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EXPERIMENTAL STUDIES IN NATURAL GROUNDWATER RECHARGE DYNAMICS: ASSESSMENT OF RECENT ADVANCES IN INSTRUMENTATION

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ABSTRACT

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To quantify and model the natural groundwater-recharge process, two sites in south-central Kansas, U.S.A., were instrumented with various modern sensors and data microloggers. The atmospheric-boundary layer and the unsaturated and saturated soil zones were monitored as a unified regime. Data from the various sensors were collected using microloggers in combination with magnetic-cassette tape, graphical and digital recorders, analog paper-tape recorders, and direct observations to evaluate and automate data collection and processing.

Atmospheric sensors included an anemometer, a tipping-bucket raingage, an air-temperature thermistor, a relative-humidity probe, a net radiometer, and a barometric-pressure transducer. Sensors in the unsaturated zone consisted of soil-temperature thermocouples, tensiometers coupled with pressure transducers and dial gages, gypsum blocks, and a neutron moisture probe operated by an observer. The saturated-zone sensors consisted of a water-level pressure transducer, a conventional float gage connected to a variable potentiometer, soil thermocouples, and a number of multiple-depth piezometers.

Evaluation of the operation of these sensors and recorders indicated that certain types of equipment such as pressure transducers are very sensitive to environmental conditions. Extraordinary steps had to be taken to protect some of the equipment, whereas other equipment seemed to be reliable under all conditions. Based on such experiences, a number of suggestions aimed at improving such investigations are outlined.

INTRODUCTION

Groundwater-recharge rates of many regions in Kansas, U.S.A., are not sufficient to meet the current or anticipated future demands, and the water resources are presently being mined in many areas. The Division of Water Resources of the Kansas State Board of Agriculture and the groundwater

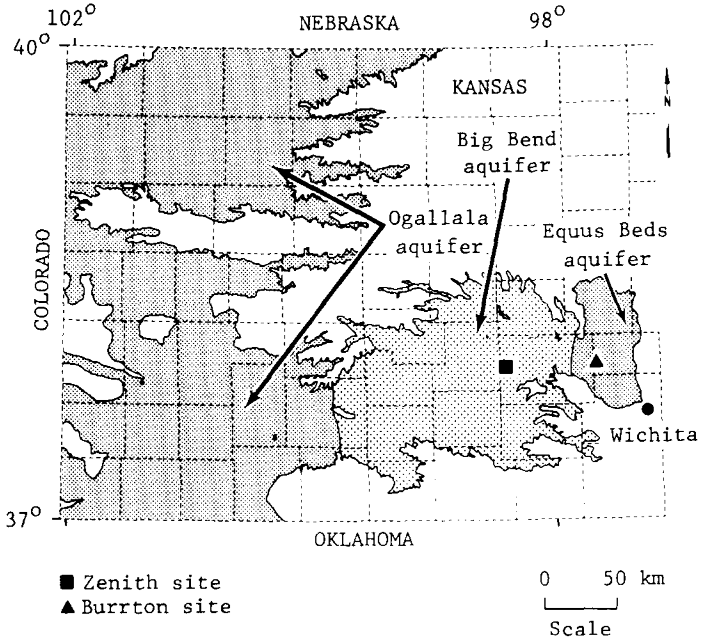

Fig. 1. Map showing location of study areas.

management districts use estimated recharge as an integral part of their depletion formulas in order to adjudicate groundwater rights. Better estimates of recharge would make the depletion formulas more accurate and fair. Groundwater recharge is also one of the most sensitive elements in digital groundwater-flow models. Incorrect assumptions in representing recharge can invalidate the predictions made by such mathematical models.

It is now widely recognized that the groundwater-flow region and the unsaturated soil zone above it are part of a continuous and interacting system (Freeze, 1969; Freeze and Banner, 1970; Vachaud et al., 1975). Therefore, the flow of water in this combined system can be described physically and mathematically without the imposition of artificial boundaries, such as the water table. The mechanisms that control this interrelationship are, however, less well understood. Recharge cannot be measured directly, and therefore methods of estimation must be devised based on detailed measurements of all relevant environmental factors.

