# A METHOD OF MEASUREMENT OF THE GROUND WATER TABLE AND SOIL HYDRAULIC CONDUCTIVITY

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## INTRODUCTION

A ground water table is defined as the locus of all points in a saturated soil-water system at which the pore water pressure is atmospheric. Its location within the soil profile is important to both agriculturalists and engineers. From an agricultural standpoint, the position of the water table influences: (a) plant growth and root development, (b) development of saline-alkali conditions and (c) the amount of water used in evapotranspiration. To the engineer, a knowledge of the water table position is requisite for proper design of foundation, highway, hydraulic, and drainage and irrigation works.

## MEASUREMENT OF A WATER TABLE

The method commonly used for locating the position of the water table below the ground surface is by direct observations taken from piezometers or observation wells. In these installations, it is common practice to flush out the tube several times prior to commencing observations. The rise or fall of the water level with time is followed until an equilibrium condition is attained. As shown by Hvorslev (2), the time required for equalization of the water pressure inside the pipe and the pore water pressure is directly related to the diameter of the well and the depth of the tube below the water table and inversely related to a flow factor — a geometric factor characterizing the flow system, the hydraulic conductivity of the soil and the effective hydraulic head. In coarse - textured soils, the equalization occurs rapidly whereas in fine - textured relatively-impermeable soils this process may take long periods of time, during which, the initial static water level may undergo a change in position.

The results of water level investigations in light-textured soils have indicated that readings taken from small-diameter piezometers are quite relible in reflecting the position of the ground water table. Hore and Kidder (1) report results of a study conducted by Walker in light-textured soils in Virginia in which there were no significant differences in readings taken from 1-inch and 10-inch observation wells and a 3/8-inch piezometer in reflecting the position of a receding water table. Conversely, great controversy has been voiced as to the relative ability of different-sized observation wells, cased or uncased, and piezometers, to measure the position of the water table in heavy-textured soils. Hore and Kidder (1) compared the effectiveness of four installations; (a) 2-inch diameter auger hole, (b) 3/8-inch and 2-inch diameter perforated observation wells, and (c) 3/8-inch diameter piezometer to locate the water table in a drainage experiment in soils in Michigan. Their findings showed there was a significant lag in the response time in the piezometer as compared with readings taken on the other installations. The difference in readings taken from the auger hole and observation wells were small and considered of doubtful practical importance. In a more recent study conducted in a lucustrine silt loam in North Dakota, Lenz *et al.* (4) report that 3/8-inch observation wells gave a better estimate of the water table position and were more responsive to influences causing water table fluctuations than 4-inch diameter wells.

It is the purpose of this paper to descibe an instrument, a probe, which is used in a piezometer installation to measure the water table position and the hydraulic conductivity of a soil. Such aspects as the mathematical basis of its development and a report of its performance are included.

## THEORY OF THE PROBE

According to Kirkham (3), the quantity of water entering a piezometer per unit time, under constant head, Q, is given by the expression,

$$Q = kG\,(d-h) \quad \ldots\ldots\ldots\ldots \quad 1$$

where $k$ = soil hydraulic conductivity,

$G$ = geometric function which characterizes the geometry of the flow system,

$h$ = depth of water in the piezometer as measured from the bottom, and

$d$ = depth of pipe below the water table (see figure 1).

Equation 1 was the basic mathematical relationship used in the design of the probe. Suppose the head in a given piezometer was maintained successively at two constant levels, $h_1$ and $h_2$, and the flow rates under these head, $Q_1$ and $Q_2$ were calculated by observing the times $t_1$ and $t_2$ taken to fill a container of given volume, V. Accordingly, from 1, the volume V can be expressed by the equations,

$$V = Q_1t_1 = kG_1\,(d-h_1)\,t_1 \quad \ldots\ldots\ldots \quad 2$$

$$\text{and, } V = Q_2t_2 = kG_2\,(d-h_2)t_2 \quad \ldots\ldots \quad 3$$

Since V and k are constant, 2 and 3 can be combined and simplified to

$$G_1\,(d-h_1)t_1 = G_2\,(d-h_2)t_2 \quad \ldots\ldots\ldots\ldots \quad 4$$

For a piezometer with a cavity contructed at its base, the G-factor is dependent on the diameter of the tube, the length and diameter of the cavity, the depth of the cavity below the water table and the distance from the cavity to an impermeable layer. If it is assumed that the position of the water table does not change during the tests, then $G_1 = G_2$ and 4 can be reduced to

$$(d-h_1)t_1 = (d-h_2)t_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 5$$

