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Soil Water Flowmeters with Thermocouple Outputs

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ABSTRACT

The construction and operation of two soil water flowmeters with microvolt outputs are described. One meter with a sensitivity of 0.1 mm of water flow per day is recommended for flux measurements in the surface meter of soil when the water matrix potential is greater than −0.8 bar. Calibration factors for three soils with different textures are presented as a family of curves. These curves may be interpolated for using the flowmeter in other soils, possibly without a loss of accuracy greater than the natural water flow variation from place to place in the field.

The second meter with a sensitivity of about 0.5 mm per day will require some additional development and testing before it can be recommended for routine use. It does offer the possibility of making measurements at soil water matric potentials less than −1 bar and at relatively deep soil depths.

The thermocouple flow transducer developed for the meters may be used to measure saturated soil water flow or other liquid flows as small as 1 ml/day.

Additional Index Words: hydraulic conductivity, drainage, leaching, thermocouples, liquid flow, seepage.

THERE are two types of soil water flowmeters. One intercepts the soil water and measures its flow directly; the other senses the displacement of a thermal field by moving soil water. If heat is added around a point in the soil, the surrounding temperatures depend on the soil's thermal conductivity and the flow of water, allowing the temperature field to be used as an indicator of soil water flux. Problems associated with this type of flowmeter develop from the transient thermal conductivity of soils, which is a function of moisture content, mineral composition, and density. Consequently, calibration requires extensive information pertaining to each situation (Suzuki, 1960; Byrne, 1971). Advantage lies in the instrument's simplicity and its possible development for use over the whole range of soil water contents.

The intercepting-type flowmeter uses porous material to collect water in a bulk phase and measures its flow through a metering system (Richards, Russell, and Neal, 1938; Cary, 1968). Calibration problems are also inherent with this type of meter. If the porous material has a higher hydraulic conductivity than the surrounding soil, the soil water flow converges to the meter and the flow through it is greater than the real soil water flux. In some cases the meter's conductivity can be varied to match that of the surrounding soil (Cary, 1970; Dirksen, 1971, 1972). The meter has the disadvantage of requiring hydraulic lines between it and the soil surface, as contrasted to the electrical leads used by the thermal displacement method.

This paper describes the construction and operation of two water flowmeters, which combine the principles of both the water-interception and the thermal field-displacement techniques. These units retain most of the advantages of both types of meters while eliminating some of their less desirable characteristics.

METER CONSTRUCTION

A sketch of one type of flowmeter is shown in Fig. 1. The frame is formed by cementing together the bottoms of two identical, thin-walled boxes. This forms two compartments, one to intercept the soil water flow and the other to release it. Holes are drilled in each compartment so that a fritted glass filter tube may be inserted on a slant, allowing any air bubbles to collect in the rounded glass ends. The tubes may be purchased from most scientific supply companies and are available in a variety of sizes and porosities. Those in Fig. 1 are approximately 15-mm in diameter with fritted sections 100-mm long. The outside dimensions of the meter's frame are 120-mm high with a cross section 52 by 105 mm.

The tubes are cemented to the compartment walls and the lower ends are closed with stoppers bored partway through to fit over the outside of the tubes. Three pieces of nylon tube, 2-mm inside diameter, are passed through the stoppers as shown in the diagram. Two of the tubes lead to the soil surface for measuring the soil water tension and for flushing air bubbles out of the system. The third carries water between the fritted tubes and through the thermocouple flow transducer. De-aired water must be used for flushing out air bubbles, and the flushing must be done in both directions to insure air removal from both tubes.

When the meter is in the soil, water may move through the soil in one compartment, across the walls of the fritted glass tube into the bulk water phase inside, through the nylon tube and flow transducer, into the second glass tube, and finally out through its porous walls into the soil in the second compartment. The soil in the compartments tends to make the average conductivity of the meter match that of the surrounding soil (Cary, 1970). The amount of water flow through the meter is known from the electrical signal at the soil surface generated by the flow transducer.