Purpose of study

The objectives of this study are to:

(1) Evaluate the latest (1980) field instrumentation and techniques to obtain more reliable and frequent groundwater recharge-related data.

(2) Investigate the mechanisms of natural groundwater recharge by measuring the unsaturated—saturated flow regime as a unified system. Emphasis will be placed on precipitation-related recharge phenomena.

(3) Quantify the amount and specify the time distribution of recharge for two areas in two significant groundwater regions of Kansas, the Equus Beds aquifer and the Big Bend region.

(4) Coordinate field and laboratory measurements with mathematical modeling techniques, thus developing improved methods of estimating groundwater recharge.

This paper emphasizes the experimental aspects of groundwater recharge. It describes the numerous difficulties and problems encountered in field-testing the necessary instrumentation for long periods of time, and the solutions devised to solve them. It concludes with recommendations for field-based research, based upon experiences gained during this study.

Approach

Two experimental field sites were instrumented for this study. One site is located in the Equus Beds area northwest of the city of Wichita, Kansas, while the other is in the Big Bend region west of Wichita (Fig. 1).

The climate of these sites is characterized by a wide range of temperatures and by moderate precipitation. Average monthly temperatures range from 27°C in July to -1°C in January. Average annual rainfall is 710—787 mm but has a high yearly variance.

The approach used is similar to that of Freeze and Banner (1970) and involves the use of instrumentation to provide integrated measurements of the subsurface flow regime, treating unsaturated and saturated flow as a continuous process.

INSTRUMENTATION

The selected sites exhibited good potential recharge characteristics, including a generally sandy soil under natural grass conditions, no extensive confining clay layers, a relatively shallow water table, and a saturated zone characterized by decreasing hydraulic head with depth.

Observation wells were augered to determine the depth to water and to confirm the lithology. Test holes for piezometers were augered to confirm downward flow of water in the saturated zone.

Neutron-probe access tubes for each site were made from 5.4 cm O.D., 0.165-cm wall, cold-rolled electric-welded (CREW) hydraulic tubing; the lower end, which was made pointed, was sealed with a rubber stopper and a concrete—bentonite mixture. This tube was pressed into a hole made by a 5.4-cm coring tube, resulting in a tight fit. The neutron-access tubes were ~6.1 m long and were installed to a depth just below the water table. The neutron probes used in this study were a Campbell—Pacific Nuclear® model

