the ceramic is approximately equal to that of the soil, the volumetric flow rate is reduced by a factor of:

$$1+((k_1)/(k_3))((a_1/a_3)+1) \qquad (2)$$

where k_1 and k_3 are the permeabilities of the ceramic and soil, respectively, a_1 is the inner diameter of the ceramic, and a_3 is the outer diameter of the backfill material.

The mini-piezometer, with a stem narrower than the screen, designed by Lee and Cherry (1979) reduces the time lag by reducing the volume of water required to equilibrate the piezometer. This design was used in conjunction with a sonar transmitter/receiver and data acquisition system to measure hydraulic conductivities in peat. Although the hydraulic conductivities of the peats measured were 10^{-7} m/s (0.014 in/hr) or slower, after filling the stems completely with water, the piezometers recovered in less than 30 minutes. (Hemond, 1982)

An extensive review of the instrumentation used to measure soil moisture in unsaturated conditions was conducted by Schmugge et al. (1980). Non-destructive methods commonly employed in this area include nuclear, hygrometric, and tensiometric methods.

The most commonly used form of nuclear soil moisture determination is the neutron scattering method (Gardner and Kirkham, 1952). Neutrons are thermalized (slowed down) when they collide with a hydrogen atom. Because nearly all hydrogen atoms below the surface layer of organic material are located in water molecules, the number of thermalized neutrons reflected back to the counter indicates the water content of the soil. In wet soils, 90% of the neutrons sensed by the counter of the neutron probe were thermalized within a 15 cm (6 in) radius about the probe.

A hygrometric method was developed by Phene et al. (1971). In this method, the heat dissipation measured in the soil gives an indication of the soil moisture content. This method, as currently marketed, can measure matric potentials to -0.3 MPa (-3.0 bars). (Moisture Control Systems, undated)

The tensiometric method of soil moisture measurement was advanced by Richards and Gardner (1936). The tensiometer employs a porous ceramic interface between the soil and a fluid reservoir. The most common fluid is water; however, McKim et al. (1976) stated ethylene glycol can provide a faster response time and can be used when water would freeze. Another method of improving response time is through the use of a pressure transducer rather than a manometer or bourdon tube gauge to sense the potential (Bischoff et al., 1983; Gillham et al., 1976; Marthaler et al., 1983; McKim et al., 1975).

Towner (1981) studied the response time of tensiometers in a soil of low hydraulic conductivity. Towner concluded that a change in the conductivity of the ceramic cup does little to improve the tensiometer time response, and the gauge is the component that requires higher sensitivity. Towner also states that pressure transducers give better time response than conventional gauges or manometers.

A pressure transducer was coupled with a porous ceramic disc and housed in polyvinylchloride (PVC) plumbing fittings by Hoover (1983, 1984). This instrument, although expensive, had the ability to measure gauge pressures either greater than zero (pressure head) or less than zero (matric potential).

METHODS AND MATERIALS

Rural Clean Water Program Master Site

The main study plots were established at the South Dakota Rural Clean Water Program (RCWP) Master Site, located on the northwest 1/4 of Section 17, R51W, T112N, Brookings County. The RCWP Master Site was approximately 40 km (25 miles) northwest of the city of Brookings, SD. Plots were on Poinsett silt loam at the top of a small knoll, surrounded by slopes of 3 to 5 percent (Figures 1 and 2). Drilling performed at the site indicated a 30 cm (12 in) black silt loam A horizon, underlain by yellow silt loam becoming calcareous at 45 cm to 60 cm (18 in to 24 in). Strata of coarse silt and fine sand were found at approximately 1.2 m (4 ft). This zone of both mixed and separated sand and silt was 36 cm to 60 cm (14 in to 24 in) thick. Underlying the sand and silt was oxidized clay loam glacial till extending to at least 6.1 m (20 ft), which was the maximum depth of drilling on the plots (Figure 3). Other drilling performed at the Master Site indicated the oxidized till extended to a depth of approximately 6.7 m (22 ft), below which depth the till was unoxidized.

Figure 1. RCWP Master Site transiometer sites 86-89. Site 89 is in foreground, left; site 87 is in background, right. The neutron probe is mounted on access tube #882 in right foreground.

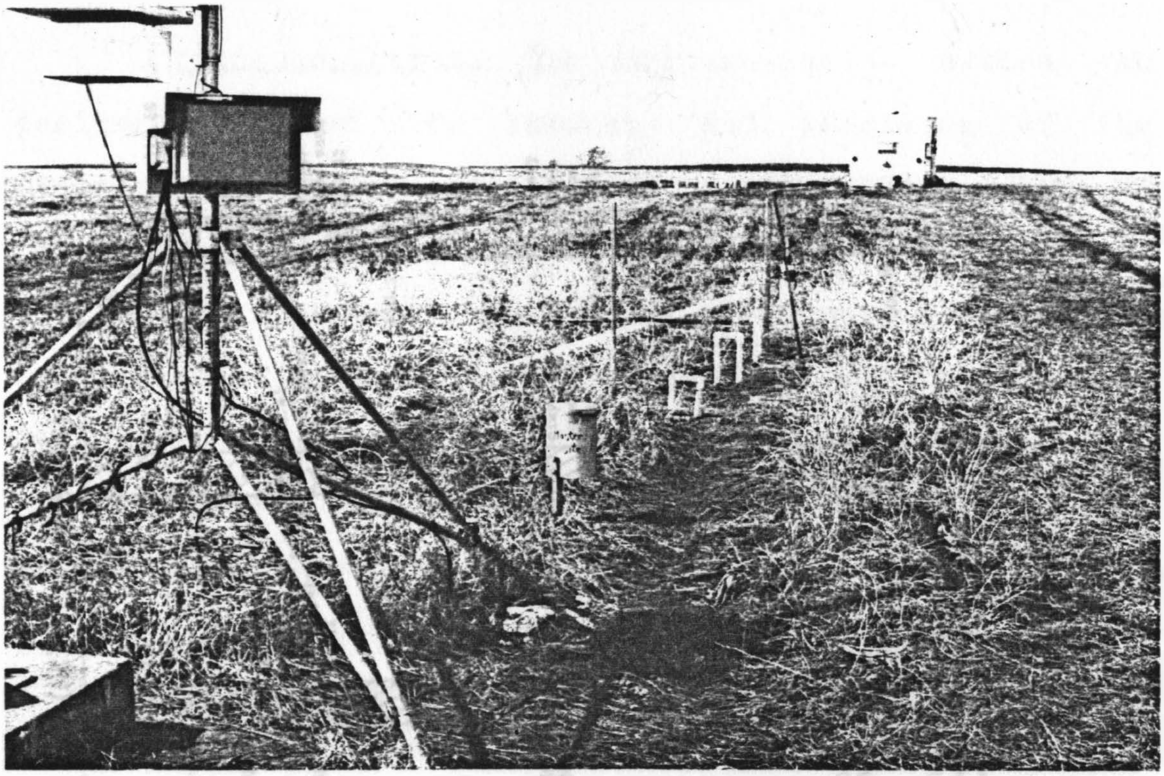

Figure 2. Weather station at RCWP Master Site, showing rain gauge and three transiometers in foreground. Sites 86-89 are in background.

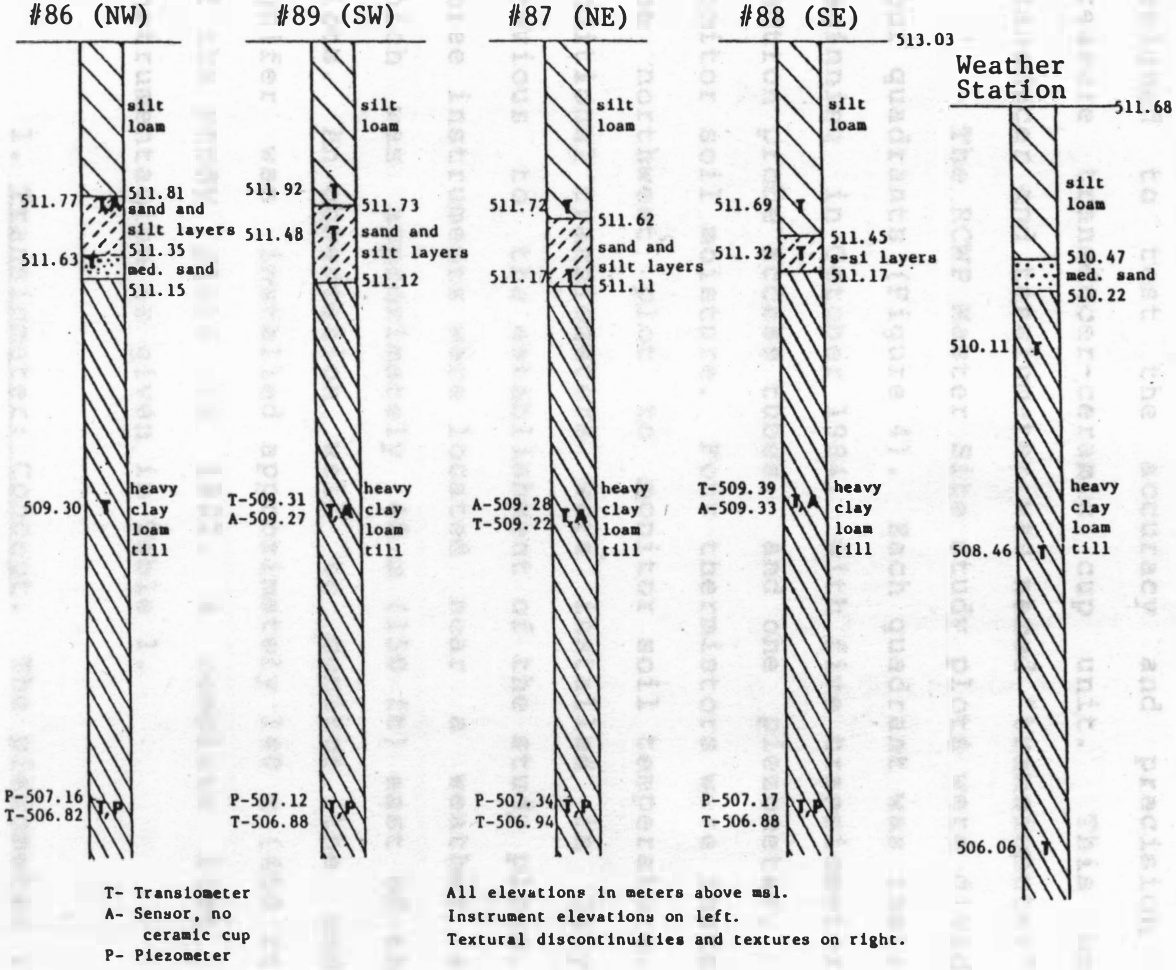

Figure 3. Drill logs of 6.10 m transiometer installation holes at RCWP Master Site.

Instrumentation. The instrumentation system was designed to test the accuracy and precision of the pressure transducer-ceramic cup unit. This union of transducer and tensiometer was named "transiometer".

The RCWP Master Site study plots were divided into four quadrants (Figure 4). Each quadrant was instrumented beginning in October 1984, with five transiometers, two neutron probe access tubes, and one piezometer, all to monitor soil moisture. Four thermistors were installed in the northwest plot to monitor soil temperature. Three additional transiometers were installed in July 1984, previous to the establishment of the study plots. These three instruments were located near a weather station, which was approximately 46 m (150 ft) east of the study plots. An observation well to monitor the underlying aquifer was installed approximately 140 m (450 ft) south of the study plots in 1982. A complete list of the instrumentation is given in Table 1.

1. Transiometer: Concept. The piezometer requires a finite amount of water flux either into or out of the instrument to measure an event. A slow flux rate causes a time lag from event to instrument response that becomes pronounced in slowly permeable soils. Although the flux

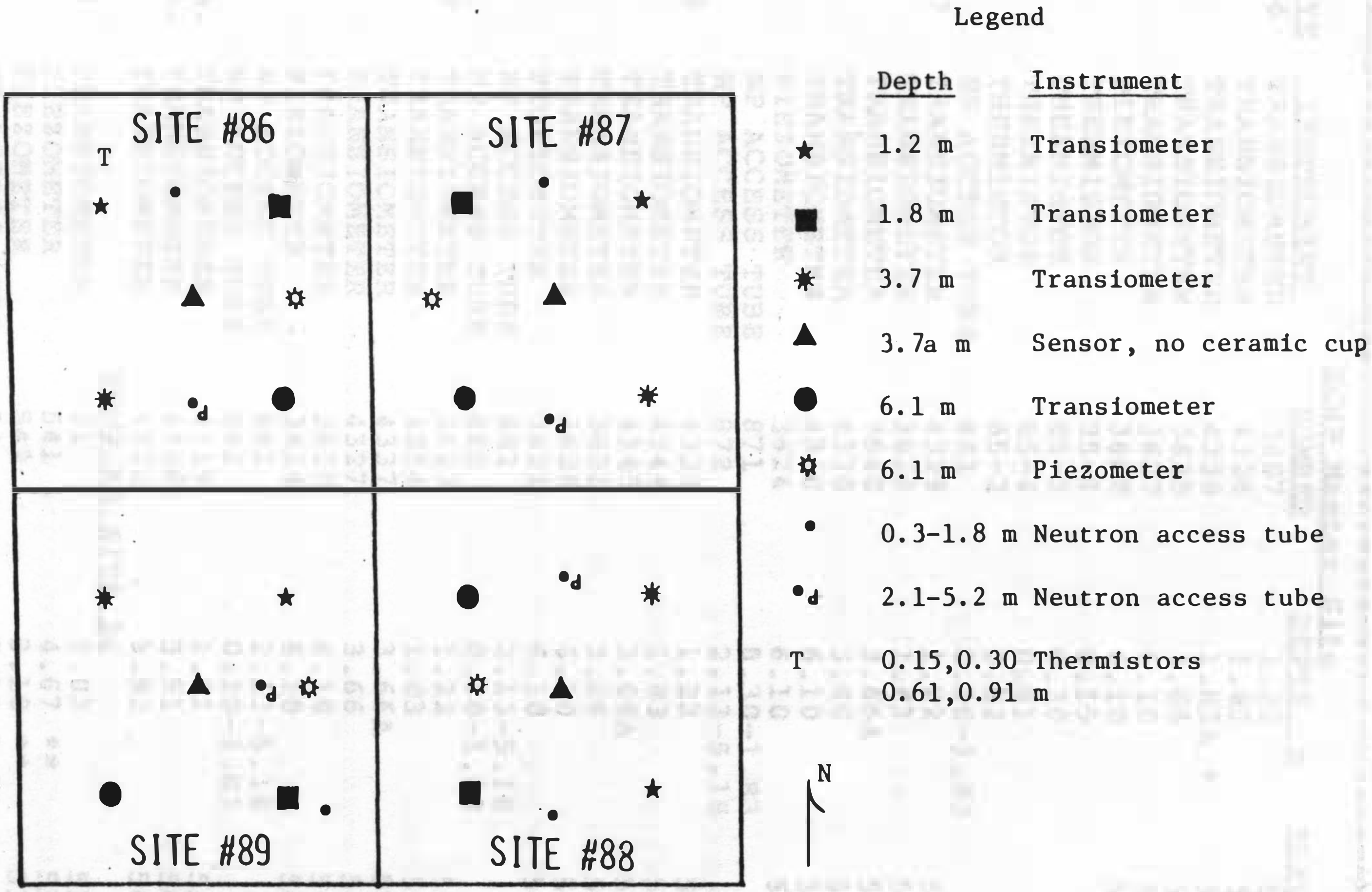

Figure 4. RCWP Master Site transiometer study site.

TABLE 1. INSTRUMENT NUMBERS, DEPTHS, AND ELEVATIONS.

SITE	INSTRUMENT	NUMBER	DEPTH, m	ELEV., m msl
		RCWP Master Site		
86	TRANSIOMETER	3607	1.22	511.77
	TRANSIOMETER	4326	1.83	511.63
	TRANSIOMETER	4338	1.83A *	511.76
	TRANSIOMETER	3625	3.66	509.30
	TRANSIOMETER	3627	6.10	506.82
	PIEZOMETER	3608	6.10	507.16
	THERMISTOR	85-1	0.15	
	THERMISTOR	85-3	0.30	
	THERMISTOR	85-4	0.61	
	THERMISTOR	85-2	0.92	
	NP ACCESS TUBE	861	0.30-1.83	
87	TRANSIOMETER	4329	1.22	511.72
	TRANSIOMETER	3629	1.83	511.17
	TRANSIOMETER	3640	3.66A	509.28
	TRANSIOMETER	4330	3.66	509.22
	TRANSIOMETER	4350	6.10	506.94
	PIEZOMETER	3624	6.10	507.34
	NP ACCESS TUBE	871	0.30-1.83	
	NP ACCESS TUBE	872	2.13-5.18	
88	TRANSIOMETER	4323	1.22	511.69
	TRANSIOMETER	4344	1.83	511.32
	TRANSIOMETER	4345	3.66A	509.33
	TRANSIOMETER	3621	3.66	509.39
	TRANSIOMETER	3628	6.10	506.88
	PIOEZOMETER	3621	6.10	507.17
	NP ACCESS TUBE	881	2.13-5.18	
	NP ACCESS TUBE	882	0.30-1.83	
89	TRANSIOMETER	3623	1.22	511.92
	TRANSIOMETER	4354	1.83	511.48
	TRANSIOMETER	4337	3.66A	509.26
	TRANSIOMETER	4327	3.66	509.31
	TRANSIOMETER	3630	6.10	506.85
	PIEZOMETER	3634	6.10	507.12
	NP ACCESS TUBE	891	2.13-5.18	
	NP ACCESS TUBE	892	0.30-1.83	
WEA. STA.	TRANSIOMETER	4319	1.91	510.11
	TRANSIOMETER	4346	3.51	508.46
	TRANSIOMETER	4322	5.92	506.06
		RCWP RS SITE 54		
54	TRANSIOMETER	31	5.03	512.26
	PIEZOMETER	541	4.67 **	513.22
	PIEZOMETER	542	3.18 **	513.80
	NP ACCESS TUBE	54	0.30-3.35	

* "A" indicates sensor installed without ceramic cup.

