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Measuring Unsaturated Soil Moisture Flow With a Meter[1]

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ABSTRACT

A meter for measuring unsaturated soil moisture flow was constructed and tested in the laboratory. The meter was made from a single porous plate mounted in a thin brass cylinder. Flow through the meter was calculated from measurements of hydraulic head loss in the porous ceramic plate. The unit was calibrated in silt loam, silty clay, and loamy sand soils under nonisothermal but steady state conditions. It responded to water vapor flow induced by thermal gradients, as well as to liquid flow. Transient tests made in the silt loam soil indicated that it is possible to calibrate the meter under such conditions. Design analysis indicates that increasing the length of the cylinder reduces the sensitivity of the meter's calibration to changes in soil moisture content.

Additional Key Words for Indexing: **flow meter, hydraulic conductivity.**

ACCURATE measurement of soil moisture transfer in the field is one of the major problems confronting soil scientists. Development of a reliable unsaturated moisture flow meter would partially solve this problem. Preliminary reports on the performance of such a unit were published in 1968.[3] Basically, this unit measured the pressure drop across a porous plate buried in the soil. Since the porous plate remained saturated, it had a constant hydraulic conductivity so the flow through the plate was always known. The problem was to relate the flow of moisture through the plate to the flow of moisture through the surrounding soil. If the plate was more permeable than the surrounding soil, water tended to converge and flow through the plate faster than through the undisturbed soil. This convergence or calibration factor could be measured in the laboratory under steady state conditions, but the procedure was time consuming and tedious. Consequently, additional work was undertaken with two objectives in mind. One was to design a transducer in which the calibration factor was less dependent upon soil conductivity, and the second was to develop a more rapid method of calibrating the units for use in various soils.

THEORY

A sketch of the transducer used in this study is shown in Fig. 1. When the transducer is buried in the soil, water flowing through the soil will also flow through the plate. The head loss in the plate can be measured with hydraulic lines coming to the surface and can then be used to calculate the flow of water through the plate. The cylinder surrounding the porous plate has two purposes. The first is to make the convergence of water and thus the calibration factor less dependent upon the surrounding soil water conductivity, while the second is to make the unit more sensitive to thermally induced water vapor flow.

The cylinder around the plate tends to make the average conductivity of the transducer adjust to that of the surrounding soil. The moisture content of the soil enclosed by the cylinder tends to change with the moisture content of the soil outside of the cylinder, so the longer the cylinder, the closer the overall average conductivity of the transducer will be to that of the surrounding soil. Consequently, the calibration factor will be less dependent upon soil moisture content.

When there is a thermal gradient through soil, water vapor diffuses from the warm to cooler regions. In order to detect this flow with the transducer, the water vapor must condense on the warm side of the plate and evaporate on the cool side. The brass cylinder around the porous plate should enhance this action. Because of its high thermal conductivity, the temperature gradient along the cylinder's wall will be less than the gradient in the surrounding soil. Thus the perimeter of the warm side of the porous plate should be a bit cooler than the soil, while the perimeter of the cool side of the plate should be a bit warmer than the surrounding soil. Since the relative humidity of moist soil is very near 100%, water vapor will tend to condense in the area which is cool with respect to the surrounding soil, go through the plate in the liquid phase, and then re-evaporate in the area which is warm with respect to

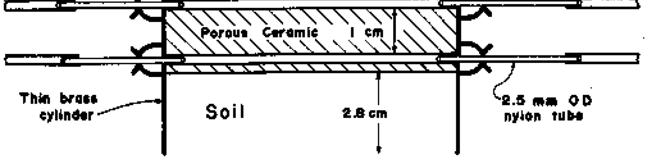

Fig. 1—A sketch of the cross section of the transducer used in this study. Details are given in the text.

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[3] Cary, J. W. 1968. An instrument for *in situ* measurements of soil moisture flow and suction. Soil Sci. Soc. Amer. Proc. 32(1):3–5.

the surrounding soil, utilizing any heat transported by the brass cylinder.