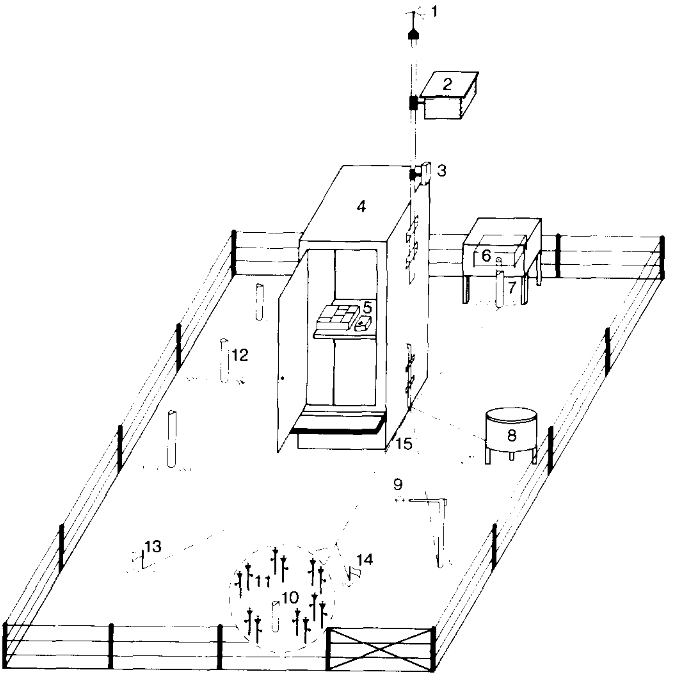

Fig. 2. Site instrumentation diagram (not to scale) (*1* = anemometer; *2* = temperature and relative humidity sensors; *3* = barometer; *4* = housing unit; *5* = data loggers; *6* = water-level recorder; *7* = water-table well, *8* = precipitation gage; *9* = net radiometer; *10* = neutron-probe access tube; *11* = tensiometer nest; *12* = piezometer nest; *13* = thermocouple hole; *14* = gypsum blocks; *15* = underground connecting lines).

*501** with moisture and density readings and a model *502* probe with moisture readout only.

U.S. Geological Survey gage houses were used to protect the electronic equipment. The houses also provided support for several of the atmospheric sensors (Fig. 2). The houses were located near a utility line for 110-V A.C. power to operate the system, although A.C. power was not required. All sensor cables outside the gage house were inserted into PVC pipes and buried.

Data collection and storage were accomplished by microcomputer data loggers, conventional digital and graphical recorders, and observers' notes. All data were placed on magnetic tapes. The data loggers at each site consist of a CR-*5* and a CR-*21* (Campbell Scientific, Inc.) units. Both data loggers output data on to magnetic cassette tapes that were transferred by a cassette reader to the office computer.

The CR-*5* data logger (Fig. 3), having modular flexibility, allowed configuration of a time-control module, a digital printer, cassette interface,

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*The use of trade names in this report is for identification purpose only and does not imply endorsement by either the Kansas or the U.S. Geological Surveys.

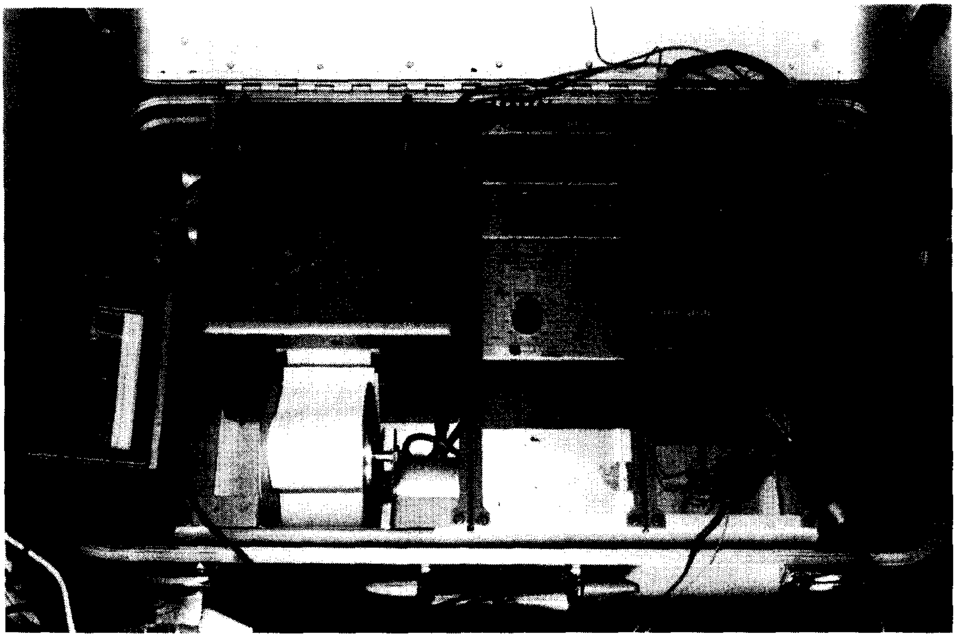

Fig. 3. Photograph showing CR-*5* data logger and cassette recorder.

power supply, and a 50-channel scanner with thermocouple and 0—10-V signal-conditioning cards.