** Depth to top of screen.

can be reduced by properly dimensioning the piezometer, a time lag due to the flux will still occur. If the system measurand were the pressure imparted by the water rather than a flux due to a pressure differential, the lag time created by the flux of water through a slowly permeable soil could be significantly reduced. This soil water pressure can be measured by using a pressure transducer. The volume of water required to equilibrate the transducer to the soil water pressure is infinitesimal, virtually eliminating the instrument response lag time associated with a flux of water.

Another advantage of the pressure transducer in the transiometer is its provision of an output suitable for continuous monitoring with data acquisition equipment. Data can be collected as frequently as desired, closely monitoring any changes with time.

Furthermore, because all hydraulic components are beneath the ground surface, diurnal temperature variations do not affect the transiometer output. If the transiometer is installed below the frost zone of the soil, data can be collected continuously throughout the year without transiometer malfunction caused by freezing.

Finally, with the employment of a porous ceramic cup and a bi-directional pressure transducer, the transiometer can measure either matric tension or pressure head. The measurement of negative pressure is limited by the air entry value of the ceramic cup used; however the pressure head measurement is limited only by the range of the pressure transducer. (Trooien et al., 1984)

2. Transiometer: Materials and Components. The transiometer was constructed from four main components: the extension pipe, the sealing extension, the sensor unit, and the cup unit (Figure 5). The raw materials required for the four components were a pressure transducer, a porous ceramic cup, polyvinylchloride (PVC) pipe, four conductor electrical leads, 17 gauge wire, polypropylene tubing, vinyl tubing, heat-shrink tubing, o-rings, epoxy, and adhesives (Table 2). Tools required for the construction of a transiometer included a turning lathe, a tap and die, a drill, and a soldering iron.

Strain gage pressure transducers offer the ruggedness required during construction of the transiometer. Design criteria 2 through 5 from Table 3 were satisfied using a piezoresisistive pressure transducer. The semiconductor strain sensor of a piezoresistive unit is more sensitive than the standard resistive strain sensor, allowing stiffer and more durable construction of the sensing element without sacrificing instrument sensitivity. The increased sensitivity of the

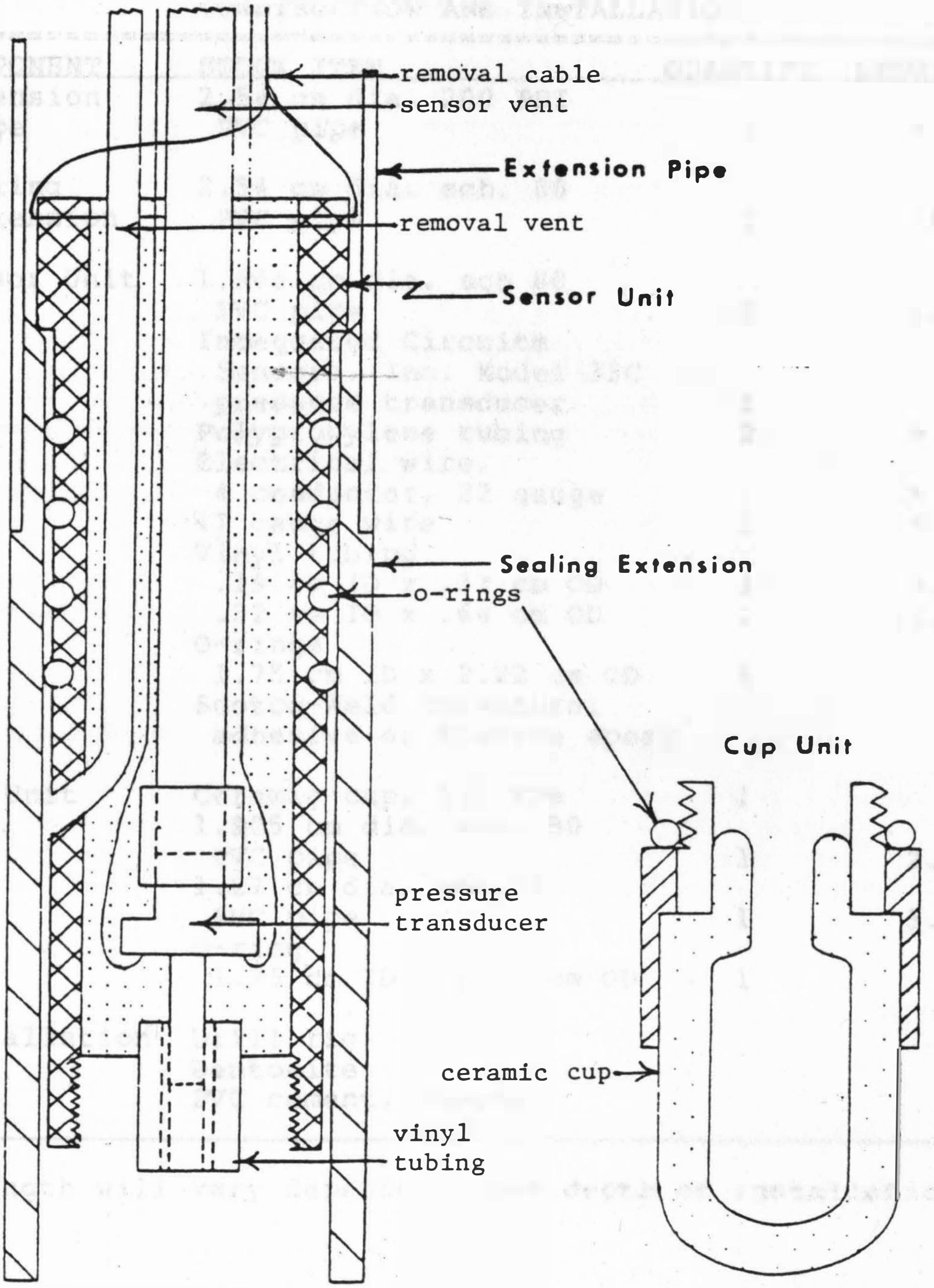

Figure 5. Transiometer components. Major components are boldface.

TABLE 2. MATERIALS USED FOR TRANSIOMETER CONSTRUCTION AND INSTALLATION.

COMPONENT	STOCK ITEM	QUANTITY	LENGTH,cm
Extension pipe	2.54 cm dia. 200 PSI PVC pipe	1	*
Sealing Extension	2.54 cm dia. sch. 80 PVC pipe	1	18.4
Sensor Unit	1.905 cm dia. sch 80 PVC pipe	1	18.4
	Integrated Circuits Sensors, Inc. Model 33C pressure transducer	1	
	Polypropylene tubing	2	*
	Electrical wire, 4 conductor, 22 gauge	1	*
	17 gauge wire	1	*
	Vinyl tubing .19 cm ID x .31 cm OD	1	3.18
	.32 cm ID x .64 cm OD	1	1.90
	O-rings 1.75 cm ID x 2.22 cm OD	4	
	Scotch-Weld structural adhesive or Flexane epoxy		
Cup Unit	Ceramic cup, 0.1 MPa	1	
	1.905 cm dia. sch. 80 PVC pipe	1	2.54
	1.27 cm dia. sch.80 PVC pipe	1	3.81
	O-ring 1.75 cm ID x 2.22 cm OD	1	
Installation	Drill rig		
	Bentonite		
	PVC cement, cleaner		

* Length will vary dependent upon depth of installation.

semiconductor strain element also allows the size of the transducer to be reduced (Beckwith et al., 1982). Piezoresistive pressure transducers having an unamplified output signal can measure either pressure or vacuum, and many different pressure ranges are available.

TABLE 3. DESIGN SPECIFICATIONS OF THE PRESSURE TRANSDUCER TO BE USED IN THE TRANSIOMETER AND SPECIFICATIONS OF THE INTEGRATED CIRCUITS SENSORS, INC. DIFFERENTIAL PRESSURE TRANSDUCER.

Criterion	Design Value	I. C. Sensors, Inc. Model 33C-10 PSID[1]
Cost	<$80.00	$66 *
Linearity	<±1.0% FS	±0.50% FS
Span voltage	>50 mV	>50 mV
Hysteresis	<±1.0%	±0.15% span
Operating temperature	0 to 40 Deg. C	-40 to 120 Deg. C
Pressure Range	≥ ±10 psid	±10 psid **

* Cost per individual unit when odering 5 or more, cost will be less if ordering more than 25 transducers.

** Many different pressure ranges are available.

---

[1] Use of product names are for benefit of reader and do not imply endorsement or preference by South Dakota State University.

The 33 series pressure transducers made by Integrated Sensors Circuits, Inc. combined the favorable operating characteristics of a piezoresistive pressure transducer with low price and desirable size and shape, and was therefore selected for use in the transiometer. The specifications for the Model 33C are listed in Table 3. The cylindrical shape and small diameter of these transducers allowed the packaging of the sensor within 1.90 cm (0.75 in) diameter PVC pipe. A smaller sensor unit allowed the installation of the transiometer in a smaller diameter borehole.

Ten transiometers were constructed with Integrated Circuits Sensors, Inc. model 33C pressure transducers, 14 with model 33B transducers, and 1 with a model 33A pressure transducer. The model 33A has the most desirable operaring characteristics such as sensitivity, linearity, null output, and thermal accuracy. The model 33C is not as desirable as the model 33A, but only costs about half as much.

The main housing material was PVC pipe. PVC was available in various sizes, easily machined, waterproof, and relatively inexpensive. Adhesives bond well to PVC, making it easy to produce a watertight seal along the walls of the pipe. Lastly, ceramic could be bonded to PVC, making PVC compatible with all materials required in the construction of a transiometer.

Three different sealants were used in the construction of the transiometers. The first was a two part contact cement, MVP 33 made by Devcon. The other two were epoxies which were used in different units to test their sealing properties. They were: Scotch-Weld structural adhesive, a flexible organic epoxy made by 3M, and Flexane, a rubber-base epoxy made by Devcon. Scotch-Weld structural adhesive had working properties superior to those of Flexane, e. g. higher viscosity, longer working time before hardening, and easier mixing. However, the effects of continuous exposure of the organic epoxy to free water were not known.

An installed transiometer must have provisions for retrieval, to allow inspection of the unit or recharging of the ceramic cup without disturbing the entire installation site. Such retrieval was designed for by placing a removable sensor unit within a stationary casing. A removable sensor unit required a seal between two PVC components that was impervious to water while retaining the ability of one surface to slide across the other. This was accomplished using rubber o-rings. O-rings are readily available at low cost and are easy to seat into one of the PVC surfaces.

Used as vent tubes from the sensor to the ground surface was polypropylene tubing. Polypropylene offered the rigidity required to remain vertical within the extension pipe without becoming unmanageable.

Because the electrical wire needed would be well protected, inexpensive four conductor, 22 gauge telephone station wire was used to bring the electrical signal from the transducer to the ground surface. Better insulation of the electrical wire was not required until it emerged from the extension tube at the ground surface.

3. Transiometer: Construction. Construction of the transiometer was conducted in two separate locations. The four main components were fabricated in the laboratory. Final assembly of the four components was completed at the site of installation.

The four main components were the extension pipe, sealing extension, sensor unit, and cup unit (Figure 5). The extension pipe consisted of 2.54 cm (1 in) diameter 200 psi PVC pipe. The only required modification of the extension pipe was cutting to the desired length, which could easily be done at the installation site with a hacksaw and a tape measure.

One 18.4 cm (7.25 in) length of 1.90 cm (0.75 in) diameter schedule 80 PVC pipe was machined to encase the sensor. The outside diameter was reduced to 2.59 cm (1.02 in) for 15.88 cm (6.25 in) of its length, and four grooves were cut around the circumference of the reduced portion. These grooves accomodated the sealing o-rings. The polypropylene removal vent was inserted into a 0.318 cm (0.125 in) hole drilled through the side of the machined section of the sensor housing. Holes of 0.238 cm (3/32 in) diameter drilled through both sides of the sensor housing on the other end accomodated the removal cable. A 1.90 cm (0.75 in) NF thread tap was used to thread the inside of the machined end of the sensor housing for coupling with the cup unit.

To prevent electrical short circuiting through its metal housing, the pressure transducer was encased in heat-shrink tubing. The electrical leads were soldered to the transducer pins, and polypropylene tubing was connected to the reference port. A short section of vinyl tubing was connected to the active port of the transducer for insertion into the ceramic cup. The assembled transducer was then placed in the PVC sensor housing and the housing was filled with either Scotch-Weld structural adhesive or Flexane epoxy. Only the threaded portion of the housing and the vinyl tubing attached to the active port of the transducer were left exposed.

The sealing extension was made from 2.54 cm (1 in) schedule 80 PVC pipe 18.4 cm (7.25 in) in length. The inside diameter of the sealing extension was expanded to 2.629 cm (1.035 in) using a 1.9 cm (0.75 in) boring tool on a turning lathe. The inside of the sealing extension must be smooth after machining because a rough finish would not allow the o-rings of the sensor unit to seal properly against the sealing extension. The outside diameter was machined down to 2.92 cm (1.15 in) for a length of 3.81 cm (1.50 in) on one end. This reduced end fit inside the extension pipe. The inside diameter of of the sealing extension was chamfered at the reduced end to ease the insertion of the sensor unit.

Two lengths of PVC pipe were used for the cup assembly. A 3.80 cm (1.5 in) length of 1.27 cm (0.5 in) diameter schedule 80 PVC was joined with a 2.54 cm (1 in) length of 1.90 cm (0.75 in) diameter schedule 80 PVC, with one half of the smaller PVC protruding. The protruding end was threaded with a 1.90 cm (0.75 in) NF die. The two PVC sections were bonded together using PVC cement, and an o-ring was placed about the threaded end.

The outside diameter of the 1.90 cm (0.75 in) PVC of the cup unit was reduced on the turning lathe to 2.59

cm (1.02 in) to allow the unit to pass freely through the sealing extension. The inside diameter was enlarged to 2.22 cm (0.875 in) using a 0.64 cm (0.50 in) boring tool on a turning lathe. This allowed the ceramic cup to fit inside, protecting the cup from snapping off at the neck. The cup was then bonded to the PVC, with the neck inside the 1.27 cm PVC and 2.54 cm (1 in) of the major diameter within the 1.90 cm (0.75 in) PVC. Devcon MVP 33 was used to bond the ceramic cup to the PVC portion of the cup unit.

The assembled transiometer is shown in Figure 6. An Integrated Circuits Sensors, Inc. model 33C pressure transducer, a sensor unit, and a cup unit are shown in Figure 7.

The final assembly took place at the installation site in three steps. A ceramic cup saturated with water was filled with tensiometer fluid. The vinyl tubing extending from the sensing port of the pressure transducer was also filled, completing the hydraulic connection between the ceramic cup and the sensor. The cup unit was then threaded into the sensor housing. The o-ring on the cup unit sealed between the 1.90 cm (0.75 in) portion of the cup unit and the sensor housing.