If one assumes that the conductivity of the soil in the cylinder is exactly equal to the conductivity of the soil outside the cylinder, the relationship between the average conductivity of the transducer and the length of the cylinder may be determined. The flow of water through the transducer must equal the flow of water through the plate in the transducer under steady state conditions. Consequently,

$$\bar{K}\,\frac{H_s + H_p}{l_t} = \frac{K_s H_s}{l_s} \qquad [1]$$

where $\bar{K}$ is the average conductivity of the transducer, H_s is the head loss in the soil, H_p is the head loss in the plate, l_t is the overall length of the transducer, and l_s is the length of the soil in the cylinder. The flow of water through the plate will also be equal to the flow through the cylinder, thus

$$\frac{K_p H_p}{l_p} = \frac{K_s H_s}{l_s} \qquad [2]$$

where l_p is the thickness of the plate.

Using equation [2] to eliminate H_s from equation [1], the result follows as:

$$\bar{K} = \frac{l_t K_p K_s}{l_s K_p + l_p K_s}. \qquad [3]$$

The relationship between the average conductivity of the transducer, the conductivity of the soil, and the length of soil in the cylinder may then be plotted as shown in Fig. 2. The more closely these curves approach the 1:1 line, the less dependent the transducer calibration will be on the soil moisture content.

In practice, the calibration factor is accounted for by "k" (Fig. 3) in the relation

$$J = kH'_p \qquad [4]$$

where J is the net water flux through the soil in millimeters per day and H'_p is the hydraulic head change in the plate between the drilled holes (Fig. 1). H'_p is measured in centimeters of difference between the oil-water interfaces of the manometer[3] and is equal in magnitude to approximately five times the head loss measured in units of centimeters of water.

METHODS

A sketch of the transducer is shown in Fig. 1. The holes through the plate are approximately 1.75 mm in diameter. These were made with the drill press using low speed and a continuous stream of water on the bit. The nylon tubes have the same outside diameter as the holes in the plate, so that a friction fit can be made by twisting the end of the tubes into the holes. Silicon rubber cement, or similar material, may be used to lubricate and seal these joints. The copper tubes soldered to the brass cylinder were crimped on the nylon tubing to take up external strain and prevent twisting of the nylon-ceramic joint.

The porous plate was made from a standard 2-bar ceramic with a hydraulic conductivity of approximately 0.5 mm of water per day. While the single-plate model used here is more difficult to construct than the three-plate type previously used,[3] it has the advantage of easily being flushed of air bubbles.

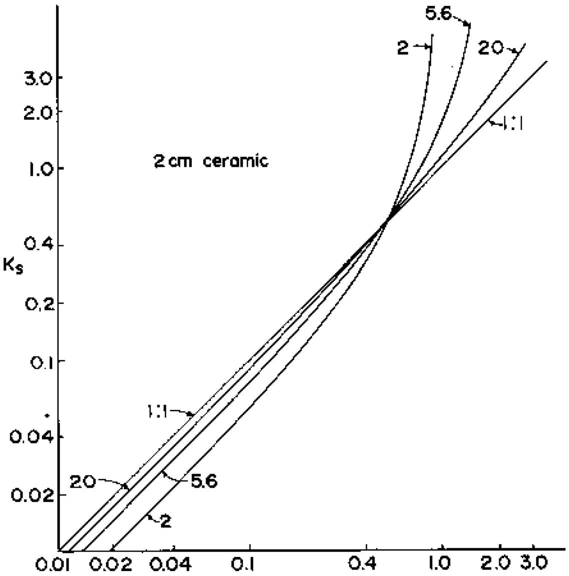

Fig. 2—Relationships between soil conductivity and average conductivity of the flow meter. The ideal relationship is the 1:1 line. The curved parameters designate the length in cm of soil enclosed by the transducer. Each of the three curves assumes a 2-cm-thick ceramic plate with a conductivity of 0.5 mm/day.

Steady state calibration of the transducer was made for three soils—a silt loam, a silty clay, and a loamy sand. The calibration apparatus was similar to that described previously using a column 19.6 cm in diameter.[3] The principal modification was a heating coil in one water reservoir, and a cooling coil in the other, so that thermal gradients could be created across the sample in addition to hydraulic head gradients. During these measurements, the soil column was placed in a styrofoam box filled with vermiculite insulation.