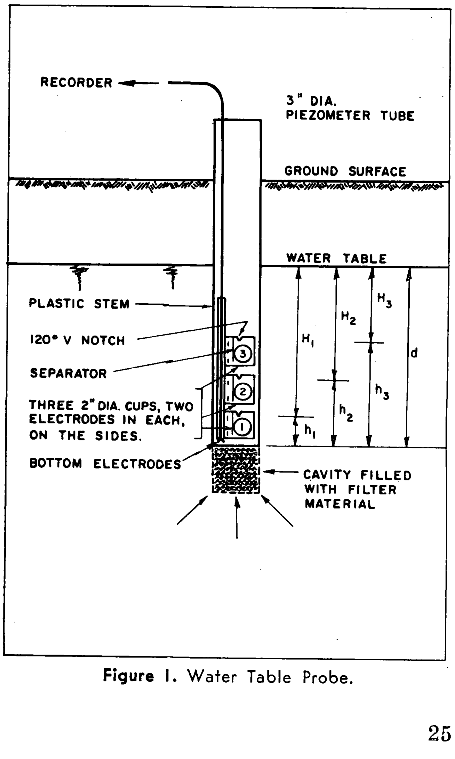

**Figure 1.** Water Table Probe.

Equation 5 can be used to solve for the depth of pipe below the water table, d. The position of the water table is obtained by subtracting the value of d from the known length of pipe below the soil surface.

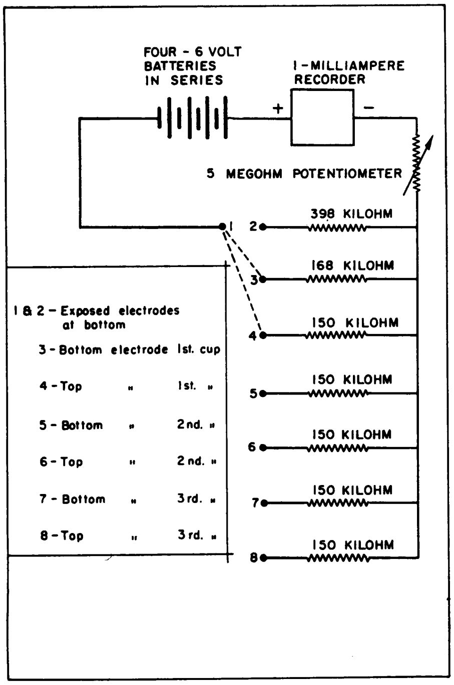

**Figure 2.** Electrcial circuit.

## DESCRIPTION OF PROBE

A probe was fabricated to measure the flow rate to a 3-inch piezometer under three constant heads. The probe (figure 1) consisted of three, 2-inch diameter by 1¾-inch plastic cups, rigidly-mounted one over the other approximately ½-inch apart on a plastic stem. Each cup contained two plastic-pin electrodes, spaced so that the volume enclosed between them was 50 cc. In addition, a separate pair of electrodes were affixed to the lower end of the probe. Insulated leads connected to the electrodes were conducted up through the plastic stem and connected to a recorder. A schematic diagram of the electrical circuit is shown in figure 2.

Equation 5 can be extended for a three-cup probe to be,

$$(d\text{-}h_1)t_1 = (d\text{-}h_2)t_2 = (d\text{-}h_3)t_3 \quad \ldots\; 6$$

where d = depth of pipe below the water table,

$h_1$, $h_2$, $h_3$ = distances from bottom of the pipe to tops of cups 1, 2 and 3 respectively, and

$t_1$, $t_2$, $t_3$ = times required to fill cups 1, 2 and 3 under three constant head conditions.