After the four o-rings of the sensor unit were lubricated with silicone grease, the sensor-cup assembly

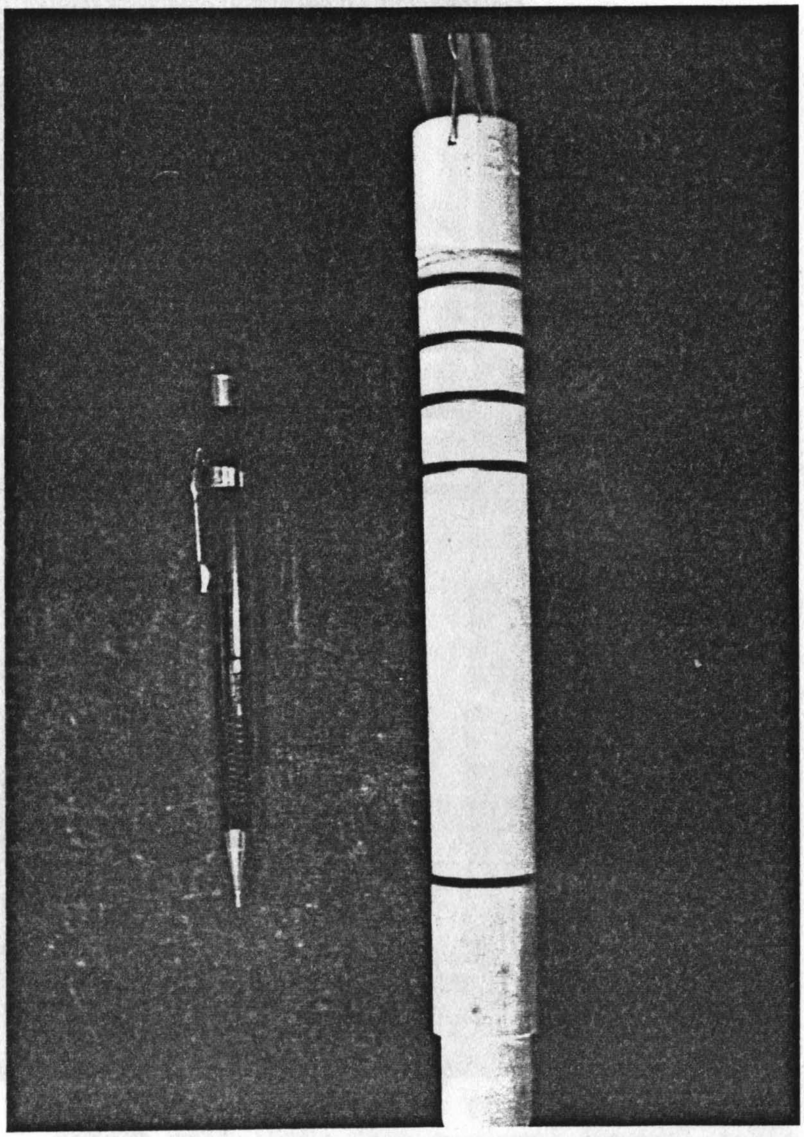

Figure 6. Assembled transiometer: sensor unit at top, cup unit at bottom. Note protrusion of ceramic cup from PVC pipe of sensor unit, o-ring seal between sensor unit and cup unit, and four o-rings placed on sensor unit.

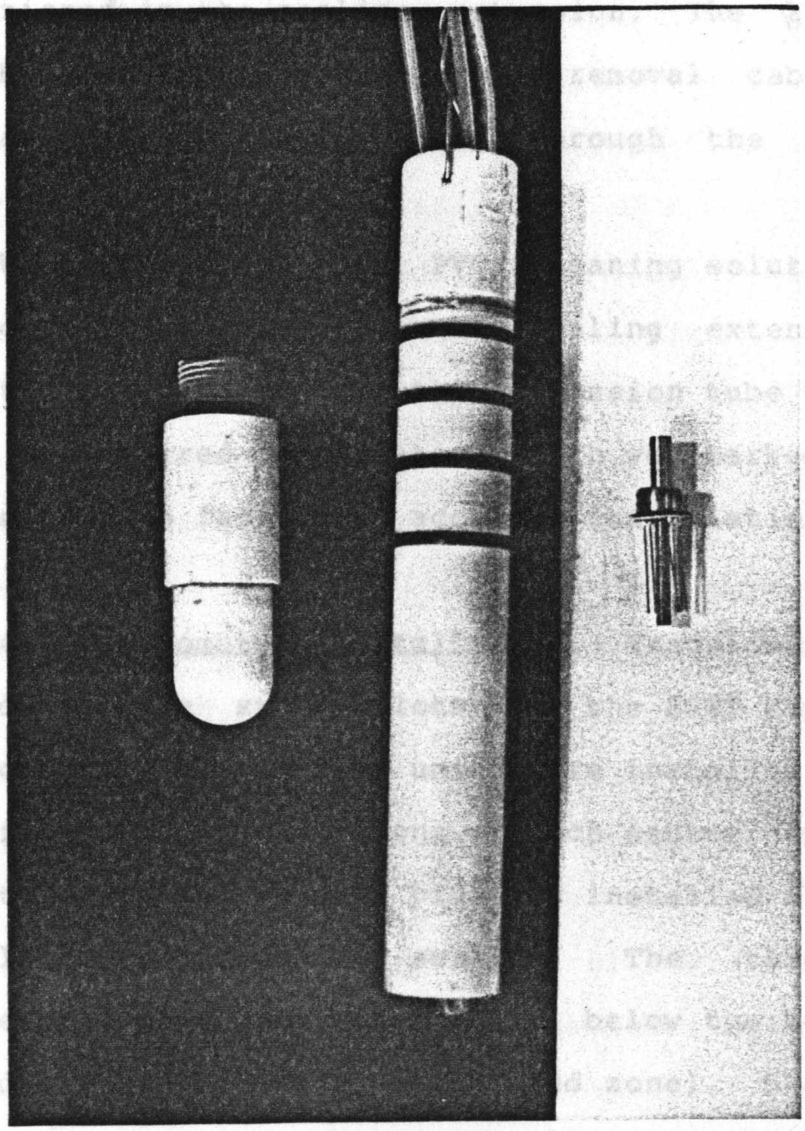

Figure 7. Transiometer components. From left: cup unit, sensor unit (note four o-rings; removal cable, electrical leads, removal vent, and sensor vent exiting the top; and vinyl tubing protruding at the bottom), and Integrated Circuits Sensors, Inc. model 33 pressure transducer.

was positioned in the sealing extension. The transducer vent tube, removal vent tube, removal cable, and electrical leads were all pushed through the extension tube.

Upon cleaning with PVC cleaning solution, the reduced outside diameter of the sealing extension was bonded to the inside of the extension tube using PVC cement. The desired installation depth was marked on the extension tube to facilitate accurate installation.

4. Transiometer: Installation. Transiometers were installed in the study plots at the RCWP Master Site during October, 1984. Five units were installed in each plot, giving four replications of each sensor depth. The deepest transiometer in each plot was installed 6.1 m (20 ft) below the ground surface. The three other transiometer depths were 1.8 m (6 ft) below the bottom of the sand-silt layer (in the saturated zone), 5 cm (2 in) above the bottom of the sand-silt layer (in the unsaturated zone), and 5 cm (2 in) above the top of the sand-silt layer (also unsaturated). At Site #86 the shallow transiometer was inadvertently placed in the sand-silt layer. The fifth unit in each plot was installed without a ceramic cup to measure the air pressure in the soil. Three of the air pressure units were placed 1.8 m

(6 ft) below the sand-silt and one, due to installation difficulties, was placed in the sand-silt layer.

An assembled transiometer was installed in seven steps. The first step was preparation of a hole with a 10 cm (4 in) auger on a Giddings hydraulic soil probe, augered to a depth slightly below the desired installation depth. Secondly, moist silt loam soil was backfilled to the desired placement level. Thirdly, the transiometer was inserted into the hole. Following transiometer insertion, more silt loam soil was used to backfill to approximately 30 cm (12 in) above the sensor. If the hole did not contain free water, the backfill was wetted peiodically during placement. Fifth, the removal vent was sealed with 5 minute epoxy as soon as possible. The sixth step was to backfill the majority of the hole with bentonite to prevent short-circuiting of any surface water inputs. Because of its low price, granular bentonite was used except where free water existed in the hole. Granular bentonite will float on a free water surface, therefore a pelleted form of bentonite was used to fill below any free water surface in the hole. Finally, silt loam soil was used to fill the top 60 cm (2 ft). A side view of a transiometer installation is shown in Figure 8.

Special care must be taken when preparing the hole for a transiometer installation near the top of a more

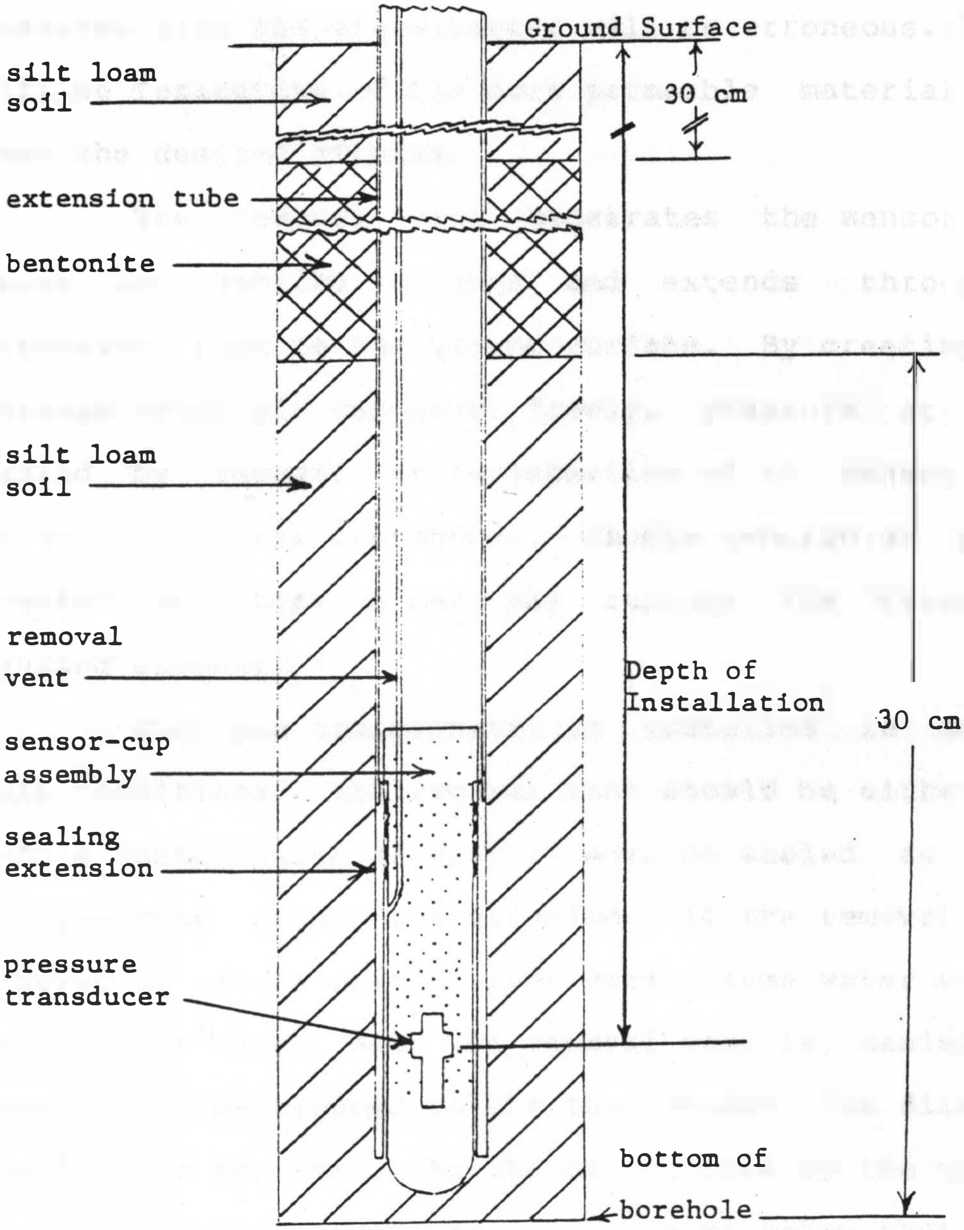

Figure 8. Transiometer installation.

permeable stratum. If the disturbed material is in contact with the more permeable material, the hydraulic properties measured with the transiometer will be erroneous. The data will be reflective of the more permeable material rather than the desired stratum.

The removal vent penetrates the sensor housing below the sealing o-rings and extends through the extension tube to the ground surface. By creating a path through which air can move freely, pressure or tension caused by removal or re-insertion of the sensor unit is relieved from the transducer. Excess tension or pressure created at these times may rupture the transducer's sensing element.

When the transiometer is installed in saturated soil conditions, the removal vent should be either sealed before installation or else it must be sealed as quickly as possible after installation. If the removal vent is allowed to remain open in free water, some water will move up into the tube. When the removal vent is sealed, this water will be trapped in the tube because the diameter of the tube is too small for the air to pass by the water. If the water table were to fall to a level below that of the water trapped in the removal vent, the water table indicated by the transiometer will be the water level in the tube rather than in the soil.

5. Piezometer. Four piezometers were installed in the study plots at a depth of 6.1 m (20 ft), one in each quadrant. The material used for the piezometers was 3.80 cm (1.5 in) PVC pipe. To simulate the intake of the transiometer, no screen was used on the piezometer. The bottom end of the piezometer tube was left open and placed at the bottom of the borehole. After the bottom of the piezometer was covered with backfill of sufficient depth (approximately 30 cm) the hole around the piezometer was backfilled with bentonite. The top of the PVC pipe was capped and air vents were created so air could enter and exit the piezometer.

The disturbed material placed at the bottom of the hole for the installation of the piezometers was to act as a screen. However, the bottom of the piezometer was pushed into the undisturbed glacial till substratum, significantly reducing the effects of the disturbed material.

6. Neutron Probe. Monitoring the volumetric soil moisture content throughout the soil profile with a neutron attenuation moisture probe required two 4.13 cm (1.625 in) diameter aluminum conduit access tubes in each quadrant, because aluminum conduit was not available in

sufficient length to monitor the entire profile with one access tube. One was installed to monitor from the ground surface to 1.8 m (6 ft), and was inserted directly into a 4.13 cm (1.625 in) diameter auger hole.

To reach the depth required of the other access tube, a 3.6 m (12 ft) section of conduit was fused to a 1.8 m (6 ft) section. This allowed monitoring of the soil moisture content to a depth of 5.2 m (17 ft). For the installation of the deep access tube, a 10 cm (4 in) diameter hole was required to a depth slightly greater than 1.8 m (6 ft) below the ground surface so the coupling collar between the 3.6 m (12 ft) section and the 1.8 m (6 ft) section could be inserted with no interference from the perimeter of the hole. The 4.13 cm (1.625 in) auger was used below this point. The access tube was inserted, and the large area around the tube above the depth of 1.8 m (6 ft) was filled with bentonite.

7. Thermistors. To monitor soil temperature and the presence of frost, four thermistors were installed in the northwest plot. These thermistors were installed on 26 February 1985 at depths of 15 cm (6 in), 30 cm (1 ft), 60 cm (2 ft), and 90 cm (3 ft). The main purpose of the study of the soil temperatures was to correlate any moisture migration with the presence and recession of

frost.

8. Data Acquisition System. On 10 December 1984, the data acquisition system consisting of a Hewlett-Packard 9825T computer, two Keithley 705 scanners, a Keithley 195 digital multimeter with 5 1/2 digit resolution, and a Honeywell strain gage power supply was installed. Used with the Keithley 705 scanners were two general purpose relay-terminal cards and one low-voltage card. The transiometers, piezometers, and thermistors were monitored bi-hourly with the data acquisition system. The data was recorded on magnetic tape and paper tape with the HP 9825T. The data acquisition system is shown in Figure 9.

Monitoring. After installation during October of 1984, the transiometers were monitored manually with a regulated voltage supply and hand-held digital voltmeter with 3 1/2 digit accuracy. The water levels in the piezometers were monitored with a tape measure with 0.003 m (0.01 ft) precision. The site was monitored three to four times per week. After the installation of the data acquisition system on 14 December 1984, the transiometers were monitored bi-hourly.

Piezometers were monitored with a tape measure

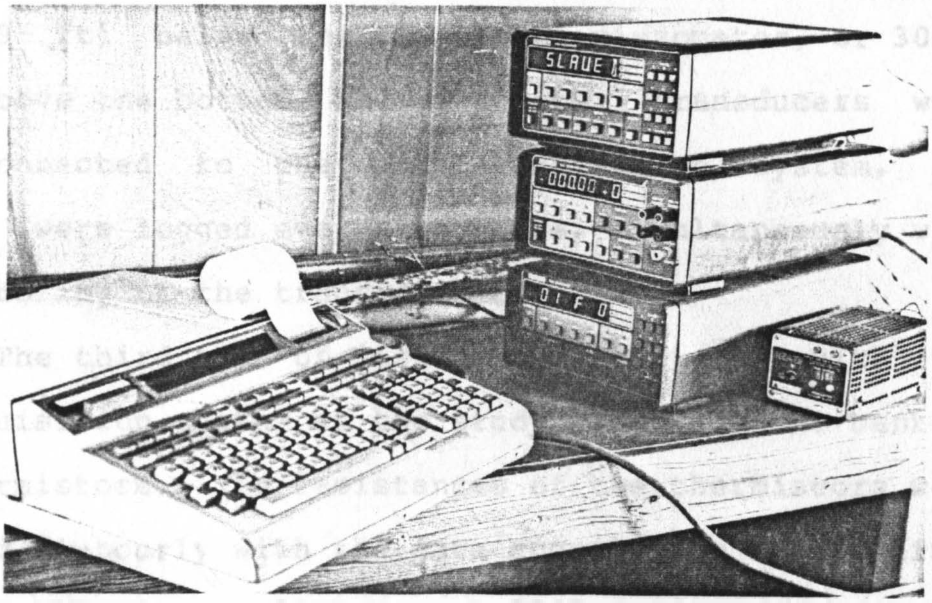

Figure 9. Data acquisition system consisting of Hewlett-Packard 9825T computer (left), Keithley 705 scanners (center, top and bottom), Keithley 195 digital multimeter (center), and power supply (right).

until 1 March 1985. At that time, a piezoresistive pressure transducer of the same type as those used in the transiometers was encased in Flexane epoxy and installed in each piezometer (Figure 10). These units were suspended 5.8 m (19 ft) below the top of the piezometer, or 30 cm (1 ft) above the bottom. The piezometer transducers were then connected to the data acquisition system, and readings were logged every two hours, simultaneously with the monitoring of the transiometers.