In addition to the steady state observations, two transient experiments were carried out. The first was done in a soil column approximately 26 cm in diameter. This soil column had a porous plate on the bottom connected to a vacuum system so that this boundary could be maintained at any desired suction. The transducer was placed 13 cm beneath the surface of the silt loam soil packed to bulk density of 1.02. The water flow transducer was connected to a pressure transducer, which, in turn, was connected to an electrical integrator. Water net flow past the transducer was determined gravimetrically by sampling the soil above the transducer, adding a known volume of water to the surface of the soil and then resampling after various time intervals (Two or three soil cores were taken at each sampling time and used to determine moisture content on a volume basis. The holes left by the cores were refilled with similar soil.). These measurements were then compared to the net water flow predicted by the transducer with equation [4], using the volt-hour reading from the electrical integrator converted to H'_p, the average soil moisture tension in the transducer, and the solid line calibration curve for the loam soil as given in Fig. 3.

The second series of transient experiments was carried out in a column of silt loam soil enclosed in a box approximately 60 cm square and 100 cm deep. The bottom of the column was supported on a system of screen and slats. Warm air passed across the screen to form a water sink for the bottom of the column. The average bulk density of the soil column was 1.12 g/cm³. The transducer was placed 45 cm beneath the surface of the soil in approximately the center of the column. The net water flux through the soil past the transducer was again calculated by adding water to the surface and periodically sampling for soil moisture. The hydraulic head change in the transducer for the first two drainage cycles was measured with an oil manometer, while the measurement on the third cycle

Table 1—A comparison between flow rates measured and predicted by the transducer under steady state condition

Soil	Suction cm H_2O	Net flux	Predicted flux	% thermal H_2O flux
		mm/day		
Silt laom	27	6.55	5.36	--
	34	1.25	1.10	--
	34	1.40	1.50	10
	146	0.44	0.29	--
	270	0.10	0.09	-47
	294	1.00	0.98	--
	460	0.85	0.61	85
	520	0.13	0.12	--
	570	0.42	0.67	69
	620	0.13	0.27	--
Loamy sand	79	3.40	3.20	--
	81	3.60	3.00	6
	194	0.45	0.65	--
	200	0.13	0.33	-42
	292	0.50	0.38	76
	311	0.27	0.39	22
	340	0.12	0.18	--
	490	0.05	0.04	--
Silty clay	81	6.90	6.10	--
	92	6.00	4.80	13
	252	1.70	1.56	--
	267	2.05	1.98	16
	434	0.05	0.06	-47
	440	0.45	0.66	--
	454	0.95	0.97	55
	530	0.57	0.58	--

was made with a pressure transducer. In both cases, the water suction in the flow transducer was measured with a mercury manometer enclosed in a 1-mm bore capillary tube. The solid line calibration curve for the silt loam soil was used with equation [4] to calculate water flow past the transducer in both cases. Two tensiometers were also placed in this soil column above and below the flow transducer and were used to calculate unsaturated flow from the conductivity curve given in Fig. 5.

DISCUSSION

The steady state data are summarized in Table 1. While agreement between observed and predicted net fluxes is sometimes quite close, differences of 20% or so were not unusual. Some error was encountered in the direct measurement of moisture flux as well as in the transducer measurements. When using a soil column 30 cm long, one rarely gets a true steady state. Because unsaturated conductivity tends to decrease with time, the rate of inflow is usually at best a few percentage points different from the rate of outflow, so that some average value must be taken.

Measurements of net flux were made with and without thermal gradients of about 0.6C/cm. By holding the head gradient constant, the flow due to temperature differences could be calculated. The fourth column of Table 1 records the percent of the net flux due to the thermal gradient. Negative signs indicate that the thermal water flow was opposite to the net flux. These data leave no doubt that the transducer does respond reasonably well to water flow associated with temperature differences.