Components of the thermocouple flow transducer are shown in Fig. 2. A short length of nichrome wire, having a resistance of 1 Ω, is wound around the nylon tube that connects the lower ends of the two fritted glass filter tubes. The coil is cemented in

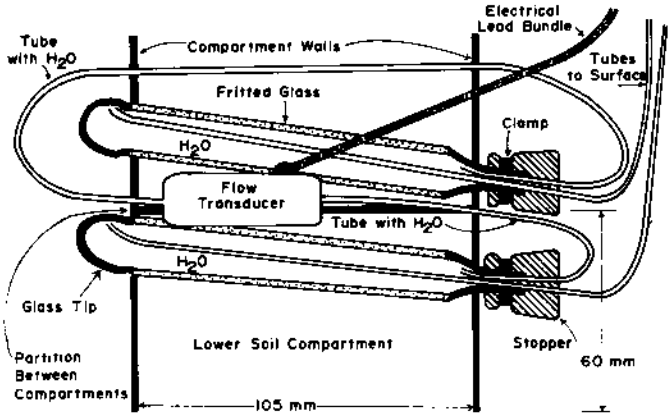

Fig. 1—A cross-section diagram of a soil water flowmeter.

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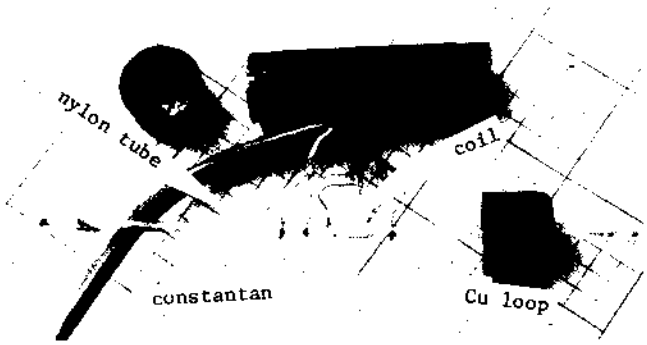

Fig. 2—Photograph of the thermocouple flow transducer ready to assemble. The grid squares are 5 mm on a side.

place with epoxy resin and connected to two copper leads that go to the soil surface. Three loops of small copper wire are then wrapped around the nylon tube, two on one side of the heater and one on the other. The distance between the first copper loops and the ends of the heater coil is 4 mm. Each of the copper loops is connected to a copper lead that goes to the surface. The loops are also connected in series by a fine gauge constantan wire as shown in Fig. 2. Two copper tubing caps are partly filled with solder and drilled to the exact outside diameter of the nylon tubing. This insures good thermal contact to isolate the thermocouples from transient soil temperature waves. The nylon tube is then passed through one cap and cemented in place. A piece of copper tubing 13-mm in diameter is slit, passed over the electrical leads, and its end secured in the cap cemented to the tubing. The second cap is then placed on the other end and the whole unit taped to make the system water tight and to secure the electrical leads.

On the soil surface, 0.40 of a volt DC is connected to the nichrome coil leads. This creates a temperature gradient along the nylon tube which is displaced by water flowing inside the tube and is measured by the thermocouples. Before calibrating the transducer, it should be fastened to the flowmeter as shown in Fig. 1. During calibration, and when in place in the soil, the transducer must be horizontal to reduce convection. A typical calibration curve is shown in Fig. 3, with the microvolt output as a function of both the actual flow in ml/day through the nylon tube, and as flow in cm/day through a 53 cm^2 cross-sectional meter. The two curves give the voltage measurements from the two thermocouple junctions on the left side of the heater with respect to the single junction on the right side. Because the emf passes through a peak as the flow increases, the second curve and the unsymmetric junction indicate on which side of the negative peak any set of signals lie. For example, if the output from the symmetric set were -300 μV, the other thermocouple output would be either -130 or -250 μV, depending on the waterflow rate. The two outputs also serve as a check on the electrical system and detect any air bubbles that might move into the flow transducer.