The third type of instrument monitored with the data acquisition system at the study plots was the bank of four thermistors. The resistances of the thermistors were monitored bi-hourly with the data acquisition system after their installation on 26 February 1985.

The three transiometers installed near the weather station were monitored exclusively with a regulated voltage supply and hand-held digital voltmeter.

Rural Clean Water Program RS Site #54

An auxiliary site was established at the RCWP RS Site #54, located on the southwest 1/4 of Section 13, R53W, T112N, Kingsbury County. RCWP RS Site #54 was 14.4 km (9 miles) west of the RCWP Master Site. This site was located on a shoulder slope of 5 to 7 percent. The soil profile was fairly uniform to the maximum depth of

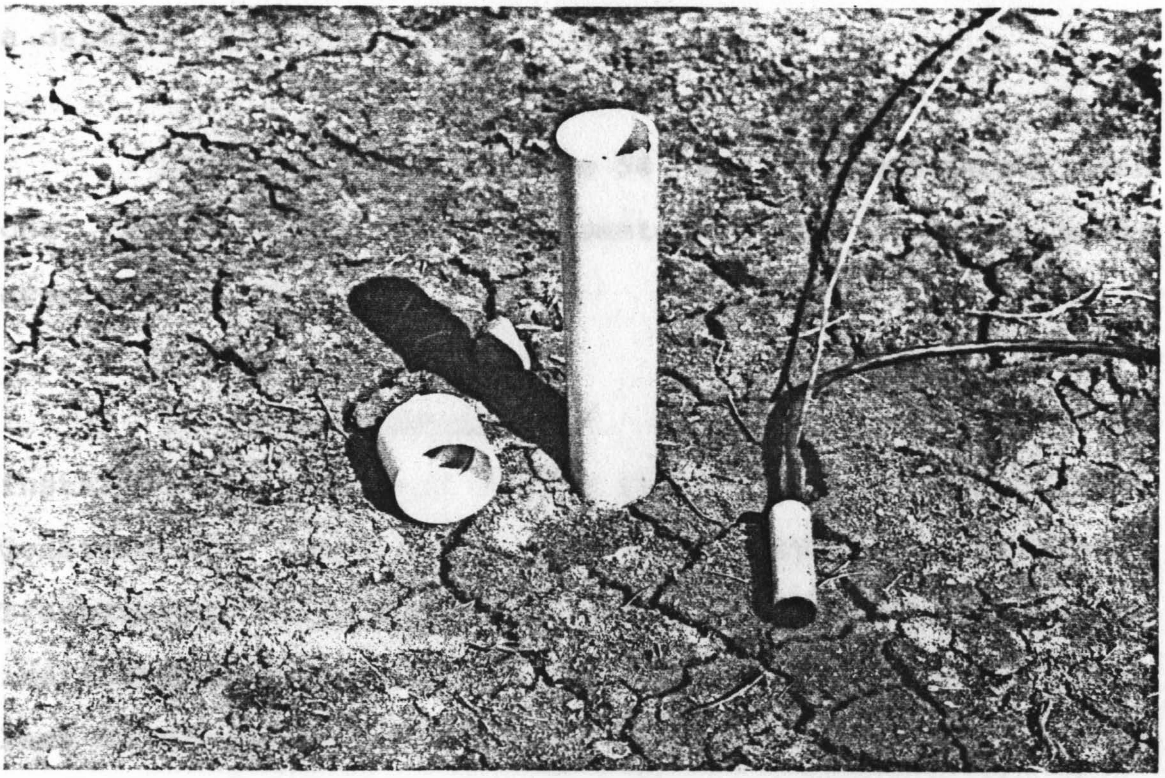

Figure 10. Piezometer top and piezometer pressure transducer unit. The transducer unit consisted of an Integrated Circuits Sensors, Inc. model 33 pressure transducer mounted within 1.27 cm (0.5 in) diameter PVC pipe and cast in Flexane epoxy. Note the fractures in the soil surface.

drilling with a black silt loam A horizon of 30 cm (12 in) thickness overlying yellow silt loam to silty clay loam to a depth of 5.2 m (17 ft).

Instrumentation. Site 54 was instrumented with one transiometer, two piezometers, and a neutron probe access tube (Figure 11).

1. Transiometer. A single transiometer was installed at a depth of 5.03 m (16.5 ft) on 2 July 1984. Construction procedures were as previously outlined. Transiometer installation was attempted at other instrumentation sites of the RCWP RS Site, but a thick lens of saturated sand present at all other sites caused the hole to fill in with water and soil before the transiometer could be inserted into the borehole. At Site #54, the borehole remained open long enough to allow installation of a transiometer, mainly because a sand lens was not encountered. The installation procedures noted previously were followed. The hole did not contain any free water at the time of installation, allowing the use of granular bentonite rather than requiring the use of the pelleted form.

2. Piezometers. Two piezometers made of 5 cm (2

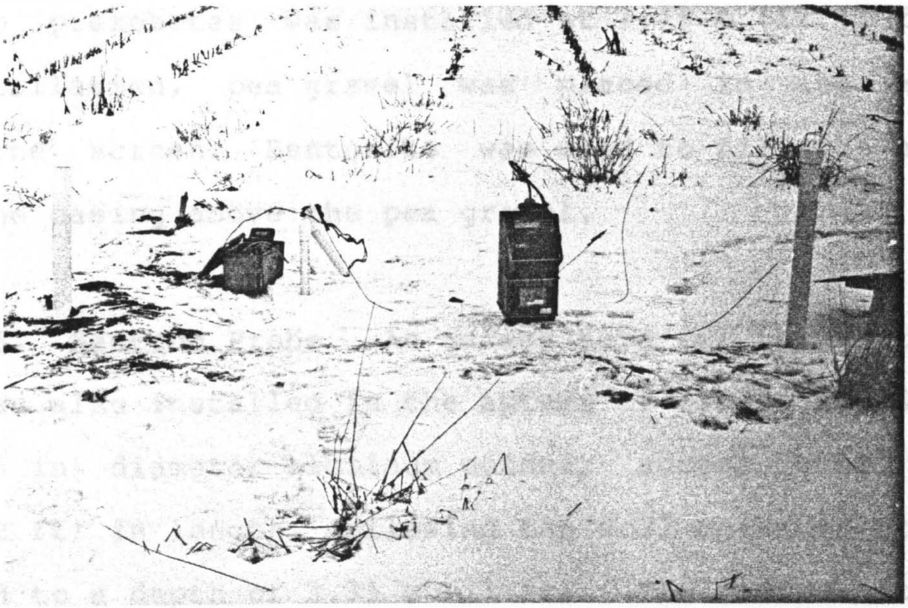

Figure 11. RCWP RS Site 54. Piezometers are at left and right, neutron probe is mounted on access tube, and regulated voltage supply and hand-held digital multimeter are shown monitoring transiometer.

in) diameter PVC pipe were installed in the autumn of 1983. Each piezometer had a screened length of 0.91 m (3 ft). The shallow piezometer was installed with the top of the screen at 2.26 m (7.43 ft) below the ground surface, the deep piezometer was installed at 3.76 m (12.33 ft). Upon installation, pea gravel was placed in the hole around the screen. Bentonite was used to fill the hole around the casing above the pea gravel.

3. Neutron Probe. An access tube for the neutron probe was also installed in the autumn of 1983. The 4.13 cm (1.625 in) diameter aluminum conduit access tube was 3.6 m (12 ft) in length, allowing the soil moisture to be monitored to a depth of 3.35 m (11 ft). The access tube was inserted directly into a 4.13 cm (1.625 in) diameter hole prepared with an auger and a Giddings hydraulic soil probe. No disturbed material or bentonite was needed as fill material.

Monitoring. Due to the lack of data acquisition equipment available for the monitoring of a solitary location, RCWP RS Site #54 was monitored exclusively by hand. This data collection normally took place on a weekly basis; however, RS Site #54 was not monitored for the majority of the summer of 1984.

The transiometer of RS Site #54 was monitored with a hand-held digital voltmeter with 3 1/2 digit precision and a regulated voltage supply. The water levels in the piezometers were measured with a tape measure with .003 m (.01 ft) precision. Neutron probe data were collected from 30 cm (1 ft) to 3.35 m (11 ft) at 30 cm (1 ft) intervals.

RESULTS AND DISCUSSION

Response Time After Installation

Basic time lag is defined by Hvorslev (1951) as:

$$T = \frac{v}{q} \qquad (3)$$

where T is the basic response time, v is the volume required to equilibrate the sensor, and q is the flow rate to the sensor. Because the water volume requirement to bring the transducer of the transiometer to equilibrium is very small, the major time lag occurs in saturating the silt loam backfill. The time lag involved in bringing the backfill to saturation is given as:

$$T = \frac{(2PLkH)/\ln(L/R+(1+(L/R)^{2})^{1/2})}{1+(8/P)(L/2R)(k/k_{v})} \qquad (4)$$

where T is the time lag, P is pi, L is the depth of backfill material, k is the soil coefficient of permeability, H is the head, R is the borehole radius, and k_v is the soil coefficient of vertical permeability (from Hvorslev, 1951).

The basic time lag of the piezometer due to the volume of water required to fill the piezometer stem was calculated using:

$$T = \frac{P\ D}{11\ k} \qquad (5)$$

where T is the time lag, D is the piezometer diameter, k is the soil coefficient of permeability, and P is pi.

RCWP Master Site. Figure 12 shows the time lag difference after installation between the transiometer placed at a depth of 6.10 m and the piezometer of Site #87.

1. Transiometers. The transiometer was installed at Site 87 on 4 October 1984. Twenty-eight hours after installation the total hydraulic potential calculated from the pressure measured with the transiometer was 509.40 m above msl, indicating the transiometer had equilibrated with the surrounding soil conditions (point 1 on Figure 12). This observed response time correlates well to the 3.3 hr response time calculated using Hvorslev's method (Table 4). All of the other observed response times were greater than calculated values. The observed response times ranged from 1 day (sensor without the ceramic cup at a depth of 3.73 m) to a maximum 55 days, found for a transiometer installed at a depth of 3.73 m, while the maximum calculated response time for a transiometer was 16.4 hr. Only two transiometers had response times greater than the response time of the piezometer that equilibrated.

2. Piezometers. The piezometer installed in Site #87 on 29 October 1984, was the only piezometer installed at the Master Site to come to equilibrium before the

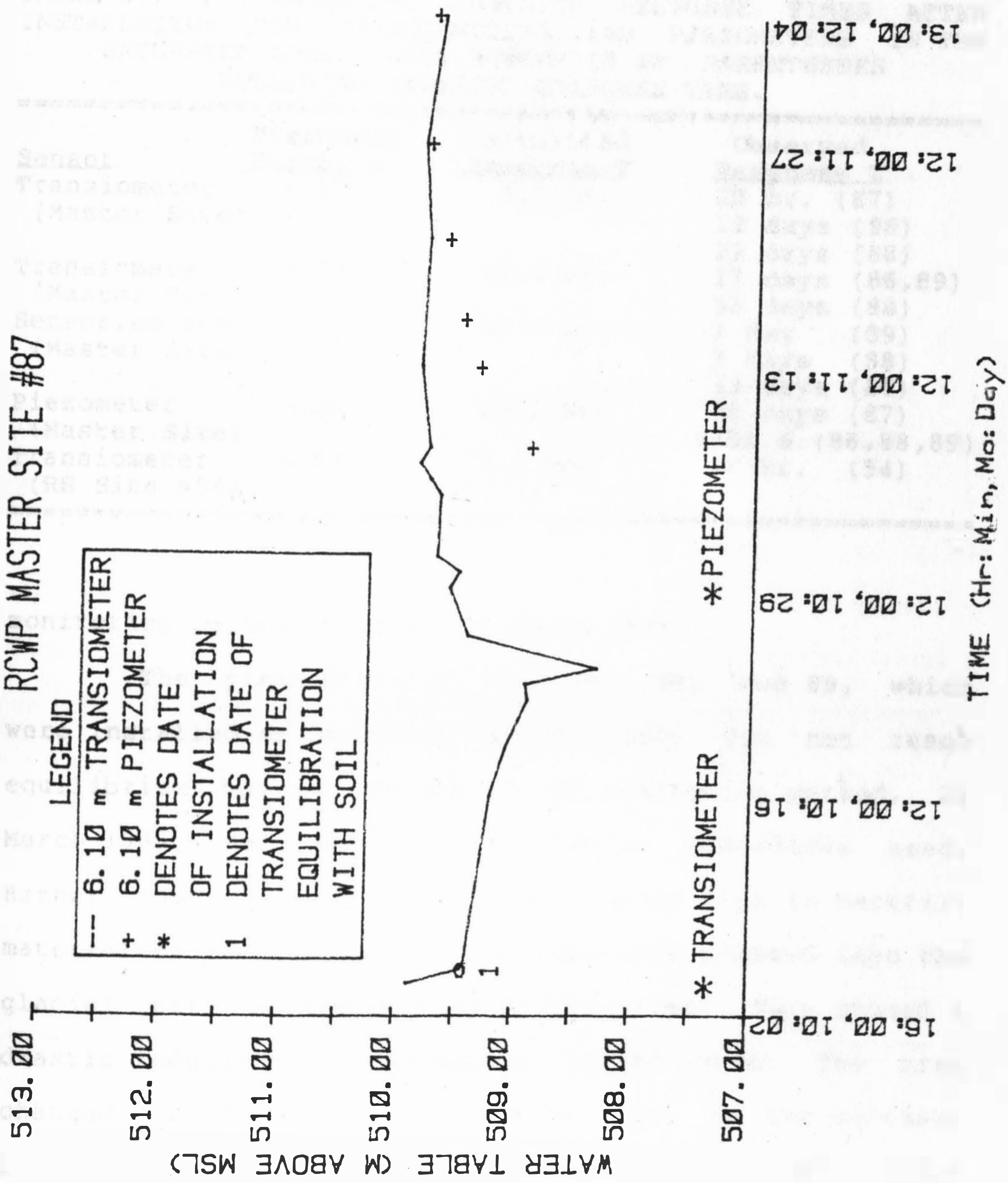

Figure 12. Response of 6.10 m transiometer and piezometer after installation at RCWP Master Site #87. The transiometer was installed 4 October, and the piezometer was installed 29 October.

TABLE 4. CALCULATED AND OBSERVED RESPONSE TIMES AFTER INSTALLATION FOR TRANSIOMETERS AND PIEZOMETERS IN THE SATURATED ZONE. SITE NUMBER IS IN PARENTHESES FOLLOWING OBSERVED RESPONSE TIME.

Sensor	Placement Depth, m	Calculated Response T	Observed Response T
Transiometer (Master Site)	6.10	3.3 hr.	28 hr. (87) 12 days (86) 12 days (88)
Transiometer (Master Site)	3.73	16.4 hr.	17 days (86,89) 55 days (88)
Sensor,no cup (Master Site)	3.73	16.4 hr.	1 day (89) 3 days (88) 13 days (86)
Piezometer (Master Site)	6.10	43.1 hr.	29 days (87) >151 d (86,88,89)
Transiometer (RS Site #54)	5.03	0.3 hr.	18 hr. (54)

monitoring period ended on 21 March 1985.

The piezometers of Sites 86, 88, and 89, which were installed on 29 and 30 October 1984, did not reach equilibrium before the end of the monitoring period, 21 March 1985, due to the installation procedures used. Rather than installing the piezometer tips in backfill material of the boreholes, the ends were pressed into the glacial till at the bottoms of the holes. This caused a drastic reduction of effective intake area. The area changed from the circumferential area of the borehole bottom containing silt loam backfill of 972.8 cm^2 (150.8 in^2), to the cross-sectional area of the piezometer stem of 11.4 cm^2 (1.8 in^2)

Because of this installation procedure, the piezometers of Sites 86, 88, and 89 measured the till intergranular properties rather than the bulk till properties.

RCWP RS Site 54. The transiometer at RS Site 54 was installed 2 July 1984. It had reached equilibrium with surrounding soil conditions by the next time of monitoring, which was 18 hours after installation. The corresponding calculated time lag was 0.3 hours (Table 4). No installation time lag data was recorded for the piezometers installed at RCWP RS Site #54.