The probe used in the study was constructed with the following dimensions,

$$(d\text{-}h_1) = H_1 = H_3 + 5.38,$$

$$(d\text{-}h_2) = H_2 = H_3 + 2.78, \text{ and}$$

$$(d\text{-}h_3) = H_3.$$

where $H_3$ is expressed in inches and 5.38 and 2.78 are the distances in inches from the top of cup 3 to the tops of cups 1 and 2, respectively (figure 1). Rewriting 6 in terms of $H_3$, the depth below the water table to the top of the uppermost cup (cup 3), one obtains the expression,

$$(H_3 + 5.38)t_1 = (H_3 + 2.78)t_2 = H_3t_3 \quad \ldots\ldots\; 7$$

## LABORATORY CALIBRATION

Laboratory tests were conducted with the probe to test its workability prior to using it in the field (6). In these tests, the operation of the probe was evaluated under different head conditions when insterted in two reservoirs; a 3-inch diameter piezometer and 6-inch diameter lucite cylinder. A summary of the pertinent findings of these tests are given below.

1. Surface tension effects and irregularities of the lip of a cup may produce inconsistencies in the flow pattern to the cup under a given head. These effects were eliminated by constructing a V-notch in the lip of the cup and by applying a detergent solution (alconox) to the cup prior to the test runs.
2. Reproductibility in the times required to fill the cup under given head could not be obtained when the probe was used in the larger reservoir. If the difference between the outer diameter of the cup and the inner diameter of the piezometer is large, the storage effects of the reservoir influences the flow pattern. That is, insufficient head is built up in the reservoir to produce equalization of flow between inflow to the cup and inflow to the piezometer during the time required to fill the cup. This factor is extremely important in measurements taken at low flow rates. Perhaps the problem could be rectified by either repositioning the bottom electrode in the cup to a greater height above the bottom or by redesigning the shape of the cup.

The results obtained using the probe in the 3-inch diameter piezometer showed that the measured values for $H_3$ agreed favourably with those computed from the probe readings (see Eqn. 7). Table 1 gives a summary of these results.

## FIELD INVESTIGATIONS

Field investigations were conducted with the probe in 3-inch diameter piezometer installations in two soils of different hydraulic conductivities. At the bottom of each piezometer, a cylindrical cavity of equivalent pipe radius and six inches in length was constructed and filled with sand. At one installation, the soil adjacent to the cavity was texturally classified as a sandy loam; at the other a clay soil.

In the field tests, measurements were taken of, (a) the depth of the water level in the piezometer below the ground surface at the start of the test (by the air tube method), (b) the times required to fill the cups of the probe, and (c) the depth below ground surface to the top edge of cup 3 (see figure 1). The difference in testing procedure between runs was that in some cases the water level in the piezometer was pumped down from the static position whereas in other trials it was pumped before the static position had been attained, the so-called non equilibrium case.

### *Water Table Measurements*

The results of the field tests with the probe are given in table II. In the table, an estimate of the effectiveness the probe are given in table II. In the table position can be obtained by comparing the results given in columns 3 and 10. From the direct measurements reported in column 3 it is evident that the water table in the clay soil was approximately 126.5 to 127.0 inches below the ground surface whereas in the sandy loam it was at a depth of approximately 32.5 to 33.0 inches. No appreciable changes in these positions were noted over the test period. In the clay soil, the water table was deep enough not to be influenced by evaporation or transpiration losses. In the sandy loam soil the water level was maintained by seepage from an adjacent stream.

**TABLE I. RESULTS OF LABORATORY CALIBRATION OF PROBE**

| $H_3$ measured (inches) | Maximum difference $H_3$ (calculated) —$H_3$ (measured) (inches) | Maximum Variation % of measurement |
|---|---|---|
| **2.75** | **0.04** | **1.46** |
| **8.50** | **0.22** | **2.59** |
| **12.13** | **0.11** | **0.87** |
| **14.75** | **0.32** | **2.17** |
| **29.50** | **0.55** | **1.87** |

In all trials, independent of whether the water level in the piezometer had been pumped from the known static position or not the calculated positions of the water table agree favourably with the direct measurements.