Increasing the flow capacity of the transducer by increasing the diameter of the nylon tube is not recommended. Larger tubes become increasingly susceptible to convection currents, leading to an unstable calibration. Presumably, the flow capacity of the transducer could be increased with an external bypass tube. The heater and thermocouples would be placed at the high point of the system so that convection in the loop would not develop.

The output from the flow transducer may be measured with a portable microvolt meter like those used with soil and plant psychrometers. The transducer's output is a sensitive function of the heater voltage, so this input must be accurate and stable during the measurement. The heater voltage can be monitored before and after the thermocouple readings with the microvolt meter, since most have millivolt scales. Under these conditions, the transducer should be stable within a few microvolts and the flowmeter will have a sensitivity near 0.1-mm water flow per day.

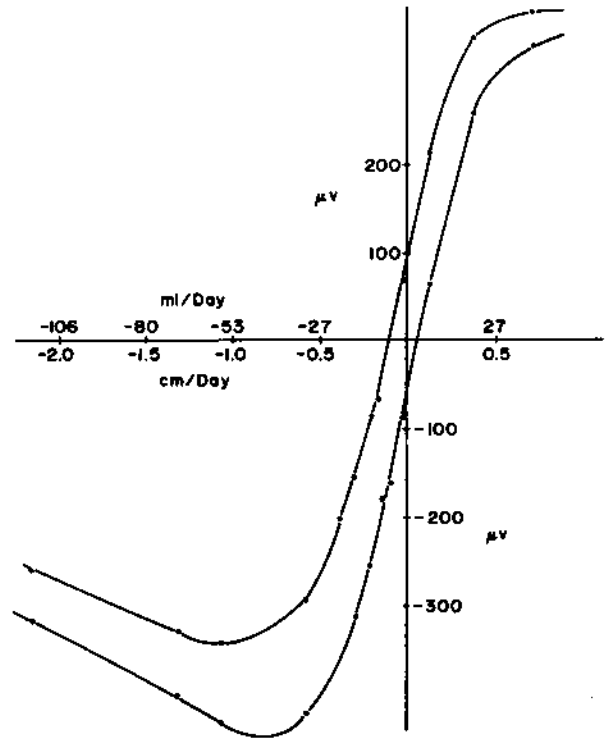

Fig. 3—A typical set of calibration curves for the transducer shown in Fig. 2. The lower curve is for the symmetric thermocouples.

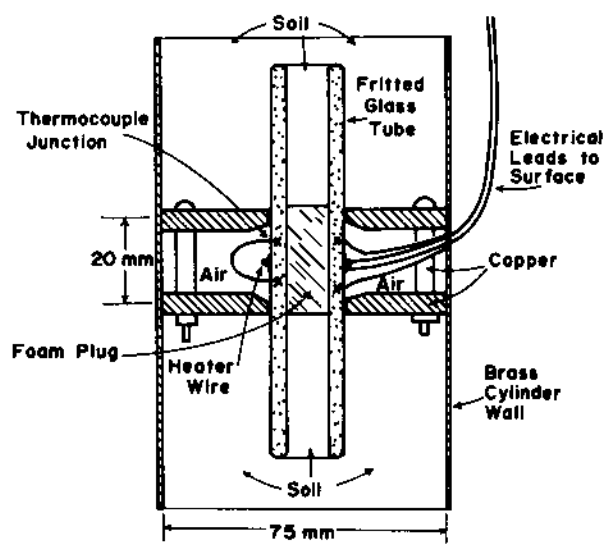

Fig. 4—Cross-section drawing of a soil water flowmeter.