The observation of a longer response time than calculated can be partly accounted for by the installation procedures used to seal the borehole. The bentonite used to seal around the piezometer stem is a form of montmorillonite, which has a very high water holding capacity. Measurements taken at the access tubes monitoring the soil moisture from a depth of 2.13 m (7 ft) below the ground surface to a depth of 5.18 m (17 ft) at sites 87 and 88 indicated the bentonite backfill reached a moisture content of greater than 0.48 m^3/m^3 in the unsaturated zone. Assuming bentonite can reach a moisture content of 0.65 m^3/m^3 when saturated, and using Darcy's Law and the assumptions of initial moisture content of the bentonite of 0.10 m^3/m^3 and isotropic soil, with $K_{sat}=9x10^{-8}$ m/s (.013 in/hr, based on results to be presented later), the time required to saturate a 3.05 m (10 ft) profile of bentonite would be slightly greater than 72 hours. However, the assumptions of isotropic soil conditions and unit hydraulic gradient are open to question. The horizontal hydraulic conductivity is probably less than noted above, therefore underestimating the response time.

Water Table Measurement

Water table definition in fine-textured soils is a complex problem due to the small drainable porosity of the soil. Small volumetric additions to or subtractions from the water table can cause large fluctuations of the water table elevation. These large fluctutions induce errors when monitoring the water table with instruments dependent upon a flux of water to indicate a response, such as piezometers, because of low permeability.

Not only is water movement restricted in soils of low permeability, but air flow through the soil is also inhibited. This causes problems when using a transiometer with a differential pressure transducer to measure pressure below the ground surface. The reference side of the transducer is vented to the ground surface, and responds to atmospheric pressure changes immediately. However, because the soil restricts air movement from the ground surface to the depth of installation,the sensing side of the transducer does not respond to the change of atmospheric pressure. The transiometer measures a change of pressure, but the pressure change is not due to a change of soil moisture conditions, e. g. water table movement, but is caused by atmospheric pressure fluctuation.

Also in fine-textured soils of low porosity, the capillary fringe directly above the water table will be thicker due to higher capillary rise in the smaller diameter pores of a fine-textured soil. The thick capillary fringe disguises the volumetric moisture content data obtained with a neutron probe, which makes water table definition with the neutron probe valid only to describe the water table as within a range of elevations.

Other difficulties in water table measurement with a neutron probe are caused by the nature of the measurement. Because the neutrons emitted by the neutron probe will travel through the soil until striking a hydrogen atom, the volume of soil sampled by the probe expands in soils of lower moisture content. The size of the sphere of influnce also decreases the effectiveness of the neutron probe when locating a water table. Because the instrument will count neutrons that are attenuated as far as away as 7.6 cm (3 in) from the probe even in saturated conditions, the maximum precision of the neutron probe is 7.6 cm (3 in)

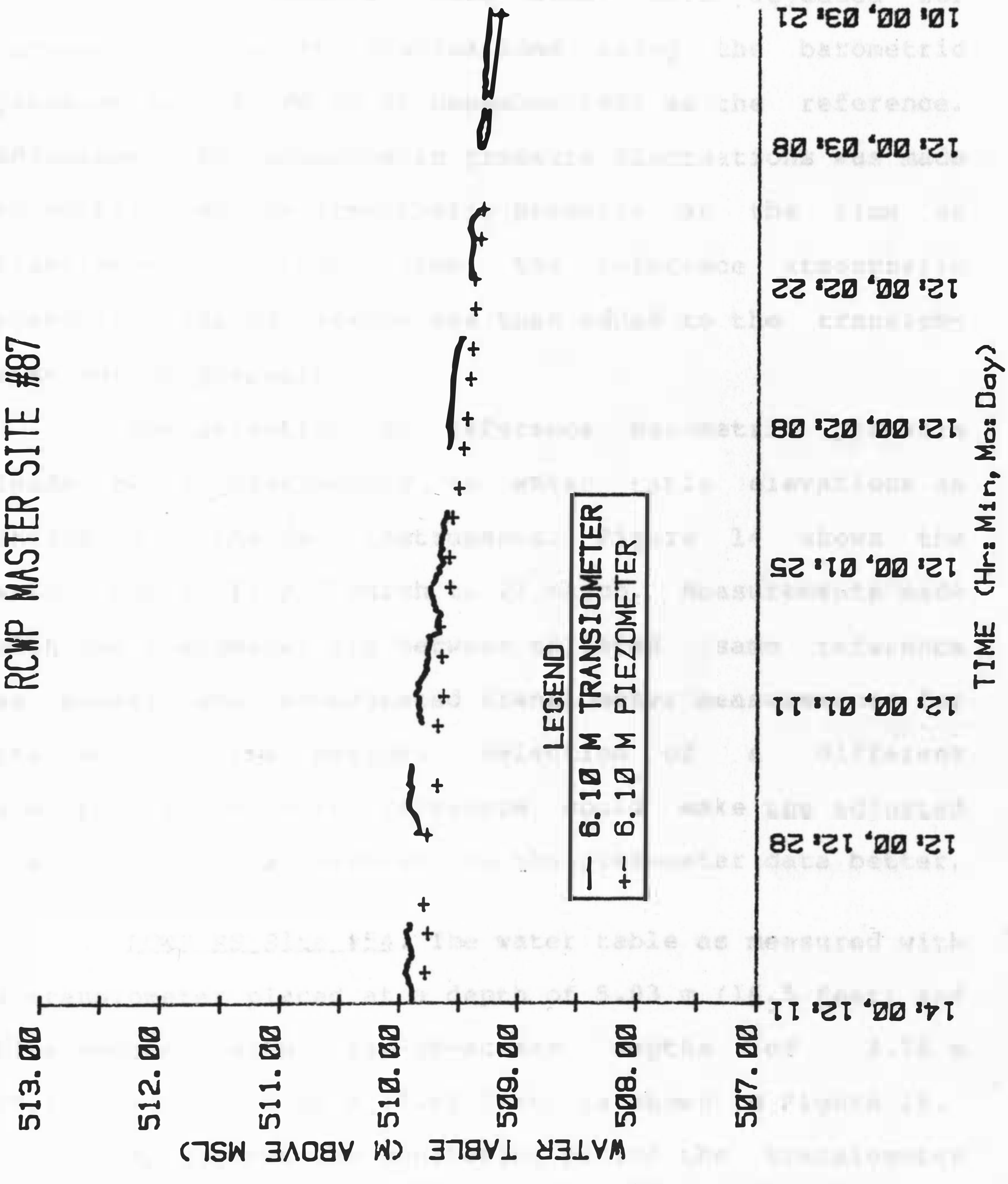

Figure 13. Water table at RCWP Master Site #87 as measured with 6.10 m transiometer (adjusted for atmospheric pressure changes) and 6.10 m piezometer from 11 December 1984, to 21 March 1985.

The neutron probe is limited when trying to detect a water table surface at a given time, but is valuable in the determination of moisture migrations. By considering the soil moisture content changes over time, zones of moisture loss, moisture gain, and no moisture change can be identified.

RCWP Master Site. Figures 12 through 14 depict the total hydraulic potential as calculated from the transiometer pressures and as measured with piezometers located at the RCWP Master Site. At Sites 87 and 88 the total hydraulic potential represents the water table elevation. Sites 86 and 89 contain transiometers operational in the unsaturated zone, which measure matric potential rather than piezometric head.

Site 87 is the only plot at the RCWP Master Site where a direct comparison between transiometer and piezometer can be made. The piezometers of Sites 86, 88, and 89 had not reached equilibrium before the end of the monitoring period. Figure 13 compares the water table at Site 87 as measured with the deep (6.1 m placement depth) transiometer to the measurements made with the piezometer, which is also installed at a depth of 6.1 m (20 feet). The responses of the transiometer and the piezometer correlate quite well.

The transiometer data shown were adjusted for barometric pressure fluctuations using the barometric pressure at 2:00 PM on 11 December 1984 as the reference. Adjustment for atmospheric pressure fluctuations was made by subtracting the atmospheric pressure at the time of transiometer output from the reference atmospheric pressure. The difference was then added to the transiometer output pressure.

The selection of reference barometric pressure leads to a discrepancy in water table elevations as indicated by the two instruments. Figure 14 shows the water table from 7 March to 21 March. Measurements made with the piezometer are between adjusted (same reference as above) and nonadjusted transiometer measurements for the entire time period. Selection of a different atmospheric pressure reference could make the adjusted transiometer data correlate to the piezometer data better.

<u>RCWP RS Site #54</u>. The water table as measured with a transiometer placed at a depth of 5.03 m (16.5 feet) and piezometers with top-of-screen depths of 3.76 m (7.43 feet) and 2.26 m (7.43 feet) is shown in Figure 15.

Throughout the monitoring period the transiometer indicated a higher water table than either of the piezometers (Figure 15, Table 5). When the water table fluctuation is plotted rather than the water table elevation,

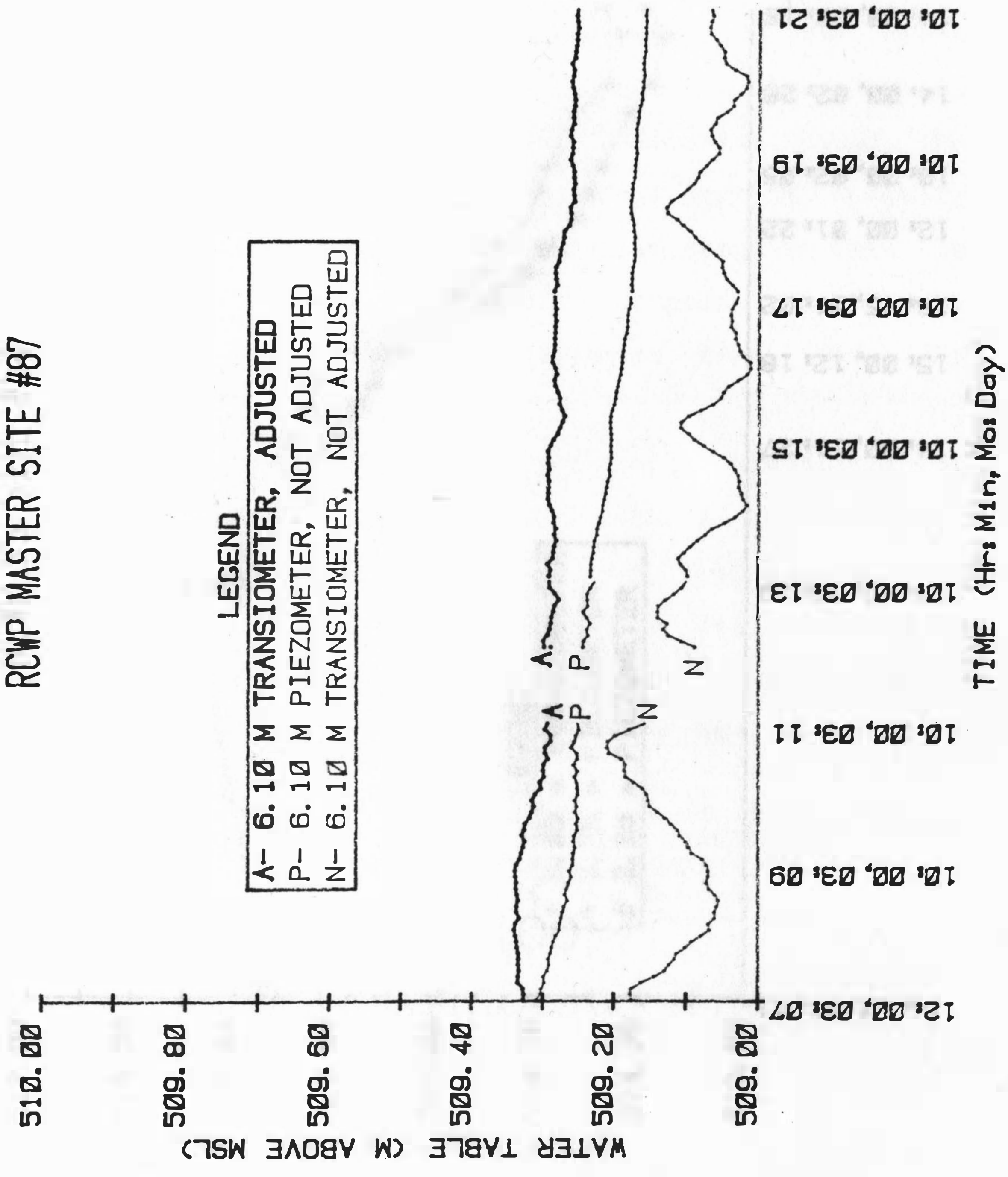

Figure 14. Water table as measured with 6.10 m transiometer, both adjusted and not adjusted for atmospheric pressure changes, and 6.10 m piezometer from 7 March 1985, to 21 March 1985.

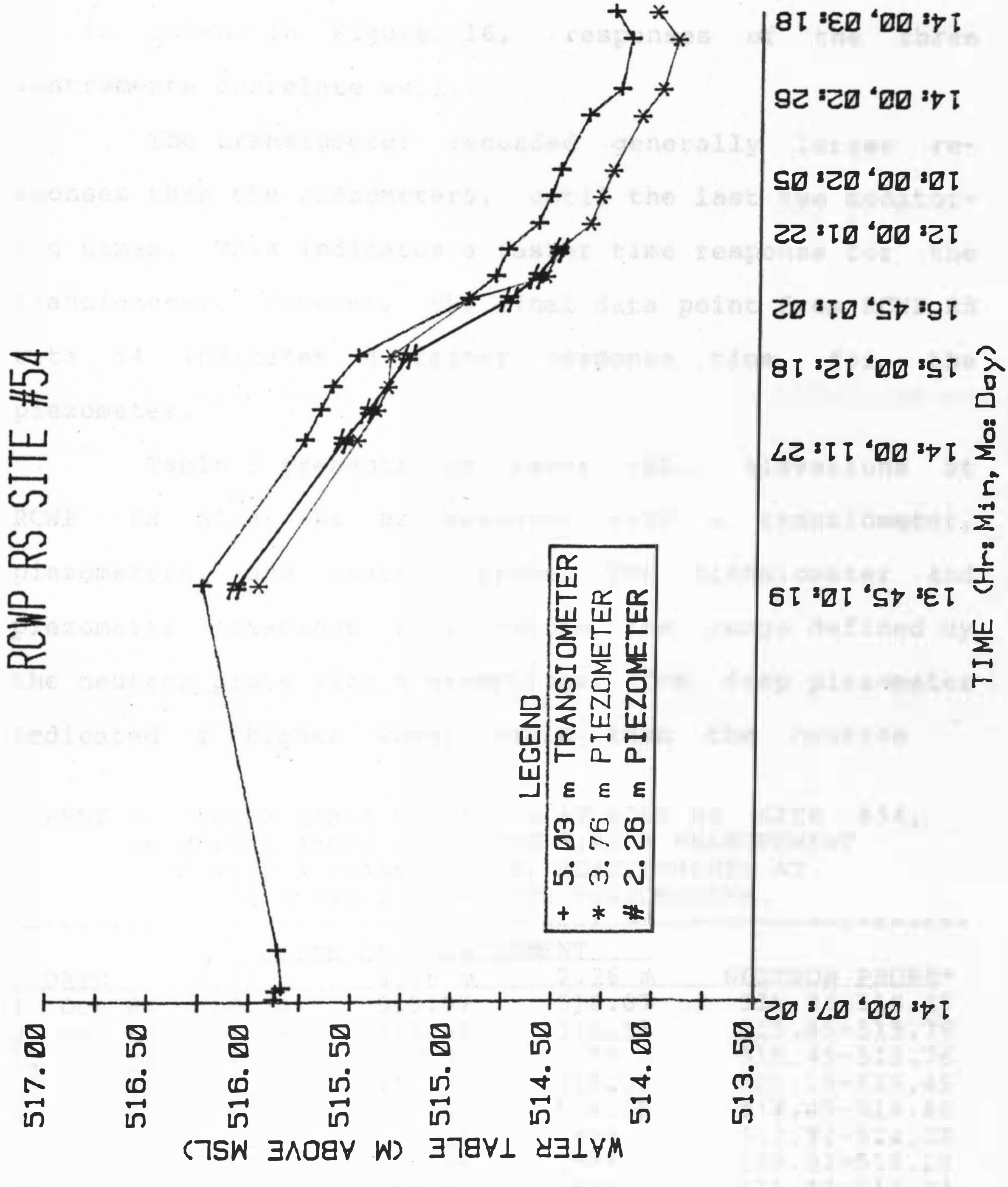

Figure 15. Water table at RCWP RS Site 54 as measured with transiometer and piezometers from 2 July through 18 March.

as is shown in Figure 16, responses of the three instruments correlate well.

The transiometer recorded generally larger responses than the piezometers, until the last two monitoring times. This indicates a faster time response for the transiometer. However, the final data point from RCWP RS Site 54 indicates a faster response time for the piezometer.