Readings were taken every 3 hr. on 15 soil-temperature thermocouples at various depths from near ground surface to 7.6 m, and on 12 pressure transducers connected to soil tensiometers. The soil-temperature thermocouples were made from wires of copper and constantan (Omega Engineering, Inc., PR-T-*24*). The junctions of the dissimilar metals were protected from corrosion by coating them with an epoxy possessing good thermal conductivity and electric insulation (Omegabond® *100* from Omega Engineering, Inc.). The pressure transducers sensed the negative pressure inside 12 jet-fill tensiometers (Soilmoisture, Inc., *2725* series) arranged in pairs at depths of 15, 30, 61, 91, 122, and 152 cm. The pressure transducers (National Semiconductor Corp. model No. LX*1804*GBZ) had a gage-pressure range of 0 to ± 15 bar. A separate power supply of + 12 and − 5 V and an external circuit were needed to calibrate and operate each transducer. A series of soil-moisture gypsum blocks were installed at various depths to supplement tensiometer data. Some blocks were read manually, while others were connected to the CR-*21* data logger.

The CR-*21* unit (Fig. 4) is a battery-powered microcomputer with a real-time clock, a serial data interface, and a programmable analog-to-digital converter that can handle seven analog inputs and two pulse-counting inputs. Once each minute the CR-*21* samples the input signals according to input

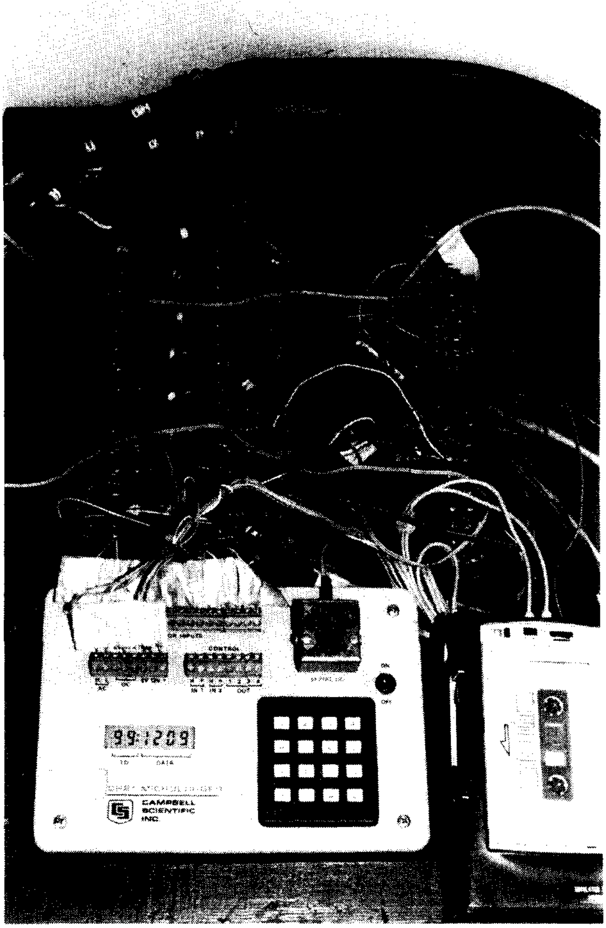

Fig. 4. Photograph showing CR-*21* micrologger with electrical connection board and cassette recorder.

programs specified in a user-entered input table, processes the data, and stores them according to user-entered output programs.

Various sensors were connected to the CR-*21* which was programmed to output hourly and daily values. A barometric-pressure transducer (Yellow Springs Instrument Co., model *2014*) measured ambient station pressure. Air temperature and relative humidity were measured by the Campbell—Scientific® *201* thermistor and relative-humidity probe. Soil-moisture measurements at two depths were included in the CR-*21* data by using Beckman® soil-moisture blocks (model CEL-WFD). Wind speed was measured with a Met One® model *014*A anenometer located approximately 4.6 m above the ground. Radiation was measured by a Fritschen-type net radiometer (Weathertronics® model *3032*). Rainfall was measured with a Sierra—Misco® model RG-*2501* tipping-bucket raingage. The rainfall data at the