The flowmeter shown in Fig. 4 is similar to that in Fig. 1, except no bulk phase of water is required. Only electrical leads are brought to the soil surface, and there are no hydraulic leak or air bubble problems. A single, fritted glass filter tube is used. The ends are removed, leaving a fritted glass tube approximately 100-mm long and 15-mm in diameter. An electrical resistance wire insulated by a narrow strip of plastic tape is wound around the middle of the tube. Holes 0.5-mm in diameter are drilled in the tube approximately 5 mm on each side of the heating element. Thermocouple junctions are cemented in these holes with epoxy resin, or short pieces of varnished copper wire may be cemented in the holes and the thermocouple junction made on the end of the wire where it protrudes from the hole. The copper constantan thermocouple junctions are made from

wire approximately 5×10^{-3} mm in diameter. The thermocouple junctions are connected in series to form a thermopile, which in turn is connected to two copper wires leading to the soil surface.

A styrofoam plug is placed in the center section of the fritted glass tube to eliminate soil and prevent moisture flow. Two copper washers are made from 6-mm thick plate, and beveled as shown in Fig. 4, so that the thermocouples are midway between the heater and copper sink. Copper must be used to reduce the effect of any soil temperature transients on the thermocouples. After constructing the electrical circuit, the washers are cemented to the tube with epoxy resin, and are further secured to each other by six brass bolts passing through sections of copper tubing used as spacers and for heat tranport between the washers. Since warming the moist fritted tube when the heater is turned on will cause water to evaporate and recondense on the electrical circuits in the central air chamber, the outside of the tube in this section must be sealed. This may be done with waterproof epoxy enamel or any other inert waterproof material which flows easily but does not penetrate the pores in the tube. The final step in construction is to wrap a a thin brass or copper plate around the outside of the copper washers to form a cylinder open on both ends to straighten the soil water flow lines through and around the meter.

During calibration, the meter should be placed in soil to provide a realistic thermal environment. A water reservoir may be sealed around each end of the fritted glass tube and the water allowed to flow through the tube walls from one reservoir to the other under a small hydraulic gradient with the pressure in the fritted glass held less than atmospheric. A heating energy of 0.25 w is supplied to the resistance wire, and the thermopile voltage is measured as a function of flow. Calibration curves for meters with six- and eight-junction thermopiles are shown in Fig. 5. The microvolt output is shown as functions of both the total water flow through the walls of the fritted glass tube in ml/day, and as soil water flow in cm/day for the flowmeter as a whole with a cross-sectional area of 44 cm^2.

In measurements of soil water flux, the soil solution moves from the soil into the wall of the fritted glass tube, through its capillaries, past the thermocouple junctions in the center section, and then on out of the tube wall back into the soil. Depending on the pore size of the fritted glass, the meter has the potential of operating at soil matric potentials below −1 bar. The unit has disadvantages of lower sensitivity and lower hydraulic conductivity when compared to the meter in Fig. 1. Calibration curves shown in Fig. 5 are for units using a "very fine" fritted glass tube with an air entry value slightly less than 1 bar. The effective cross-sectional hydraulic conductivity of the meters was generally a bit under 1 mm/day and their daily signal stability was around ± 3 μV on the lab bench. This gave them a soil water flux sensitivity near 0.5 mm/day. Their long-term stability and sensitivity in the soil under field conditions has not been determined.

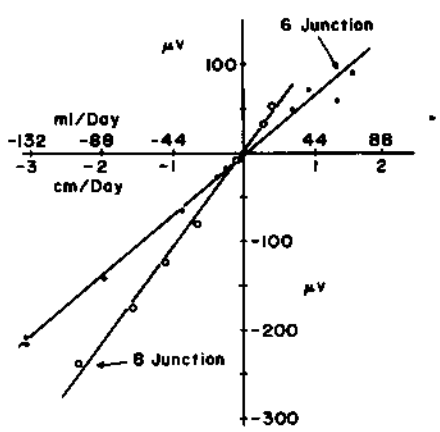

Fig. 5—Typical calibration curves for the type of meter shown in Fig. 4.