Table 5 presents the water table elevations at RCWP RS Site #54 as measured with a transiometer, piezometers, and neutron probe. The transiometer and piezometer readings fall within the range defined by the neutron probe with 6 exceptions. The deep piezometer indicated a higher water table than the neutron

TABLE 5. WATER TABLE ELEVATION AT RCWP RS SITE #54, IN METERS ABOVE MSL. THE 5.03 M MEASUREMENT IS WITH A TRANSIOMETER, MEASUREMENTS AT 3.76 M AND 2.26 M WITH PIEZOMETERS.

	DEPTH OF MEASUREMENT			
DATE	5.03 m	3.76 m	2.26 m	NEUTRON PROBE*
19 Oct 84	516.24	515.97	516.07	516.06-516.37
27 Nov 84	515.74	515.48	515.55	515.45-515.76
10 Dec 84	515.60	515.33	**	515.45-515.76
18 Dec 84	515.48	515.32	515.23	515.15-515.45
8 Jan 85	514.80	514.55	514.59	514.45-514.84
29 Jan 85	514.53	514.28	***	513.92-514.23
19 Feb 85	514.34	514.08	***	513.92-514.23
26 Feb 85	514.19	513.98	***	513.92-514.23

* Due to neutron probe sampling interval of 0.30 m, water table may only be defined as within the indicated range.
** No check.
*** Indicates water table below 514.49 m above msl.

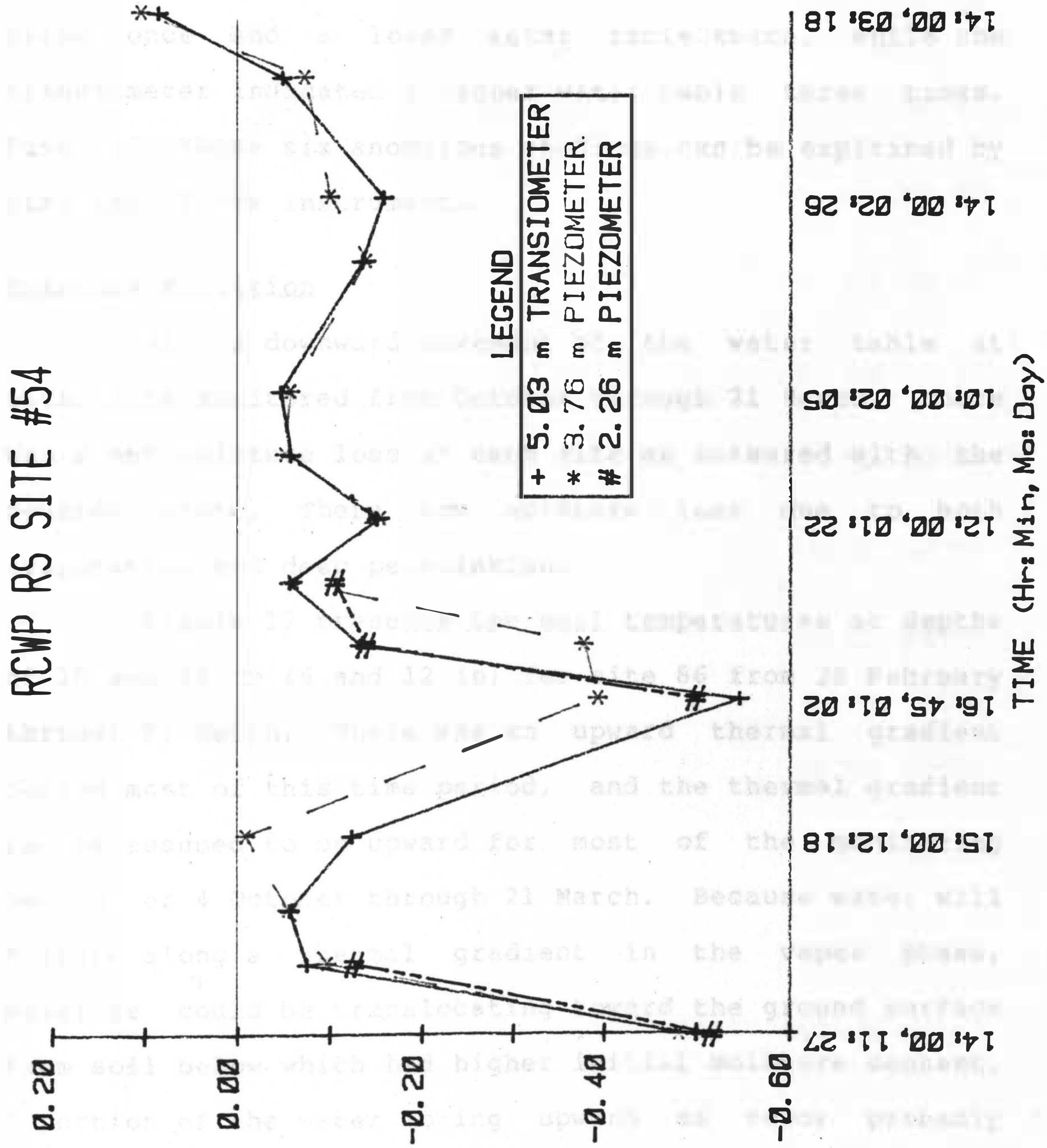

Figure 16. Water table fluctuations at RCWP RS Site 54 from 27 November through 18 March.

probe once and a lower water table twice, while the transiometer indicated a higher water table three times. Five of these six anomalous readings can be explained by time lag of the instrument.

Moisture Migration

With a downward movement of the water table at each site monitored from October through 21 March, there was a net moisture loss at each site as measured with the neutron probe. There was moisture loss due to both evaporation and deep percolation.

Figure 17 presents the soil temperatures at depths of 15 and 30 cm (6 and 12 in) for site 86 from 26 February through 21 March. There was an upward thermal gradient during most of this time period, and the thermal gradient can be assumed to be upward for most of the monitoring period of 4 October through 21 March. Because water will migrate along a thermal gradient in the vapor phase, moisture could be translocating toward the ground surface from soil below which had higher initial moisture content. A portion of the water moving upward as vapor probably moved into the atmosphere, evaporating from the soil surface and fractures at the soil surface. The RCWP Master Site had numerous fractures at the soil surface for most of the monitoring period, facilitating evaporation of

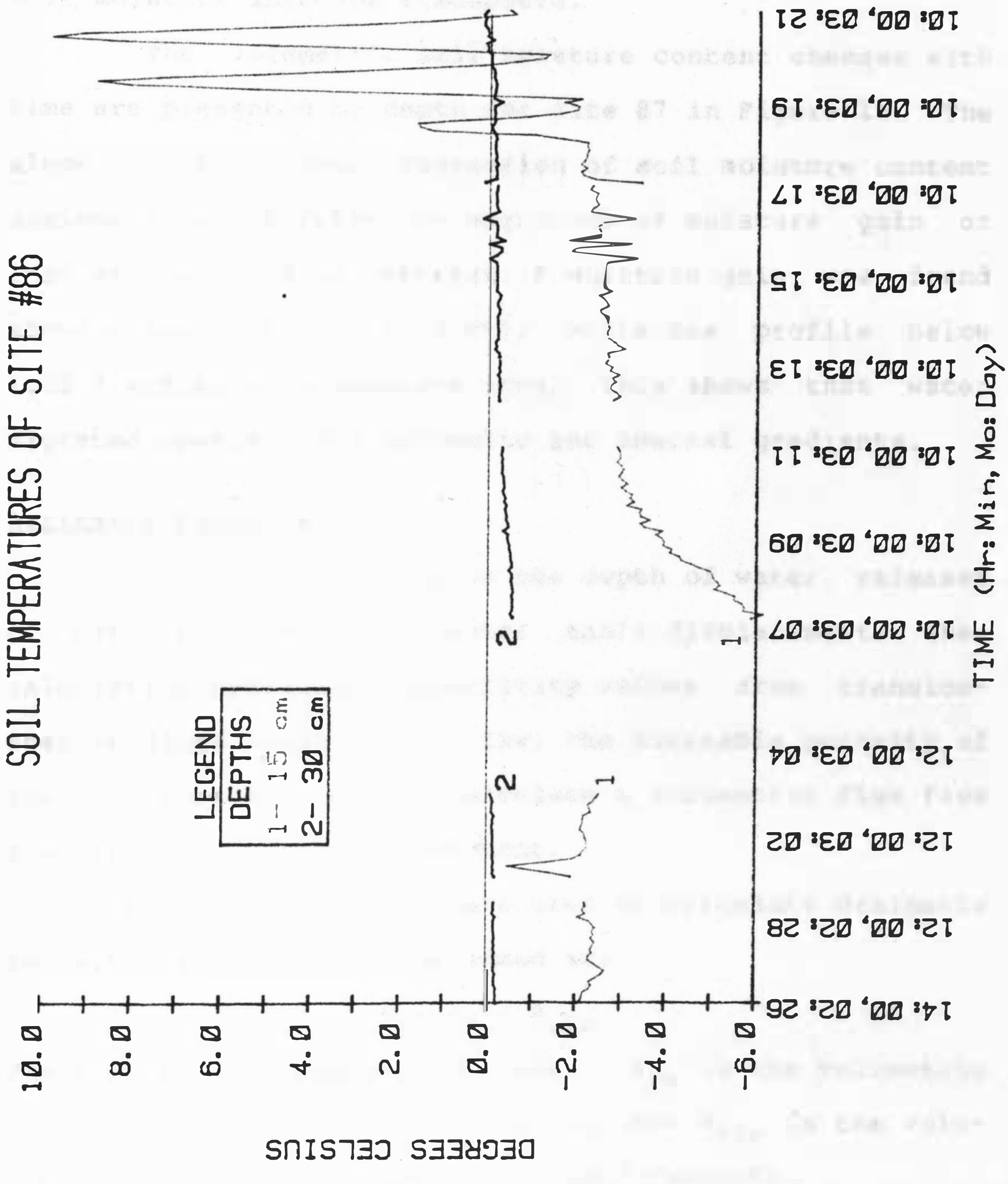

Figure 17. Soil temperatures at Site 86 from 26 February through 21 March.

soil moisture into the atmosphere.

The volumetric soil moisture content changes with time are presented by depth for Site 87 in Figure 18. The slope of the linear regression of soil moisture content against time indicates the magnitude of moisture gain or loss at the depth of interest. A moisture gain was found above a depth of 1.22 m (4 ft), while the profile below 1.22 m exhibited a moisture loss. This shows that water migrated upward along hydraulic and thermal gradients.

Drainable Porosity

Drainable porosity is the depth of water released or used per depth of water table displacement. When calculating hydraulic conductivity values from transiometer readings using Darcy's law, the drainable porosity of the soil must be used to calculate a volumetric flux from a water table elevation movement.

Neutron probe data were used to calculate drainable porosity, which can be expressed as:

$$E_d = \theta_{vs} - \theta_{vfc}$$

where E_d is the drainable porosity, θ_{vs} is the volumetric soil moisture content at saturation, and θ_{vfc} is the volumetric soil moisture content at field capacity.

RCWP Master Site. The fluctuation of measured volumetric soil moisture content at the Master Site was

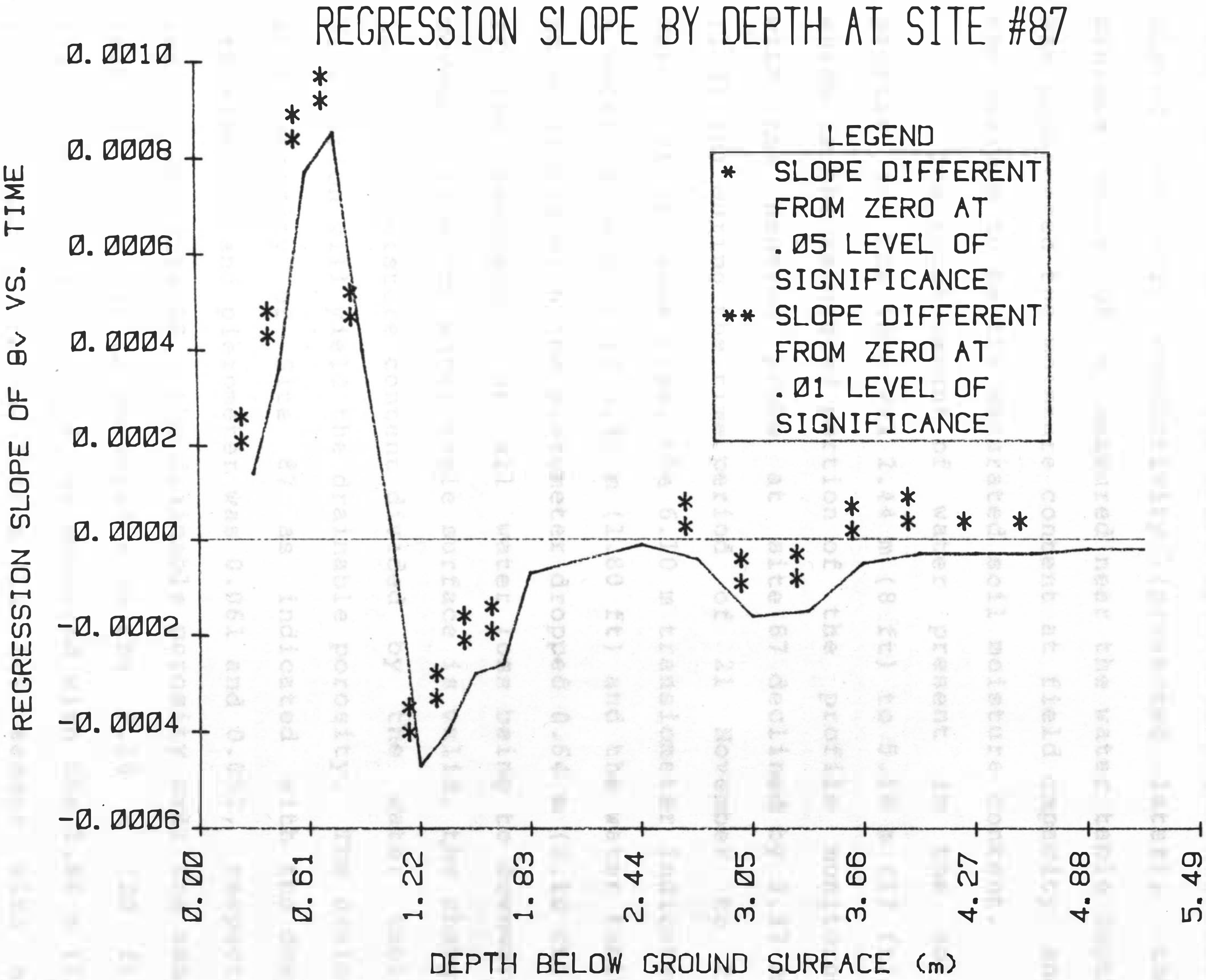

Figure 18. Regression slope (θ_v vs. time) by depth for RCWP Master Site 87.

very small. Due to the small fluctuation and low calculated hydraulic conductivity (presented later), the minimum value of θ_v measured near the water table depth was considered the moisture content at field capacity and the maximum to be the saturated soil moisture content.

The total amount of water present in the soil profile in the interval 2.44 m (8 ft) to 5.18 m (17 ft), which is the saturated portion of the profile monitored with the neutron probe at site 87 declined by 3.33 cm (1.31 in) during the time period of 21 November to 21 March. At the same time, the 6.10 m transiometer indicated a water table drop of 0.55 m (1.80 ft) and the water table as monitored with the piezometer dropped 0.64 m (2.10 ft). If the assumption of all water loss being to downward movement from the water table surface is valid, the change in profile moisture content divided by the water table fluctuation will yield the drainable porosity. The drainable porosity of Site 87 as indicated with the deep transiometer and piezometer was 0.061 and 0.052, respectively. At Site 88, the drainable porosity over the same interval was 0.024 as measured with the 6.10 m (20 ft) transiometer, and 0.019 as measured with the 3.66 m (12 ft) transiometer and the 3.66 m (12 ft) sensor with no ceramic cup. Drainable porosity values calculated in the same manner for Site 89 were 0.052 (with the 3.66 m transiometer) and 0.044 (as measured with the 3.66 m sensor, no cup). The values calculated from transiometer data and piezometer data were generally higher than the drainable porosity values calculated from neutron probe data, which averaged 0.033 (Table 6).

TABLE 6. DRAINABLE POROSITY OF GLACIAL TILL AT RCWP MASTER SITE AS INDICATED WITH NEUTRON PROBE.

SITE	DEPTH,m	θ_{vs}	θ_{vfc}	E_d
87	3.05	0.384	0.350	0.034
87	3.35	0.372	0.339	0.033
88	2.74	0.354	0.331	0.023
89	2.44	0.400	0.356	0.044
89	2.74	0.385	0.348	0.037
89	3.05	0.385	0.360	0.025
Average		0.380	0.347	0.033

The values calculated for Site 88 from transiometer data are less than the true drainable porosity. From a depth of 4.27 m (14 ft) to 5.18 m (17 ft) there was a zone of moisture gain over the monitoring period. Thus, the volumetric removal of water from the water table is underestimated, resulting in a smaller calculated drainable porosity.