*Discussion*

Ordinarily only readings obtained from two cups or two positions are necessary to calculate the position of the water table. One of the objectives in using the three cup probe was to obtain three sets of readings which could be compared to ascertain whether drawdown of the water table above the cavity had occurred during the test.

In comparing the results given in columns 6, 7, 8 and 9 of Table 2, one can observe that the three values of $H_3$, calculated from the different combinations of readings agree fairly closely. The maximum discrepancy of any individual calculated value of $H_3$ compared with the average $H_3$ (see column 9) was six percent in the clay soil and nine percent in the sandy soil. The greater variation in readings for the sandy soil can be attributed to the fact that the error involved in calculation of $H_3$, produced by a given error in timing varies inversely as the time required to fill the cup. This factor enhances the value of the probe for use in heavy-textured soils.

Further, in table 2, it can be observed that in twenty-three of the twenty-five trials conducted, the values of $H_3$ calculated from time readings $t_2$ and $t_3$ were larger than the average value of $H_3$. Conversely, $H_3$ as calculated using times $t_1$ and $t_2$ were lower than the average value. Examination of Eqn. 7, suggests that such differences would occur when the time, $t_2$, was longer in proportion to the times $t_1$ and $t_3$. The nature of the discrepancy suggests that it could have been caused by either a malfunction of the second cup or drawdown of the water table. Additional calculations of $H_3$ using data collected from a given cup with the probe set at different depths did not indicate drawdown had occurred. Similarly, however, a malfunction of the second cup could not be substantiated by laboratory tests. It is suggested that additional study should be conducted with a multiple - cup probe of similar design as the one described in this paper to investigate the validity of the assumption that little or no drawdown occurs over a pumped piezometer.

*Hydraulic Conductivity Determinations*

Readings taken with the probe can be used to calculate the hydraulic conductivity of the soil. Rearranging 1 to express the discharge per unit time, Q, in terms of the volume of the cup, V, and the time required to fill the cup, one obtains the expression,

$$d - h = \frac{V}{kG} t^{-1} \quad \text{.......} \quad 8$$

For a given piezometer installation and probe, the quantity V/kG is assumed constant. Thus, from 1, the relation between acting head, H, and time, t, should plot as a straight line on logarithmic paper with a slope equal to -1.