CALCULATING SOIL WATER FLUX FROM MEASUREMENTS OF FLOW THROUGH THE METER

The hydraulic conductivity of the soil water flowmeters will generally be different from that of the surrounding soil, so the water flux through the meter will not be identical to that through the surrounding soil. If two meters with identical shapes but different hydraulic conductivities are placed in soil where a uniform water flux is occuring, the water flow through the soil can be calculated from the water fluxes through the two meters by the relation

$$J = j\,A\,(n-1)/(n-m) \qquad [1]$$

where J is the true soil water flux, j is water flow through one meter, A is a constant dependent only on the shape of the meter, m is the ratio of water flux through one meter to the water flux through the other, and n is the constant ratio of the conductivity, without soil, of one meter to the conductivity of the other (Cary, 1971).

The numerical value for A in equation [1] may be found by comparing soil water flux to meter flux at τ equal 40 or 50 cm of water since m approaches one in this region. This constant is presumably independent of soil properties and needs to be evaluated only once for any given meter shape. A reasonable value for A for the meter shown in Fig. 1 appears to be 0.95.

Preliminary field tests using two flow sensors placed 1 m apart were not successful in utilizing equation [1] because of the variation in water flux from place to place in the field, particularly under transient conditions following irrigation or rain. A better method proved to be a single meter with an auxiliary hydraulic resistance on the soil surface (Cary, 1971). In this case, flow from the first compartment (Fig. 1) was routed to the surface, through a bubble-type flowmeter, and then through an additional fritted glass filter tube before returning to the tube in the second compartment for release back to the soil. Since the fritted tube on the surface could be switched in or out of the flow path, m in equation [1] could be measured under steady state conditions. This system worked satisfactorily in relatively nontransient situations such as ditch seepage measurements, but under crops following irrigation or rainfall the external resistance method was not satisfactory because the time required to adjust for the change in meter conductivity was large, compared to the transient changes of the soil water flow around the meter.

If one chooses to use the thermocouple flow transducer attachment on the flowmeter itself, it is not convenient to switch an external hydraulic resistance in and out of the system. However, equation [1] can be modified for use with the flowmeters shown in Fig. 1 and 4. If, for a given meter, one arbitrarily assigns n a value of 3, m is fixed as a function of soil water conductivity which, in turn, is related to matric potential. Obviously m must lie between 1 and 3. Previous experience with this type of system (Cary, 1968, 1970) suggests that m might be approximated as an exponential function of water tension,

$$m = a\,(\exp - b\tau) + 1 \qquad [2]$$

Table 1—Comparison of predicted and observed flows in three soils with two different porosity flowmeters

Meter	j	Flow: J predicted	Flow: J observed	τ cm H_2O
		mm/day	mm/day	
	Silt loam			
"Very fine" tube	3.0	3.6	4.0	86
	7.0	8.4	9.3	82
	3.0	3.6	3.3	86
	3.5	3.8	2.9	102
	3.2	3.2	3.3	125
	4.8	7.2	7.2	52
	4.6	6.8	6.0	55
"Fine" tube	9.8	9.3	9.3	41
	4.2	4.0	3.3	57
	3.5	3.3	3.3	20
	4.5	4.3	2.9	48
	7.2	6.8	7.2	48
	7.0	6.6	6.0	48
	Loamy sand			
"Very fine" tube	7.5	12.0	9.7	20
	7.2	8.6	9.2	45
"Fine" tube	9.5	9.0	9.7	40
	Silty clay			
"Very fine" tube	3.0	4.4	4.7	68
	2.7	4.2	4.3	58

where a and b are constants and τ is tension in cm of water. The constant a may be evaluated by combining equations [1] and [2] and solving at $\tau = 0$, using measured values of J and j under saturated conditions; or as a first approximation, J/j may be taken as the ratio of saturated soil conductivity to meter conductivity. One independent measurement of J and j with τ about 20 cm of water may then be used to find a numerical value for b.

The relation between meter flux and soil flux follows then as,

$$J = j \frac{1.9}{2 - a\,(\exp - b\tau)}. \qquad [3]$$

MEASUREMENTS OF SOIL WATER FLOW

The water flowmeter shown in Fig. 1 was tested in laboratory soil columns and in the field. In the laboratory tests, two meters were used. One had "very fine" porosity tubes with air entry values near 1 bar, and an effective cross-sectional conductivity of about 2 mm/day. The second meter was identical, except that the fritted tubes were of "fine" porosity, which increased the conductivity severalfold but lowered the air entry value to about ⅓ bar.