The average saturation percentage (θ_{vs}) found with the neutron probe at the RCWP Master Site was 0.380 (Table 6). The standard laboratory procedure for the determination of saturation percentage involves air-drying, then grinding a sample before saturating it. The average saturation percentage between the depths of 2.74 m (9 ft) and 3.66 m (12 ft) found using the standard laboratory procedure was 0.466, a difference of 0.086 from the values measured in situ with the neutron probe.

RCWP RS Site 54. The drainable porosity values obtained for RS Site #54 as measured with the neutron probe are quite similar to the values found for the RCWP Master Site and are presented in Table 7. The maximum soil moisture content was again assumed to be θ_{vs}. Because of a larger water table fluctuation and greater calculated hydraulic conductivity than the Master Site, the minimum volumetric soil moisture content was no longer assumed to correspond to field capacity. The moisture content at field capacity was considered to be the first sample following a significant drop of soil moisture below saturation.

Moisture contents at saturation and field capacity should be measured about 17 days apart. Considering the saturated hydraulic conductivity of Site #54 to be 10^{-7} m/s (.014 in/hr, to be presented later) the 15 cm (6 in.) diameter sensed volume of the neutron probe would drain from saturation to field capacity in less than 18 days. Using a shorter time interval would underestimate E_d, and vice versa.

The total water present in the 3.35 m (11 ft) soil profile as measured with the neutron probe declined by 7.44 cm (2.93 in) from 19 October to 18 March. The water table as measured with the 5.03 m (16.5 ft) transiometer fell 2.02 m (6.63 ft), indicating a drainable porosity of 0.037. Similar calculations on the data from the 3.76 m piezometer yielded a drainable porosity of 0.038. These values are greater than the average drainable porosity measured with the neutron probe of 0.025, presented in Table 7, due to the fact that the profile from 0.91 m (3 ft) to 2.13 m (7 ft) drained to a moisture content below field capacity.

TABLE 7. MAXIMUM AND DRAINABLE POROSITIES OF RCWP RS SITE #54 AS CALCULATED FROM NEUTRON PROBE DATA.

DEPTH,m	θ_{vmax}	θ_{vmin}	E_{max}	θ_{vs}	θ_{vfc}	E_d
0.91	0.390	0.305	0.085	0.390	0.365	0.025
1.21	0.391	0.331	0.060	0.391	0.367	0.024
1.52	0.399	0.364	0.035	0.399	0.370	0.029
1.83	0.397	0.359	0.038	0.397	0.368	0.029
2.13	0.389	0.357	0.032	0.389	0.370	0.019
2.44	0.393	0.370	0.023	0.393	0.370	0.023
Average	0.393	0.348	0.045	0.393	0.368	0.025

Hydraulic Conductivity

Soil hydraulic conductivity values were calculated from piezometer responses following installation using the method suggested by Kirkham (1945):

$$K_{sat} = \frac{Pr^2}{A\ t} * \ln(Y_0/Y_t) \qquad (6)$$

where K_{sat} is the saturated hydraulic conductivity, r is the piezometer radius, t is the elapsed time, y_0 is the distance from the static water table to the water table measured at t=0, y_t is the same measurement made at t=t, P is pi, and A is a constant dependent upon the geometry of the piezometer (Youngs, 1968). The piezometer of Site #87, which was the only one at the Master Site to equilibrate during the monitoring period, was assumed to be the only piezometer to give a true indication of the bulk till hydraulic conductivity. Because equilibrium did not occur in the 151 day monitoring period, the piezometers of Sites 86, 88, and 89 were assumed to be measuring the intergranular hydraulic conductivity, K_{int}. K_{int} was calculated to be as much as 30 times slower than the bulk hydraulic conductivity. Hydraulic conductivity values are shown in Tables 8 and 9.

Hydraulic conductivity was calculated from transiometer data using Darcy's Law, solved as such:

$$K_{sat} = \frac{q}{at(dh/dz)} \qquad (7)$$

where q is the volumetric water flux, a is the flow area, t is the elapsed time, and dh/dz is the hydraulic gradient. From 11 December 1984 to 21 March 1985, a time period of 99 days, the maximum water table drop at the Master Site was 0.29 m (0.95 feet) at Site 89. Assuming the drainable porosity to be 0.037, found with the neutron probe at a depth of 2.74 m (9 ft), the water table drop corresponds to a loss of 1.07 cm (0.42 in) of water. Because the transiometer installed at the 6.10 m depth failed prior to this time, the downward hydraulic gradient as measured at Site #88 between 3.66 m (12 ft) and 6.10 m (20 ft) was used in the calculation of K_{sat}. The gradient at the beginning of the monitoring period was 0.0208 and was used in the calculation of K_{sat}.

The piezometer at site 87 indicated a saturated hydraulic conductivity of 9×10^{-8} m/s (0.001 in/hr). The average conductivity indicated by the transiometers at the RCWP Master Site was 4×10^{-8} m/s (0.006 in/hr). The transiometer at RS Site 54 indicated a greater hydraulic conductivity, 4×10^{-7} m/s (0.06 in/hr). Values of K_{sat} are given in Table 8. The average intergranular hydraulic conductivity measured with the piezometers at Sites 86, 88, and 89 was 4×10^{-9} m/s (0.0006 in/hr, Table 9).

Values of hydraulic conductivity were calculated from neutron probe data, but were not valid. When calculating hydraulic conductivity from neutron probe data, water movement is assumed to be downward only. However, water moved upward from the water table into the unsaturated zone. This upward flux caused the hydraulic conductivity calculated from neutron probe data to be less than the true value.

TABLE 8. SATURATED HYDRAULIC CONDUCTIVITY OF THE TILL BULK AT RCWP MASTER SITE AND RS SITE 54.

PLOT	DATE	INSTRUMENT	DEPTH, m	K_{sat}, m/s
87	27 Nov	Piezometer	6.10	9×10^{-8}
86	21 Mar	Transiometer	6.10	2×10^{-8}
87	21 Mar	Transiometer	6.10	3×10^{-8}
88	21 Mar	Transiometer	6.10	3×10^{-8}
89	21 Mar	Transiometer	3.66	6×10^{-8}
54	18 Mar	Transiometer	5.03	4×10^{-7}
	Average for RCWP Master Site			5×10^{-8}
	RCWP RS Site 54			4×10^{-7}

The gradients used in hydraulic conductivity calculations on Master Site transiometer data were the gradients as measured between the 3.66 m (12 ft) and the 6.10 m (20 ft) transiometers of the plot under consideration. Gradients used in the calculations with Master Site piezometer data were the gradients from the water level in the piezometer stem to the water table as measured by the 6.10 m (20 ft) transiometer. The indicated hydraulic conductivity of RS Site 54 assumed a constant gradient below the water table, equal in magnitude to the gradient measured between the piezometers. The gradient between the deep piezometer and the transiometer was not used because the instruments indicated an upward gradient.

TABLE 9. INTERGRANULAR HYDRAULIC CONDUCTIVITY AS MEASURED WITH PIEZOMETERS AT RCWP MASTER SITE.

PLOT	86	88	89	Ave.
K_{int}, m/s	4×10^{-9}	3×10^{-9}	6×10^{-9}	4×10^{-9}

Error

Transiometer error originated from two general sources, electrical and environmental.

RCWP Master Site. Most probable error was calculated for error of electrical origin using the calibration regression equation of a typical transducer and for a transducer having maximum error. The regression equation is of the form:

$$y=B_1*(V_o/V_s)+B_0 \tag{8}$$

where y is the pressure head or matric potential in cm water, B_1 is the regression line slope, B_0 is the regression line intercept, V_o is the transducer output voltage in volts, and V_s is the supply voltage to the transducer in volts. The sensed pressure is a continuous function of V_o, V_s, B_0, and B_1, therefore the function plus its deviation can be written as:

$$y+y_E=f(V_o+\Delta V_o,\ V_s+\Delta V_s,\ B_0+\Delta B_0,\ B_1+\Delta B_1) \tag{9}$$

where y_E is the random error of the measured pressure in cm water and represents the fluctuation of the indicated quantity. After expanding into Taylor's series form, all partial derivatives of second and higher order were assumed to be negligible. This assumption is normally valid only if the variables V_o, V_s, B_0, and B_1 are independent of each other. Although the output voltage of the transducer is a function of the supply voltage as well as the measured pressure, the error term of the interaction, given as:

$$2*\frac{(\partial^2 y)}{(\partial V_s \partial V_o)} * \Delta V_s * \Delta V_o \qquad (10)$$

was small enough to be disregarded, on the order of 0.0002 cm water. Realistic prediction of the random error of the measured pressure, y, is of the root-mean-square form:

$$y_E = \sqrt{\left[\frac{\partial y}{\partial V_o}*(\Delta V_o)\right]^2 + \left[\frac{\partial y}{\partial V_s}*(\Delta V_s)\right]^2 + \left[\frac{\partial y}{\partial B_1}*(\Delta B_1)\right]^2 + \left[\frac{\partial y}{\partial B_0}*(\Delta B_0)\right]^2} \qquad (11)$$

The variation of transducer output voltage had three sources: the linear regression of calibration data, uncertainty of the digital multimeter sample, and potential created at the connecting terminals of the scanner card. The largest error found due to the regression equation was 0.0016 V, while typically the variation was near 0.0006 V. The Keithley 195 digital multimeter had accuracy of 0.025% of reading (Keithley, 1983) in the 200 mV range, or a variation of 0.0063 V for a transiometer output of 0.025 V. The contact potential of the general purpose relay card used with the Keithley 705 scanners was listed as <0.05 mV, with a maximum of <0.10 mV.

Supply voltage variations originated from the scanner and digital multimeter as well as variation of the supply during the time taken by the scanner and digital multimeter to sample all the channels (28 at the end of the monitoring period). The voltage supply generally fluctuated less than 0.2 mV over the time period taken to sample 28 channels with the data acqusition system, with a maximum of 0.5 mV. Potentials generated at the scanner terminals were the same as for the transducer output voltage, <0.05 mV and <0.10 mV. The 0.025% uncertainty of the 8 V supply voltage due to the digital multimeter adds 0.002 V to the uncertainty of V_s

Calibration of each sensor was performed twice, once under vacuum and once under pressure. This process yielded two discrete calibration regression equations, where ideally the same equation would have been generated by both the pressure and vacuum calibrations of a transducer. Assuming the difference in regression constants between the pressure and vacuum calibration equations to be normally distributed, the differences were totalled and averaged. The standard deviation values used for B_0 and B_1 were the square roots of the sample means, which is true for normally distributed populations. These values are 1.5 and 30.1, respectively.

When the typical variation values are substituted into equation 11, random error is estimated as:

$$y_E = \sqrt{5.58 + 0.01 + 0.06 + 2.25} \qquad (12)$$

or 2.81 cm (0.092 ft).

The maximum random error is:

$$y_E = \sqrt{126.73 + 0.20 + 0.36 + 5.76} \qquad (13)$$

which is equal to 11.52 cm (0.378 ft).

Inspection of equations 13 and 14 indicates which component of the instrumentation system dominates the random measuring error. In both the typical and maximum cases, the largest term is the uncertainty in the measurement of the transducer output voltage, the first term. This uncertainty is largely due to the potential of the connecting terminals of the general purpose scanner card, which is a maximum of 0.10 mV. For the low-voltage scanner card used with the Keithley 705 scanner, the maximum connecting terminal potential was 0.001 mV. When using the low-voltage scanner card, the maximum random measurement error is given as:

$$y_E = \sqrt{2.22 + 0.15 + 0.36 + 5.76} \qquad (14)$$

equal to 2.91 cm (0.095 ft). Because the maximum random measurement error is only 25% as great as the error when using a general purpose card, low-voltage scanner cards should be used when monitoring transiometers.

The maximum random measurement error assumes that atmospheric conditions do not affect transiometer output. However, atmospheric pressure changes cause inverse water table measurements of a transiometer (Figure 14). The sensitivity of the transiometer output to atmospheric pressure fluctuations was calculated for the time period of 11 December through 5 January. During this period, the water table movement was small, and was considered insignificant. The sensitivity was calculated as:

$$S = \frac{dy}{dp_a} \qquad (15)$$

where S is the sensitivity in m m-1, dy was the change in water table elevations indicated by the instrument in m, and dp_a was the atmospheric pressure fluctuation in m of water.

The sensitivity of the transiometer to atmospheric pressure fluctuations increases with depth with one exception, the sensors placed in the sand-silt zone. This indicates lateral air movement through the more porous materials. At the 6.10 m (20 ft) depth in the soil almost no barometric pressure equalization took place, and as a result the sensing port of the transiometer responded only slightly to atmospheric pressure changes. Because it was vented to the atmosphere, the reference port of the transiometer responded completely to atmospheric pressure changes. For example, if the atmospheric pressure fell by 10 cm (0.33 ft) of water, the transiometers placed at the 6.10 m (20 ft) depth indicated an average water table rise of 8.41 cm (0.27 ft). Values are presented in Table 10.

The value tabulated for the piezometer is the sensitivity of the piezometer at Site 87 from 7 March through 21 March. The true sensitivity was actually closer to zero than the tabulated value due to the water table drop during that time period (Figures 14 and 15). A piezometer is less sensitive to atmospheric pressure fluctuations than a transiometer because atmospheric pressure changes are transmitted through the water in the piezometer stem to the soil at the depth of installation. The o-rings of the transiometer sensor unit seal against the sealing extension, thus any atmospheric pressure changes must be transmitted through the entire soil profile above the installed transiometer.

TABLE 10. AVERAGE SENSITIVITY TO ATMOSPHERIC PRESSURE FLUCTUATIONS.

DEPTH,m	INSTRUMENT	SENSITIVITY TO ATMOSPHERIC PRESSURE
1.22	Transiometer	-0.2899
1.83	Transiometer	-0.0413
3.66	Transiometer, no cup	-0.5501
3.66	Transiometer	-0.6177
3.66	Transiometer	-0.8410
6.10	Piezometer	-0.0469

Atmospheric pressure data from Agricultural Engineering weather station located on campus of South Dakota State University, Brookings.

<u>RCWP RS Site 54</u>. The total hydraulic potential (water table) as measured with the transiometer at Site 54 was greater than the total hydraulic potential as measured with either piezometer for the entire monitoring period of

19 October 1984 through 18 March 1985. This systematic error was probably due to a null offset shift of the pressure transducer caused by the temperature difference between calibration and installation.

The ambient temperature at calibration was approximately 18 deg. C (65 deg. F), while the soil temperature at the installation depth of 5.03 m (16.5 ft) is closer to 7 deg. C (45 deg. F). When the pressure transducer has a negative offset such as unit #31, which is installed at Site 54, a temperature drop causes an offset shift toward zero (Integrated Circuits Sensors, Inc., 1983). The offset shift toward zero caused the total hydraulic potential measurements with the transiometer to be greater than the actual potential.

The typical thermal accuracy of the transiometer installed at Site 54 was ±2% span (Integrated Circuits Sensors, Inc., 1983). For the 152 mV span of transducer #31, this results in hydraulic potential measurement error of 0.28 m (11 in).

An estimate of the true total hydraulic potential that should have been measured with the transiometer from 19 October through 2 January was calculated by assuming that the hydraulic gradient was constant from the shallow (2.26 m) piezometer to the transiometer (installed at 5.03 m). The gradient as measured between the two piezometers was extended to the installation depth of the transiometer, and the total hydraulic potential for the transiometer depth of installation was calculated. The calculated "actual" potential differed from the measured potential by an average of 0.27 m (10.6 in), with a maximum difference of 0.36 m (14.2 in). The average deviation of 0.27 m (10.6 in) correlates well with the thermal inaccuracy of 0.28 m (11 in) calculated from specifications given by Integrated Circuits Sensors, Inc. (1983).

CONCLUSIONS

Objective 1 was to design an instrument taking advantage of a pressure transducer and a porous ceramic cup to measure soil water pressure. The transiometer meets this objective.

Objective 2 was to construct the instrument. Several problems arose with the construction of the transiometer.

The pressure transducer of the transiometer must be better protected against moisture. The Scotch-Weld structural adhesive used to seal most of the transiometers was unacceptable when exposed to water. Water breaks down Scotch-Weld, and moisture reaches the pressure transducer, causing elctrical short-circuiting. Although no transiometers were removed to verify this theory, Scotch-Weld has been observed to deteriorate when exposed to moisture in various laboratory applications.

A second problem in the construction of the transiometer was the placement of the o-rings. In order to assure a good seal between sensor unit and sealing extension, four o-rings were used. The o-rings provided a very good seal; however, attempts at removal with the removal cable failed. The components worked properly upon testing before installation, but the testing was conducted immediately following the machining of the sealing extension, while the component was still warm. The heat produced by the machining process caused the PVC to expand. When installed in soil, which cooled the sealing extension, the PVC contracted enough to prohibit removal of the sensor unit. The 17 gauge removal cable had insufficient strength to remove the sensor unit from the sealing extension and broke.