TABLE II. WATER TABLE MEASUREMENTS

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | $H_3$ | $H_3$ Calculated (in) |  |  |  |  |  |
| Soil Type | No. Test | $x^a$ (in) | $z^b$ (in) | Measurement (in) | $t_1$&$t_3$ | $t_2$&$t_3$ | $t_1$&$t_2$ | Ave. | $y^c$ (in) | Water Level Position |
| Clay | 1 | 126.5 | 168.0 | 41.5 | 41.4 | 42.8 | 39.9 | 41.4 | 126.6 | Static |
|  | 2 | 154.0 | 168.0 |  | 42.0 | 43.5 | 40.6 | 42.0 | 126.0 |  |
|  | 3 | 127.0 | 172.0 | 45.0 | 44.8 | 46.3 | 43.6 | 44.9 | 127.1 | Static |
|  | 4 | 156.0 | 172.0 |  | 45.6 | 45.6 | 45.4 | 45.5 | 126.5 |  |
|  | 5 | 156.0 | 172.0 |  | 45.6 | 47.2 | 43.6 | 45.5 | 126.5 |  |
|  | 6 | 155.5 | 162.0 |  | 35.2 | 37.1 | 32.8 | 35.0 | 127.0 |  |
|  | 7 | 127.0 | 171.0 | 44.0 | 44.4 | 46.3 | 42.9 | 44.5 | 126.5 | Static |
|  | 8 | 155.0 | 171.0 |  | 44.3 | 43.4 | 45.4 | 44.4 | 126.6 |  |
|  | 9 | 127.0 | 167.0 | 40.0 | 40.5 | 42.1 | 39.1 | 40.6 | 126.4 | Static |
|  | 10 | 154.5 | 167.0 |  | 40.1 | 41.5 | 38.5 | 40.0 | 127.0 |  |
|  | 11 | 154.0 | 165.0 |  | 38.2 | 39.2 | 37.2 | 38.2 | 126.8 |  |
| Sandy Loam | 1 | 33.0 | 65.0 | 32.0 | 32.8 | 30.6 | 34.4 | 32.6 | 32.4 | Static |
|  |  |  | 59.0 | 26.0 | 26.0 | 27.6 | 24.3 | 26.0 | 33.0 |  |
|  |  |  | 54.0 | 21.0 | 22.0 | 22.8 | 20.9 | 21.9 | 32.1 |  |
|  | 2 | 32.5 | 63.0 | 30.5 | 30.7 | 32.7 | 28.5 | 30.6 | 32.4 | Static |
|  |  |  | 57.0 | 24.5 | 24.0 | 25.8 | 22.7 | 24.2 | 32.8 |  |
|  |  |  | 52.0 | 19.5 | 20.1 | 21.2 | 18.7 | 20.0 | 32.0 |  |
|  | 3 | 33.0 | 64.0 | 31.0 | 31.1 | 32.0 | 31.0 | 31.4 | 32.6 | Static |
|  |  |  | 55.0 | 22.0 | 22.2 | 22.4 | 22.0 | 22.2 | 32.8 |  |
|  | 4 | 33.0 | 63.0 | 30.0 | 30.6 | 32.7 | 28.2 | 30.5 | 32.5 | Static |
|  |  |  | 61.0 |  | 28.3 | 29.3 | 27.1 | 28.2 | 32.8 |  |
|  | 5 |  | 65.0 |  | 32.2 | 34.3 | 30.1 | 32.2 | 32.8 |  |
|  |  |  | 62.0 |  | 28.4 | 30.9 | 26.1 | 28.5 | 33.5 |  |
|  | 6 |  | 64.0 |  | 31.3 | 31.6 | 30.5 | 31.1 | 32.9 |  |
|  |  |  | 60.0 |  | 26.9 | 27.8 | 25.5 | 26.7 | 33.0 |  |

a=depth below ground level to water level in piezometer prior to pumping

b=depth below ground level to top edge of cup 3

c=position of water table below ground level determined from average $H_3$ and measured z value

Data collected from the two test sites are shown plotted in figure 3. From these data, the values of V/kG for the installations in the clay soil and sandy loam soil were calculated to be 83,900 inch-secs and 4,225 inch-secs respectively. Under the conditions of the test, V = 50 cc and G = 26.5 inches (taken from Luthin and Kirkham (5) ). Using these values, the hydraulic conductivities, k, for the soils are calculated to be 0.005 and 0.098 inches/hr respectively.

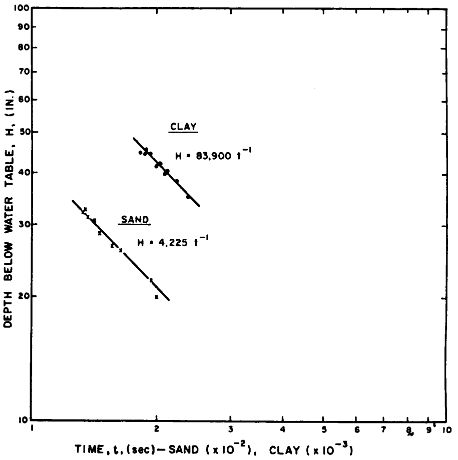

**Figure 3.** Relation of head and time used in hydraulic conductivity determination.

## SUMMARY

Details concerning the design and operation of an instrument for determining the position of the ground water table and the hydraulic conductivity of a soil have been presented. The probe, which consists of a series of small cups mounted vertically one over the other is used in a piezometer installation. The water table position and hydraulic conductivity of the soil are calcuable from observations of the times required to fill the cups under different constant heads.