One problem did develop while measuring thermal moisture transport in the loamy sand sample. When the suction on the transducer was more than 300 cm of water, the thermally driven vapor apparently tended to condense in the area of the transducer and not completely revaporize. For example, under one set of steady state conditions, the suction on the transducer was 311 cm of water, while the suctions on the ends of the sand column were 433 and 670 cm of water, respectively. This developed under a thermal gradient of less than 0.7C/cm. The condition might have been improved if the outside of the brass cylinder had been thermally insulated from the surrounding soil, causing a more direct heat flow path for the latent heat from the warm to the cool side of the transducer.

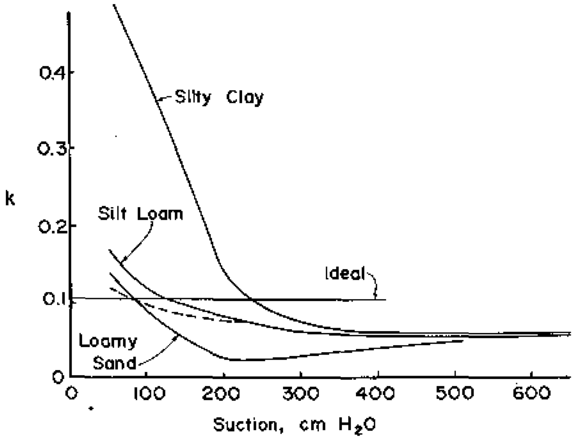

Fig. 3—The flow factor for the moisture flux transducer plotted as a function of soil moisture suction for three different soils. The units of k are mm H_2O/(day) (cm if oil-water interface displacement). The straight, "ideal" line would occur if the transducer always had exactly the same conductivity as that of the soil around it. The dotted line is the calibration curve given by the transient measurements on the silt loam soil.

The similarity of the transducer calibration curves at suctions greater than 250 cm of water is particularly striking, especially when compared to the logarithmic conductivity relations shown in Fig. 4. The shape of the curves in Fig. 3 appears to be reflected in the relation between soil hydraulic conductivity and the average transducer conductivity shown in Fig. 2. When the conductivity of the ceramic plate is greater than that of the soil, the calibration curves should lie just below the "ideal" line drawn in Fig. 3. (In locating the "ideal" line, it was assumed that the

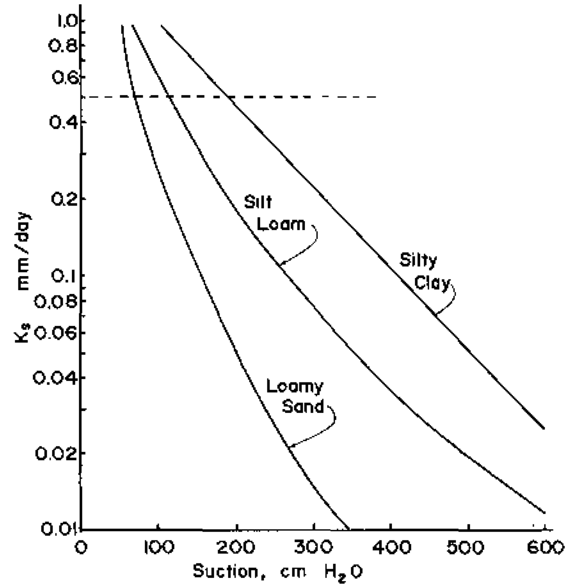

Fig. 4—The relationship between hydraulic conductivity and soil moisture suction for the three soils used in this study.

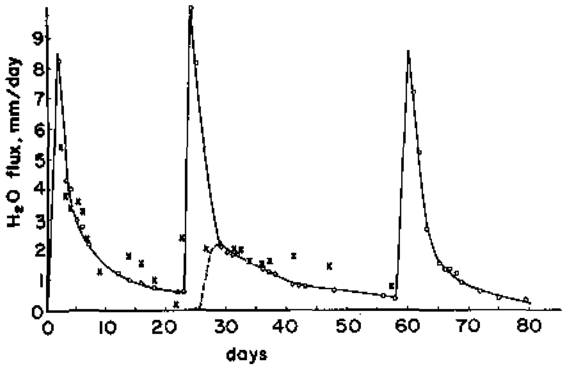

Fig. 5—The flux through the large column of soil predicted by the moisture flow transducer represented as a smooth curve drawn through the round points. The crosses represent calculations of flow from Darcy's law using the conductivity shown in Fig. 4 and tensiometer measurements. The dotted line represents a recovery rate for the oil manometer system.