Equus Beds site were supplemented with U.S. Geological Survey raingages, which consist of a catchment funnel, an accumulation well, and a float connected to a Fischer Porter® paper-tape recorder. Water levels in the water-table well were measured by a pressure transducer (Enviro-Labs, Inc., model PT-*105*V) connected to the CR-*21* by a voltage divider. An alternative method of measuring groundwater levels consisted of a conventional float gage with a Stevens® type-A graphical recorder. This recorder was connected by a chain drive to a variable potentiometer, which in turn was connected to the CR-*21*.

To facilitate wiring, an electrical connection board was constructed (Fig. 4). A ground buss bar was connected to all sensors by means of a spark gap for lightning protection. An auxilliary 12-V lead—acid battery supplied the extra current needed to operate the pressure transducers. This battery was charged intermittently by a battery charger activated by the CR-*21*. Great care was taken to avoid any cross-connections that could drain the CR-*21* batteries.

Additional data were collected by observers, who serviced the data loggers and other equipment weekly. Tensiometer dial gages were used for correlation with the pressure-transducer data. A series of soil-moisture blocks was read manually. The neutron probe was used for weekly readings of soil moisture at 15-cm intervals. Water levels in various surrounding water-table wells and piezometers were read by steel tape. All non-recorded data were manually entered into the computer.

Calibration

The sensors were checked or calibrated both in the laboratory and in the field immediately after installation. Copper—constantan thermocouples were checked in the laboratory against mercury thermometers; air temperature, relative humidity and barometric sensors were checked against a hydrothermograph and barograph placed next to the sensors; the water-level transducer was inserted into a pipe filled with water to check the indicated height of the water column above the transducer; tensiometer transducers were checked against their factory-stated specifications by comparison with a dial gage jet—tensiometer. The dial gage was removed from the tensiometer, and a T-shaped brass bushing was inserted into the tensiometer gage hole. The dial gage and tensiometer transducer were then connected to each side of the T-bushing for simultaneous comparisons, and the tensiometer was inserted into a plastic container filled with wetted soil. All tensiometers were also tested in the laboratory for porous-cup conductance and response-time constants according to procedures outlined in Danielson (1982). From such comparative experiments or verifications of their factory-stated performance standard, all sensors were calibrated. The sensors generally performed within the range of their specified accuracy.

Ethylene glycol solution was used in the tensiometers during winter to

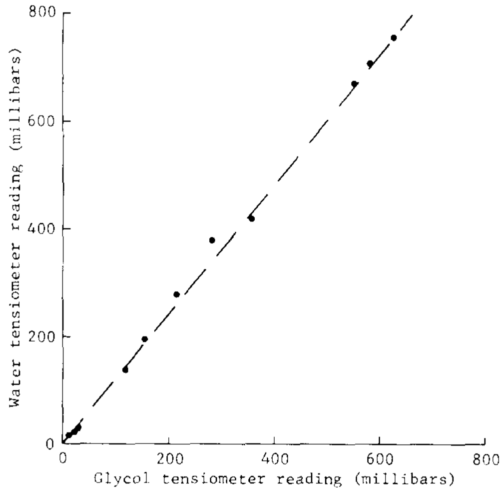

Fig. 5. Graph showing calibration curve for glycol-solution tensiometers.

avoid freezing and breaking. The tensiometer porous cup was saturated in the laboratory with distilled, deaerated water, and a 50% ethylene glycol solution was added to the tensiometer. Such tensiometers were calibrated by inserting one tensiometer filled with water and another with the glycol solution in the same soil container and comparing readings. Calibration curves between the two readings were developed with a correlation coefficient of more than 99.8% (Fig. 5).