Investigations were conducted with the probe in the field in two soils of widely different hydraulic conductivities. For each soil the position of the

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Dean of Engineering and the Heads of Departments the acquisition of additional staff members for hydrology, teaching and research. These members would be appointed by the Departments concerned if they agreed to the recommendation of the Division.

*Degrees and Diploma Courses*

Engineering studies at the Masters level to students specializing in hydrology would continue to be directed primarily from a single department. Thus a graduate student would be attached to one of the existing Engineering departments, depending primarily on his chosen area of research. The academic work required for such a degree might include basic studies in surface hydrology, groundwater hydrology and flow through porous media, if undergraduate training in these areas had not reached an acceptable level. In any case the student would have considerable freedom to specialize in any phase of Engineering hydrology. The main purpose of the division in relation to such a program would be to ensure that the class work taken would meet the needs of the student in forming a basis for his research work, and have sufficient breadth to qualify the student as an hydrologist.

Graduate Diploma courses have recently been introduced at the University of Saskatchewan to serve the needs of those students wishing to take post graduate work but who for various reasons may not wish to undertake a research program. Such diploma courses will be available to students wishing to undertake advanced studies in Hydrology. As with the degree course students will be assigned to a particular department in line with their interest or field of specialization. The graduate diploma course, through elimination of research requirements, allows students considerably more time in which to undertake formal class work, and a minimum of five full classes are required.

*Research Programs*

Generally speaking, research programs for graduate students are available within the various Engineering departments on the following basis,

1. In the Department of Agricultural Engineering work may be undertaken relating to irrigation, groundwater flow or water conservation problems. Irrigation facilities are available on the campus and in co-operation with the provincial Department of Agriculture on other irrigation development projects throughout the Province.
2. In the Department of Civil Engineering, work may be undertaken relating to problems of water development, hydraulic structures and municipal water supply. Hydraulic and Sanitary laboratory facilities are available in the department and close liaison with industry and government organizations offer the possibility of off campus facilities for research studies.
3. In the Department of Geological Sciences, work may be undertaken relating to problems of the occurrence and development of groundwater. Opportunity for field studies may be arranged in cooperation with the Geological Survey or the Saskatchewan Research Council. The Geological, Geophyshics and Petroleum Engineering laboratories are available within the department for lithological, porosity, peremeability and other aquifer studies.
4. Financial assistance to students engaged in hydrologic research in any of the departments is available from a number of sources including research institutions, government agencies and industry.

The function of the division in regard to research programs will be primarily one of co-ordinating work between the various departments. Thus duplication of effort will be eliminated, classes will be designed to meet some of the broader needs of hydrology, and students will have ready access to staff and facilities in a number of departments. It is also anticipated that the division will be in a much stronger position to obtain research funds than would an individual staff member or department.

The hydrology division and the Water Studies Institute have very similar interests in the research field, although the Institute will be limiting its consideration to the Engineering aspects of hydrology. Obviously the concerted effort of the two organizations should ensure a strong and pointed research program to meet the needs of the region, and for which financial assistance would be readily available.

## APPENDIX I

Following is a list of agencies and University Departments who have been represented in the formation of the Water Studies Institute.

Saskatchewan Department of Public Health
Saskatchewan Department of Agriculture
Saskatchewan Department of Natural Resources
Saskatchewan Research Council
Canada Agricultural Research Station (Saskatoon)
Prairie Farm Rehabilitation Administration
Canada Department of Transport—Meteorological Branch
Canada Wildlife Service
National Research Council
University of Saskatchewan:
    Department of Agricultural Engineering
    Department of Civil Engineering
    Department of Electrical Engineering
    Department of Geological Sciences
    Department of Agricultural Economics
    Department of Animal Science
    Department of Crop Science
    Department of Soil Science
    Department of Plant Ecology
    Department of Biology
    Department of Chemistry
    Department of Geography
    Department of Physics

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## SOIL HYDRAULIC CONDUCTIVITY

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water table as calculated from the probe readings compared very closely with measured depths.

It is anticipated that the probe will find wide usage in drainage and water table investigations, particularly in heavy soils, because the water table position can be calculated without having true static conditions.

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