The third objective was to evaluate the accuracy of the instrument following installation. Five transiometers failed following installation in the unsaturated zone when the hydraulic connection with the soil was broken. These included two each at Sites 87 and 88, and the shallowest transiometer installed near the weather station. Because the volume of fluid contained in the transiometer is so small, the backfill materials used must be wetted periodically during installation, particularly near the sensor. A relatively small flux of water out of the transiometer can cause the bubbling tension of the ceramic cup, -0.3 MPa (-1.0 bar), to be exceeded. This causes the hydraulic connection of pressure transducer and soil to be broken, and zero tension will be indicated with the transiometer until the ceramic cup is recharged.

Although the extension pipe was only 2.54 cm (1 in) in diameter, the borehole diameter was necessarily larger, to accommodate the fill materials of soil and bentonite that were required. Pelleted bentonite accentuated the hazard of material bridging in the hole, creating voids in the profile following installation. Any void space in the hole would create a path of no resistance for both soil water and gases. This short-circuiting would decrease the instrument's response lag time. An erroneous water level would be indicated with the transiometer until the water or air in the void space equilibrated with the surrounding soil conditions. If pelleted bentonite was not required, a borehole diameter of 7.5 cm (3 in) could be used rather than 10 cm (4 in).

Installation of a transiometer in coarse materials presents another problem, the collapsing of the hole. The soil forming the perimeter of the borehole must cohere long enough to allow the removal of the drill stem and insertion of the transiometer. If the material is too loose and collapses before the installation is completed, driller's mud could be used to keep the perimeter of the hole intact long enough to install the transiometer. Caution must be exercised when using driller's mud to ensure that the instrument or the instrumented system do not become contaminated.

Temperature inconsistencies from calibration to installation caused additional inaccuracy of 0.28 m (11 in) for the transiometer installed at RCWP RS Site 54. This was the maximum error caused by thermal offset shift due to the large span and low thermal accuracy of the pressure transducer used at Site 54. Use of a model 33A pressure transducer would reduce the thermal offset shift to 0.07 m (2.8 in) for a pressure transducer having the same span and calibrated under the same conditions. A temperature-controlled environment for the calibration of transducers would eliminate offset shift due to the temperature difference between calibration and operation.

The slow pneumatic permeability of the glacial till monitored at the RCWP Master Site introduced another random error, the variation of transiometer output due to atmospheric pressure variations. At the 6.10 m (20 ft) installation depth, the average response to atmospheric pressure change was -0.84 of the change, while the piezometer response at the same depth was only -0.05 of the atmospheric pressure change. Transiometer sensitivity to atmospheric pressure change increased with increasing depth of placement. When the transiometer was placed in the silt-sand layer, however, the response to atmospheric pressure fluctuations was lowest.

Determination of the precision of the instrument was objective 4. The maximum random error due to the measuring system of the transiometer and data acquisition system was 11.5 cm (0.378 ft), with a more probable value of 2.81 cm (0.092 ft). The maximum could be reduced to 2.91 cm (0.095 ft) through the use of low-voltage scanner cards rather than general purpose cards. This error value could be reduced further through stricter control of the transducer calibration procedure, providing more accurate values of the calibration regression slope and intercept.

SIGNIFICANT FINDINGS AND RECOMMENDATIONS FOR FUTURE STUDY

Interesting preliminary data were generated which highlight the operational features of the transiometer and characterize the glacial till which was monitored.

Significant findings. Measurements made with transiometers at the RCWP Master Site for the study period indicated an upward hydraulic gradient from 3.66 m (12 ft) to 1.22 m (4 ft) below the ground surface. A downward gradient from 3.66 m (12 ft) to 6.10 m (20 ft) was indicated with data from the same sites. These gradients were on the order of 0.1. Thermistor data from site 86 indicated a generally upward thermal gradient. Piezometer data from RS Site 54 indicated a downward hydraulic gradient on the order of 0.03.

Measurements conducted at the Master Site with the neutron probe indicated a drainable porosity of 0.023 to 0.044. When comparing the neutron probe data to water table recession as measured with transiometers, drainable porosity values of 0.044 to 0.061 were calculated. The true drainable porosity is probably between 0.03 and 0.035 at the Master Site. Maximum porosity values found for RS Site 54 ranged from 0.019 to 0.085, with a probable range of drainable porosity being 0.025 to 0.035.

Calculated saturated hydraulic conductivity of the

RCWP Master Site ranged from 9×10^{-8} m/s (0.013 in/hr) as measured with the piezometer at Site 87, to 2×10^{-8} m/s (0.003 in/hr) as measured with the transiometer at site 86. These measurements were made at a depth of 6.10 m (20 ft) Calculations made with transiometer data indicated an average hydraulic conductivity of 3×10^{-8} m/s (0.004 in/hr) at a depth of 6.10 m (20 ft). Intergranular hydraulic conductivity values, found with the piezometers at the Master Site that did not equilibrate within the monitoring period ending 21 March, averaged 4×10^{-9} m/s (0.0006 in/hr). Conductivity values for RS Site 54 were 4×10^{-7} m/s (0.057 in/hr) as calculated from transiometer data.

Some additional operating characteristics of the transiometer were noted. Transiometers had favorable response times compared to the piezometers of the RCWP Master Site. All transiometers installed at a depth of 6.10 m (20 ft) that reached equilibrium before failing responded over twice as quickly as the single piezometer that equilibrated, installed at the same depth.

During the summer of 1984, the transiometer installed at a depth of 1.91 m (6.25 ft) near the weather station measured zero tension, indicating that the hydraulic connection of transducer and soil had been disrupted. Following rainfall totalling 8.8 cm (3.47 in) in mid-October, the ceramic cup recharged in the soil, and the hydraulic connection of transducer and soil was re-established. The transiometer indicated a pressure head of 51 cm (20 in) water on 19 October. On 22 October the transiometer indicated a matric tension of 47 cm (19 in) of water.

Future study. Calibration of the pressure transducers should be changed in two ways. The first improvement required is better accuracy of the calibration. A water column was used to calibrate the transducers, but was not precise enough to prevent differences between the vacuum and pressure calibrations of a transducer. The null offset found for a transducer should be the same for both pressure and vacuum calibration, but offset differences were obvious after calibration of the transducers.

The second change that should be made is to more closely regulate the ambient temperature during calibration. A shift of the null offset of the transducer occurs due to the temperature difference between calibration and installation. This problem is not as severe for pressure transducers with higher thermal accuracy and could be minimized through the use of higher quality pressure transducers having greater thermal accuracy. The model 33A pressure transducer from

Integrated Circuits Sensors, Inc. has ±0.5% span thermal accuracy while the model 33C has thermal accuracy of ±2% span. However, the cost of the model 33A is approximately twice that of the model 33C.

Both of these problems could be alleviated through the use of a calibration bench in a temperature-controlled environment. The pressure transducers could be calibrated pneumatically rather than hydraulically, using a highly sensitive and highly accurate pressure transducer as a reference. Because the ambient temperature could be controlled to simulate installation conditions, and because the temperature fluctuation after installation would be small, more economical pressure transducers having lesser thermal accuracy could be used.

The problem of adhesive breakdown can be alleviated in one of two ways. The adhesive could be protected from the moisture by using a rubber washer to seal around the sensing port of the pressure transducer and on the inside of the sensor housing. The alternative method is the use of a different epoxy, such as rubber-based Flexane. None of the sensors cast in Flexane and placed below the water table, including two transiometers and all four piezometer transducer units, failed before 21 March. Of the 13 transiometers cast in Scotch-Weld and placed in the saturated zone at the Master Site, 4 failed before 21 March.

The use of a rubber washer to seal around the sensing port of the transducer would eliminate the need for the o-ring on the cup unit. When the cup unit is threaded into the sensor unit, the flat leading edge of the threaded portion of the cup unit would seal against the rubber washer.

Fewer o-rings should be used. Two would provide a sufficient seal. The tolerance between the sensor unit and the sealing extension should also be enlarged slightly. In addition, small diameter cable should be used as the removal wire rather than inexpensive wire.

The use of bentonite slurry rather than dry bentonite would benefit the installer in two ways: first, by elimination of the initial flux of water into dry bentonite, which accelerates disruption of the hydraulic connection of transducer to soil, and secondly, by allowing the use of a smaller diameter borehole.

Finally, the barometric pressure fluctuations need to be filtered out of the transiometer response. The correction for atmospheric pressure change could be accomplished in the installation or upon processing the data. By leaving the removal vent open on transiometers installed in the unsaturated zone, the barometric pressure in the soil should equilibrate with the atmospheric pressure in much less time than with the installation procedures noted earlier. Leaving the removal vent open on installations in the saturated zone would allow water to move up and down in the vent tube, causing a small time lag. The transiometer would then operate on the same principle as a mini-piezometer.

POTENTIAL TRANSIOMETER APPLICATIONS

The transiometer shows promise for monitoring soil moisture in slowly permeable soils. Three major concerns must be addressed to ensure dependable service from a transiometer. First, the pressure transducer calibration procedure must be changed. Second, construction techniques that protect the pressure transducer more reliably must be used to alleviate unit failure in saturated conditions. Third, in unsaturated conditions, more care must be used upon installation to retain the hydraulic connection between pressure transducer and soil.

Incorporating these physical changes with use of low-voltage scanner cards with the data acquisition system would improve the precision of the transiometer. The absolute accuracy of the system must be defined further with more testing of the transiometer, particularly making direct comparison with corresponding piezometer data.

The transiometer is ideally suited for use as a controller of an irrigation system. Augustin and Snyder (1984) and Snyder et al. (1984) used moisture sensors to control an irrigation system. They reported 42% to 95% water savings and a significant reduction in nitrogen leaching when compared to conventionally-controlled plots.

The millivolt output of the transiometer is well suited for use in control cicuits of irrigation systems.

The transiometer could also be used to monitor remote locations. To eliminate error and hazard due to very long electrical leads, telemetry equipment could be used to transmit the data to a centrally located receiving station. Large areas could be monitored in this manner without requiring long elctrical leads or numerous data acquisition systems.

REFERENCES

1 Al-Dhahir, Z. A. and N. R. Morgenstern. 1969. Intake factors for cylindrical piezometer tips. Soil Sci. 107:17-21.

2 Beckwith, T. G., N. L. Buck, and R. D. Marangoni. 1982. Mechanical measurements. Third edition. Addison-Wesley, Reading, Mass.

3 Bender, A. R., C. G. Carlson, and L. O. Fine. 1983. Preliminary appraisal of east central south dakota soils for irrigation development. Water Resources Research Institute, SDSU, Brookings, S. D.

4 Bernstein, L. 1974. Crop growth and salinity. p 39-53. In: J. van Schilfgaarde (ed.). Drainage for agriculture. American Society of Agronomy monograph no. 17.

5 Bischoff, J. H., A. E. Bartels, and C. G. Carlson. 1983. The use of piezoresistive vacuum transducers with soil tensiometers. ASAE NCR Paper no. 83-301. 20 p.

6 Campbell Pacific Neuclear Corp. 1983. 503DR hydroprobe moisture depth gauge user's manual. Pacheco, Ca. 41 p.

7 Doering, E. J., L. C. Benz, and G. A. Reichman. 1984. Internal drainage of fine-textured subsoils in North Dakota. ASAE Paper no. 84-2578. 9 p.

8 Gardner, W. and D. Kirkham. 1952. Determination of soil moisture by nuetron scattering. Soil Sci 73:391-401.

9 Gibson, R. E. 1963. An analysis of system flexibility and its effect on time-lag in pore-water pressure measurements. Geotech. 13:1-11.

10 Gibson, R. E. 1966. A note on the constant head test to measure soil permeability <u>in situ</u>. Geotech. 16: 256-259.

11 Gillham, R. S., A. Klute, and D. F. Heerman. 1976. Hydraulic properties of a porous medium- measurement and empirical representation. SSSAP 40:203-207.

12 Gray, D. M., R. J. Granger, and G. E. Dyck. 1983. Overwinter soil moisture changes. ASAE Paper no. 83-2513. 20 p.

13 Grisak, G. E., J. A. Cherry, J. A. Vonhof, and J. P. Blumele. 1976. Hydrogeologic and hydrochemical properties of fractured till in the interior plains region. p 304-333. In: R. F. Leggett (ed.). Glacial till: an inter-disciplinary study. Royal Society of Canada Special Publication 12.

14 Grisak, G. E., J. F. Pickens, and J. A. Cherry. 1980. Solute transport through fractured media. 2. column study of fractured till. Water Res. Res. 16(4): 731-739.

15 Hemond, H. F. 1982. A low-cost multi-channel recording piezometer system for wetland research. Water Res. Res. 18:182-186.

16 Hendry, M. J. 1982. Hydraulic conductivity of a glacial till in Alberta. Groundwater 20:162-169.

17 Hendry, M. J. 1983. Groundwater recharge through a heavy-textured soil. J. Hydrol. 63:201-209.

18 Hendry, M. J., R. G. L. McCready, and W. D. Gould. 1984. Distribution, sources, and evolution of nitrate in a glacial till of southern Alberta, Canada. J. Hydrol. 70:177-198.

19 Hoover, J. R. 1983. Evaluation of flow pathways in a sloping soil cross-section. ASAE Paper NAR83-201. 20 p.

20 Hoover, J. R. 1984. Instrumentation system for determining watershed hydrologic characteristics. ASAE Paper 84-2009. 22 p.

21 Hvorslev, M. J. 1951. Time lag and soil permeability in ground-water observations. U. S. Waterways Experiment Station Bulletin 36. Vicksburg, Miss. 49 p.

22 Keithley Instruments, Inc. 1983. 1983-1984 catalog and buyer's guide. Cleveland. Oh. 100 p.

23 Lee, D. R., and J. A. Cherry. 1979. A field exercise on groundwater flow using seepage meters and mini-piezometers. J. Geol. Educ. 27:6-10.

24 Marthaler, H. P., W. Vogelsanger, F. Richard, and P. J. Wierenga. 1983. A pressure transducer for field tensiometers. SSSAJ 47:624-627.

25 Mawson, C. A. 1964. Survey of hydrological applications of tracers in Canada. Atomic Energy of Canada, Ltd. AECL-2005, 14 p.

26 McKim, H. L., R. L. Bert, R. W. McGaw, R. T. Atkins, and J. Ingersoll. 1975. Development of a remote-reading tensiometer/transducer system for use in subfreezing temperatures. Proceedings of the second conference on soil-water problems in cold regions. Edmonton, Alberta, Canada.

27 Moisture Control Systems. Undated. Measuring soil matric potential by heat dissipation. Findlay, Ohio. 4 p.

28 Olsen, H. W. 1966. Darcy's law in saturated kaolinite. Water Res. Res. 2(2):287-295.

29 Phene, C. J., G. J. Hoffman, and S. L. Rawlins. 1971. Measuring soil matric potential <u>in situ</u> by sensing heat dissipation within a porous body: I. Theory and sensor construction. SSSAP 35:127-133.

30 Ping, Li Seung. 1963. Measuring extremely low flow velocity of water in clays. Soil Sci. 95:410-413.

31 Premchitt, J. and E. W. Brand. 1981. Pore pressure equalization of piezometers in compressible soils. Geotech. 31(1):105-123.

32 Richards, L. A. and W. Gardner. 1936. Tensiometers for measuring the capillary tension of soil water. J. Am. Soc. Agron. 28:352-358.

33 Schaeffer, R. L. and J. T. McClave. 1982. Statistics for Engineers. Duxbury Press, Boston.

34 Schmugge, T. J., T. J. Jackson, and H. L. McKim. 1980. Survey of methods for soil moisture determination. Water Res. Res. 16(6):961-979.

35 Snyder, G. H., B. J. Augustin, and J. M. Davidson. 1984. Moisture sensor-controlled irrigation for maintaining bermudagrass turf. Agron. J. 76(5): 848-850.

36 Snyder, G. H., B. J. Augustin, and J. M. Davidson. 1984. Moisture sensor-controlled irrigation for reducing nitrogen leaching in bermudagrass turf. Agron. J. 76(6):965-969.

37 Towner, G. D. 1981. Response of tensiometers embedded in saturated soil peds of low hydraulic conductivity. J. Agri. Eng. Res. 26:541-549.

38 Trooien T. P., J. H. Bischoff, and A. R. Bender. 1984. Construction of an electronic sensor to measure matric suction or pressure head. ASAE-NCR paper no. 84-703. 15 p.

39 Turk, L. J. 1975. Diurnal fluctuations of water tables induced by atmospheric pressure changes. J. Hydrol. 26:1-16.

40 van Schilfgaarde, J. 1974. Drainage for agriculture. American Society of Agronomy monograph no. 17.

41 Wilkinson, W. B. 1968. Constant head _in situ_ permeability tests in clay strata. Geotech. 18: 172-194.

42 Weeks, E. P. 1979. Barometric fluctuations in wells tapping deep unconfined aquifers. Water Res. Res. 19:1167-1176.

43 Youngs, E. G. 1968. Shape factors for Kirkham's piezometer method for determining the hydraulic conductivity of soil _in situ_ for soils overlying an impermeable floor or an infinitely permeable stratum. Soil Sci. 106:235-237.

44 Youngs, E. C. 1980. A note on Hvorslev's intake factors. Geotech. 30:328-331.