The neutron probe was calibrated in the field. A 5.4-cm-diameter hole was drilled with a soil-coring tube and sampled continuously. The samples were sealed in plastic bags and weighed the same day. The access tube with a sealed and pointed end was then auger-pushed into the hole for a tight fit. The combination neutron—gamma probe was inserted, and moisture and bulk-density readings were taken every 23 cm. A correlation analysis between the sample moisture content and the neutron moisture readings indicated a correlation coefficient of more than 98.5% (Fig. 6).

The water-level pressure transducer, connected to the CR-*21* data logger, was also calibrated by inserting it in the water-table well to a certain depth below the water table and raising it upwards by small increments, while at the same time taking the corresponding voltage readings from the data logger. From a regression analysis of pressure-transducer positions in the water-table well and corresponding voltage readings, a slope and offset were obtained, which were programmed into the CR-*21* memory so that the water level was read directly from the CR-*21* data logger.

A tensiometer interface was built to convert the voltage readings from each transducer based on its individual calibration curve into a centibar reading. The interface (Fig. 7) included an operational amplifier for each tensiometer in the standard inverting configuration so that gain and offset could be adjusted independently for each tensiometer. The scaling of the

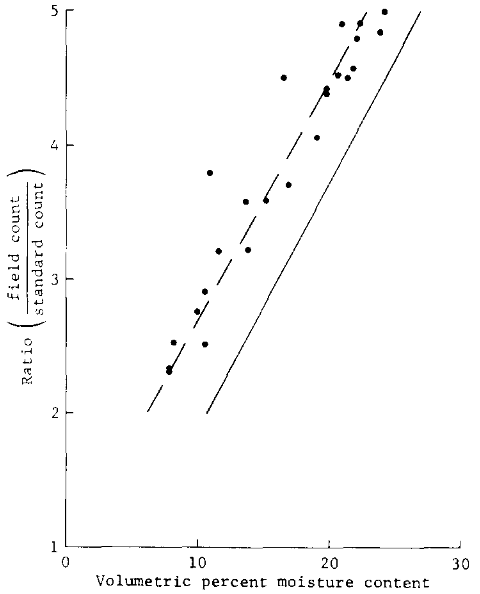

Fig. 6. Graph showing moisture-content calibration curve. *Solid line* indicates manufacturer's calibration curve; *dashed line* indicates field calibration curve.

transducer voltage output with this interface was of great help in calibrating, checking, and readjusting the transducer output in the field. A correlation analysis between transducer and dial-gage readings during a ~2.5-month period from one of the sites resulted in a correlation coefficient of 97.8% (Fig. 8). However, such transducers need periodic recalibration because of their repeatability and stability errors (N.S.C., 1977, 1981).

The tensiometer pressure transducers were calibrated in the field by applying different tensions in each tensiometer using a hand vacuum pump and comparing the tensiometer or vacuum-pump dial reading with the corresponding reading from the data logger. Through the constructed interface, suction in centibars was read from the data logger. The data logger centibar reading was matched with the tensiometer—dial reading by adjusting the various interface potentiometers (Fig. 7) for each transducer.

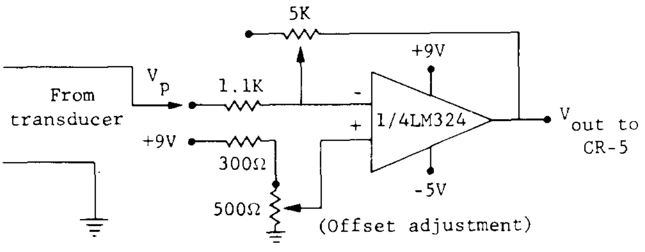

Fig. 7. Diagram showing tensiometer interface.