holes through the porous plate did not affect the pressure distribution in the surrounding ceramic material.). When the conductivity of the plate becomes less than that of the soil, the curves in Fig. 2 diverge from the 1:1 line rather rapidly, as do the calibration curves in Fig. 3 at low suction values. Consequently, it appears that the calibration curves could be forced to conform more closely to a flat line by increasing the conductivity of the porous plate and increasing the length of the cylinder. Disadvantages of doing this are that increasing the cylinder length forces one to sample a larger volume of soil, while increasing the plate conductivity decreases the sensitivity to the small fluxes at higher suctions. However, this information does provide some criteria for the design of the flow transducers for specific situations.

Transient measurements of soil water flow in the large column are shown in Fig. 5 for three wetting and drainage cycles. The head drop across the transducer was followed with an oil manometer for the first 58 days. The third cycle was monitored with a pressure transducer connected to the moisture flow meter. Table 2 shows a comparison between the water flux measured by the transducer and that calculated from gravimetric soil sampling. In general, the flow meter predicted higher values than the sampling method. This could have been caused in part by a lag in the response of the oil manometer. On the 26th day, the pressure measurement system was allowed to go to zero at all points. The dotted line in Fig. 5 shows the recovery rate and approach to equilibrium. This would indicate that under transient drainage conditions the manometer reading will overestimate the average flow through the plate. Unfortunately the diameter of the oil manometer must be at least 2.5 mm to remain reasonably free of meniscus problem at the oil-water interface.

Table 2—Comparison between transient water flux as measured by sampling and by the flow transducer in the silt loam soil

Method of pressure measurement	Suction range cm H_2O	mm/H_2O	
		J_w sampled	J_w flow meter
Oil manometer (large column)	5-145	23.9±7	35.5
	145-185	12.7	4.7
	27- 70	14.5	28.6
	70-127	10.0	19.2
	127-195	10.5	13.6
Transducer (large column)	35- 77	18.7±7	28.8
	77-162	10.0	8.7
Transducer-integrator* (small column)	≈270	6.1±2†	7.9
	65-350	7.6	11.0
	≈140	2.3	3.1
	≈195	5.7	8.1

* The collection of these data by H.D. Fisher is appreciated.

† Experimental uncertainty was less in this case because only 13 cm of soil above the transducer had to be sampled compared to 45 cm in the case of the large rectangular column.

The pressure transducer readout was not subject to the lag problem. However, it also tended to overestimate the flux of soil water, particularly in the low suction range. If the dotted line were used for the calibration curve of the silt loam soil in Fig. 3, the observations in Table 2, with one exception, would agree well within the limits of experimental uncertainties. This raises the possibility that the steady state measurements were made in too small a diameter column. If the boundaries of the column were reducing the head drop across the transducer in the low-suction, high-flow-rate cases, the resulting calibration curves could be too steep on the low suction ends. It is also possible the problem may have been associated with a higher bulk density in the steady state experiments, i.e., ≃ 1.35.

The flow meter can be calibrated under transient conditions. While it is desirable to use a pressure transducer for these measurements, the electrical integrator has no great advantage because the volt-hour count must be periodically corrected for changes in "*k*" as the soil suction changes. If the transients are not too severe, reasonably good measurements may be made with the oil manometer by recording readings once or twice a day and then plotting the data as in Fig. 5. In any case, once *k* for a single flow meter is determined in any given soil, other meters with different characteristics may be installed near it and quickly calibrated.

CONCLUSIONS

From the results reported here, one may conclude that:

1) The transducer can be designed to give a reasonably flat calibration curve by choosing the proper plate conductivity and length of cylinder.

2) The transducer can be calibrated under transient conditions using soil moisture sampling techniques.

3) It is possible to build an unsaturated flow meter that detects thermally driven water vapor as well as liquid phase fluxes.