Steady state measurements of water flow through a large column with the meters installed were carried out in a system similar to that previously described (Cary, 1968). The results of these measurements are summarized in Table 1, which shows the flow through the meter, and the predicted soil water flux utilizing equation [3] with the correction factor curves shown in Fig. 6.

The correction factor curves in Fig. 6 were plotted by finding values for a and b as outlined in the previous section. The curves are for the meter with the "very fine" porosity tubes. The correction factor for the "fine" tube meter could be taken as a constant 0.95 because of its higher effective hydraulic conductivity. When using the meter in other soils of known texture, the curves in Fig. 6 can probably be used to approximate the correction factor for equation [3] without any additional information, assuming the soil has no unusual characteristics such as high sodium or a bulk density which could grossly affect its conductivity, and provided the soil water tension does not drop below the value at which the correction factor approaches 2. For lower soil water tensions, meters with more porous tubes should be used since a constant value of 0.95 for the correction factor will apply farther into the very wet range.

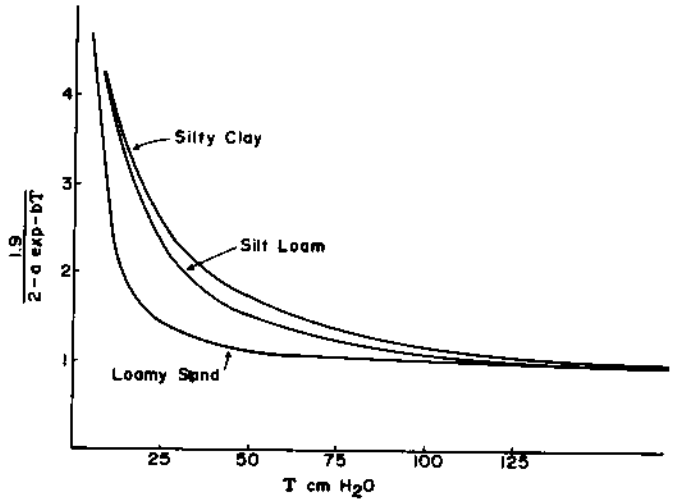

Fig. 6—Correction factors as a function of soil water tension to be used in equation [3] for the meter in Fig. 1 with "very fine" porosity tubes.

Two meters, of the type shown in Fig. 1 with "very fine" porous tubes, were tested under a fallow plot in the field. Water flow at the 1-m depth was measured through two flowmeters and compared to that calculated from measurements made in three neutron meter access tubes. The three access tubes were located in a line about 5.5 m (20 feet) apart, and the two flowmeters were offset about 0.914 m (3 feet) but were otherwise equidistant between the tubes. The soil was irrigated four times with sprinklers. Measurements of water flux through the meters are plotted as individual points in Fig. 7. Simultaneous measurements from the two meters are connected by a solid line to emphasize the variation between the two locations. Water flows through the meters were not corrected by the factor shown in Fig. 6 and equation [3] because the soil water tensions in the flowmeters were not measured directly. Tension was measured with tensiometers several feet from the flowmeters, but their readings following irrigation varied too much to be used with confidence in equation [3]. If the correction factor values were known, the soil water flow predicted by equation [3] would have been a little greater for 1 or 2 days following each irrigation. Because of the variation in tension and flow from point to point in the soil immediately following irrigation, it is recommended that the soil water pressure in each meter be measured through one of the nylon tubes leading to the soil surface.