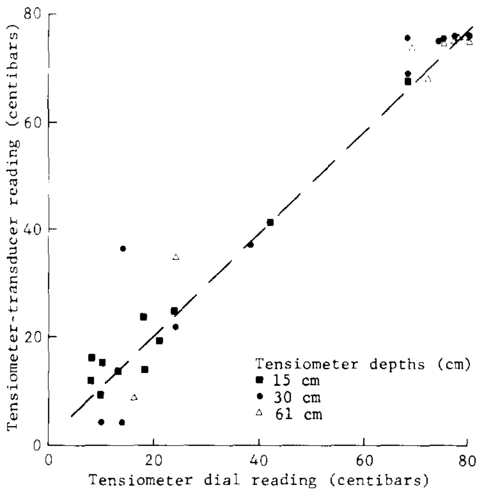

Fig. 8. Graph showing comparison of tensiometer-transducer readings and dial-gage readings.

Performance problems

Tensiometer system. Reliable field measurements can be achieved by using properly designed and calibrated instruments in combination with careful field installation involving minimal soil disturbance. However, even with appropriate precautions, many difficulties occur in assuring long-term accuracy. For example, air leaks and bubbles that occur in the tensiometers because of the partial vacuum along with temperature and humidity effects on both tensiometer and transducer caused difficulties in obtaining long-term measurements of matric potentials. Other problems included difficulties in maintaining physical contact with the soil, especially with disruptions caused by repeated servicing and recalibrations required for the tensiometer—transducers and by plant roots that tend to grow around the base of the tensiometers. Persistent problems occurred with the tensiometer transducers, which are extremely sensitive to moisture. For example, rain in contact with the sensor may result in corrosion and failure. Despite extraordinary measures taken to protect them, such as spraying with a moisture-resistant lacquer, taping with water-resistant tape, covering in plastic bags, and protecting the tensiometer—transducer system with inverted plastic buckets, most transducers eventually failed. Nevertheless, back-up measures, such as installation of two tensiometers for each depth and connection of a dial gage in addition to the transducer in each tensiometer, allowed a long period of tensiometric readings.

Although ethylene glycol-filled tensiometers performed well during winter, the Bourdon-type dial gages (Soilmoisture, Inc., model *2060*G2) connected to the tensiometers were sensitive to freezing conditions, and some became ineffective after freezing.

Water-level pressure transducers. Another problem occurred with the water-level pressure transducer connection with the recording system. Because the CR-*21* data logger accepts a maximum signal of 2.5 V, while the water-level pressure transducer outputs a maximum signal of 5 V, a voltage divider was built and connected to the transducer cable before connecting it to the CR-*21*. Graphical displays of the resulting water-level measurements indicated an unusually pronounced water-level-fluctuation cycle, very similar to the diurnal temperature cycle (Fig. 9). Fluctuations of the air and interior-housing-unit temperatures showed similar fluctuation patterns. The voltage-divider resistors were temperature sensitive, thus affecting the water-level readings. This was checked by heating the voltage divider and observing the corresponding changes in the CR-*21* output. However, daily averages of hourly water levels closely matched the manually measured weekly water-table readings. To avoid any further problems related to the temperature sensitivity of the voltage-divider resistors, the water-level pressure transducer was directly connected to the CR-*5* data logger, thus resolving the problem. This data logger, however, output voltage readings which needed to be converted to water levels.

In addition to the problem with temperature sensitivity of the voltage divider, the ressure transducer failed a number of times. To avoid loss of data, a back-up system consisting of a Stevens® graphical recorder in combination with a potentiometer was calibrated to electrically indicate the water level on the CR-*21* data logger.

Miscellaneous instrumentation problems. Other problems included the piercing of the net radiometer plastic dome by curious birds. This problem was solved by protecting the net radiometer with coarse-mesh wire. On several rainy days, moisture entered the radiometer's plastic dome. This problem was corrected by ventilating dry air through the dome. Also, expansion of the CR-*5* printer paper under high humidity rendered the printer inoperative until new dry printer paper was installed.

A more severe problem had to do with the 12-V lead–acid battery used

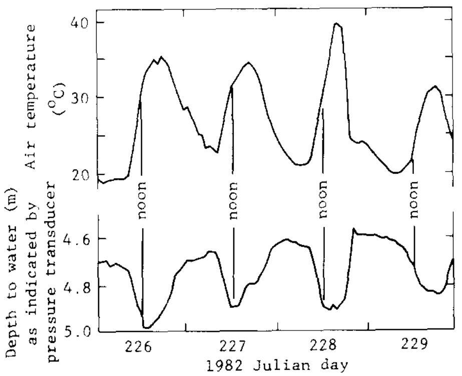

Fig. 9. Graph showing comparison of indicated water levels and air temperatures.

for the CR-*5* and CR-*21* power supply. As electric power was available at the sites, a battery charger was installed and programmed by the CR-*21* data logger to charge the battery for an interval before the hourly readings were taken. Initially, a charging time of 15 min. was set. However, with the advent of colder temperatures, this preset time was inadequate, and the battery voltage was undercharged on several occasions. Thus, for winter operations, the charging time was increased from 15 to 25 min. before the hourly readings. Also during cold weather the cassette recorders were sluggish, and some data were lost. These problems were temporarily solved by using thermostatically controlled heating units to maintain housing temperature at a nearly constant level. However, because of repeated battery problems, the batteries were replaced with regulated power supplies.

ASSESSMENT OF INSTRUMENTATION PERFORMANCE

Despite the above-mentioned problems, most of the sensors performed satisfactorily. All atmospheric sensors connected to the CR-*21* operated within expectation; the soil thermocouples performed faily well, as did the neutron probe. The water-level pressure transducer performed well after wiring problems were corrected, as did the Stevens® graphical recorders. Nevertheless, the tensiometer system is not very reliable over long periods of time, and periodic recalibrations of the system are required. However, the dual system for each depth worked to provide long-term records. The pressure transducers used with the tensiometers need to be made less sensitive to environmental conditions.

The built-in programmable memory of modern data loggers is valuable for data manipulation and interpretation. Such data loggers can provide onsite and offsite data-processing capabilities, such as calculating maximum, minimum and mean values over specified time intervals, plotting histograms, and obtaining standard deviations and times of extreme events. They can interface with cassette tapes, telephone lines, radio transmitters, and even satellites. These data loggers are portable low-power modern equipment, and for groundwater hydrology are still in the first stages of development.

Technological progress in many areas during the last few years has been very rapid, and it is anticipated that corresponding progress will occur in hydrology. Up to now, however, theoretical advances in hydrosciences have exceeded by far advances in experimental research. Coupled mass and energy flow of multiphase fluids in unsaturated—saturated porous media can be numerically simulated, but appreciable difficulties are encountered in field measuring the required parameters to implement these models. For example, considerable difficulties are recognized in obtaining field and laboratory measurements of unsaturated hydraulic conductivities over a wide range of moisture contents; or in obtaining continuous long-term tensiometer records, or just simple tensiometer records at depths greater than 2 m! We hope that through specific research in perfecting experimental measurements, field measurements will be improved and simplified.

SUGGESTIONS FOR IMPROVING INSTRUMENT PERFORMANCE

As a result of our experiences during this investigation, several recommendations are offered to enhance the reliability of the system and to minimize data losses.

(1) Purchase sensors and data loggers from reputable firms with long histories of established field performance.

(2) Arrange back-up systems in case of failure of one sensor or data logger. An additional data logger, for example, will pay for itself in the long run.

(3) Obtain electronic equipment and sensors with built-in shock and polarity protection, or install such protection before use. This is especially important with pressure transducers, which may be destroyed by reverse connections.

(4) Have available the services of a well-trained electronic technician. Also, carefully train the field observers in the servicing of equipment and in the recognition of problems.

(5) Establish two-way radio or telephone communication between distant field sites and base station.

(6) Obtain sensors with output compatible to the data loggers input requirements so that no additional electronic components are needed.

(7) Insulate the unit housing the data loggers and all electrical connections against moisture and temperature fluctuations as much as possible.

(8) Check on new advances in the area of electronic and other instrumentation because technological developments are progressing very fast in this field.

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