Soil water flow from neutron meter measurements was calculated from changes in water content in the upper meter of soil corrected for the evaporation from the soil surface, which was estimated from previous studies on the site. The three simultaneous measurements calculated from neutron meter readings are also connected by a solid line

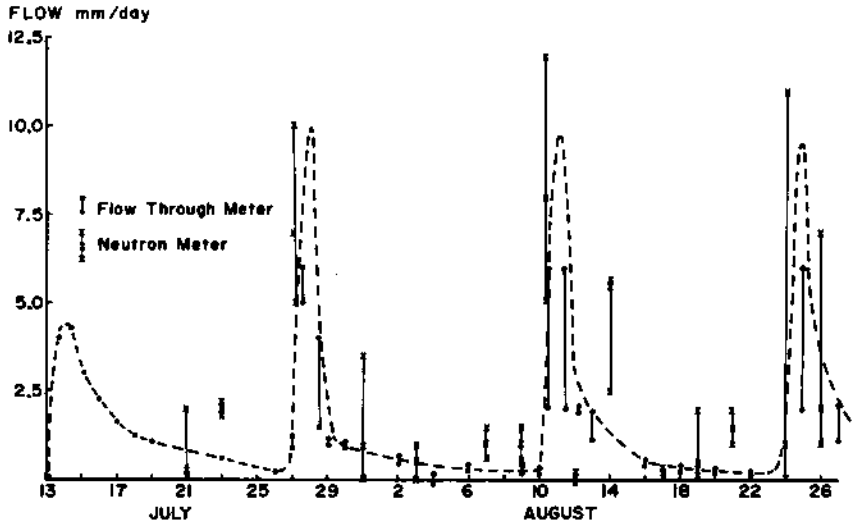

Fig. 7—Water flow downward past the 1-m depth under an irrigated fallow plot.

to emphasize their variation. The dotted line in Fig. 7 represents a best-guess curve for the actual soil water flow downward past the 1-m depth.

In general, one may conclude that the soil water flowmeter with the thermocouple output has a greater precision that calculations made from soil water content changes based on neutron meter readings when an increment of 1 m or more of soil is involved. The water flowmeter also requires much less time for measurement and data reduction.

SUMMARY

The soil water flowmeter shown in Fig. 1 equipped with the thermocouple transducer shown in Fig. 2 may be used in practical field situations. When used in soils with textures similar to those in Fig. 6, accuracy within about 25% of the true soil water flow can probably be achieved by interpolating between the curves. This would be without additional information on the soil's specific unsaturated hydraulic conductivity, assuming no unusual circumstances exist, such as high bulk density or sodium problems. If conditions are such that soil water tension occasionally becomes very low, meters with more porous tubes should be used to supplement measurements in this wet range. If the soil water flow is steady over a period of several hours, an external hydraulic resistance may be used to measure m and the true soil water flow calculated from equation [1] without recourse to the correction factor in equation [3].

The type of meter in Fig. 1 is best suited for flow measurements at relatively shallow depths in moist soils such as encountered in the normal root zone of field crops. If the soil above the meter is layered or has particularly distinct physical characteristics and structure, difficulty may be encountered in installing the unit without significantly disturbing the soil water flow lines above the meter after backfilling. Horizontal installation from an adjoining access pit should then be considered, possibly using the spring-loading method developed by Dirksen (1972).

Measuring soil water flow under saturated conditions should be relatively easy. A frame similar to that in Fig. 1 without any porous parts or hydraulic lines to the surface could be used to intercept flow and route it through the electrical readout unit shown in Fig. 2.

The meter shown in Fig. 4 has not been tested under field conditions. It may, after additional development, find its greatest use in measuring soil water flow at relatively deep depths. Presumably a soil core could be removed, the meter set in the bottom of the hole, and the core replaced. The meter has the advantage of being self-charging and the potential capability of operating at soil water matric potentials below —1 bar. Design innovations are needed to increase its sensitivity to at least 0.1 mm/day. The long-term stability of the meter has not been tested. Some difficulties have been encountered in maintaining a high electrical resistance between the thermocouple circuit and the soil solution passing through the fritted glass walls of the tube, but the preliminary laboratory performance of the unit has been encouraging and it may lead to a useful field instrument.

ACKNOWLEDGMENTS

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