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"Water Flux Measurements in Unsaturated Soils"

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WATER FLUX MEASUREMENTS IN UNSATURATED SOILS

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WATER FLUX MEASUREMENTS IN UNSATURATED SOILS

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Direct measurements of water fluxes in unsaturated soils are badly needed in hydrology and related disciplines, but are almost nonexistent. There are a number of reasons for this lack:

(1) Soil water fluxes are very small, for practical purposes ranging from about 10 to 0.01 cm^3/cm^2, day.

(2) Hydraulic conductivities vary over many orders of magnitude, depending on soil type and water content. They must either be matched by the measuring device or convergence/divergence must be determined for various soil and water conditions.

(3) Water in soils is under varying negative pressure heads, causing problems with air in hydraulic lines, contact resistances, etc.

(4) Disturbance of the soil during installation of measuring devices changes the original flow regime. This is hard to evaluate and must be minimized.

Various designs of fluxmeters are discussed and evaluated. Most requirements can be met by a spring-loaded device that intercepts the flow, feeds it through a fine-metering valve with micrometer handle, and distributes the water back into the soil. The total head loss across the device is made equal to that measured in adjacent soil. The water flux can be derived from a laboratory calibration of the valve.

INTRODUCTION

Water is rapidly becoming a scarce commodity, in terms of both quantity and quality. It is essential, therefore, that sound practices and criteria be developed to manage this natural resource. To help bring this about many scientists in hydrology and related fields are presently attempting to develop physical-mathematical models of the subsurface phase of the hydrologic cycle. The traditional description is that of precipitation either running off over land or infiltrating into the soil. The soil water either evaporates back into the atmosphere, or drains through the soil and recharges the groundwater or appears as base-flow. We need not only to describe these processes in well-studied areas, but must also be able to predict them in relatively unknown areas. In addition we must find ways in which the existing partition of the precipitation into surface water, groundwater, and water available for plant growth can be changed in the best interest of mankind. Before problems of water pollution, waste disposal, and soil erosion can be solved satisfactorily, we may need to know how much water is in the soil at any given time and position, where it is going, and how much time it will take to get there. To achieve this we must have capabilities for measuring these three aspects of soil water.

Soil water content can be measured by a number of methods, including gravimetric, neutron scattering, and gamma ray attenuation. The direction of flow is determined by potential gradients. Soil water potential or hydraulic head can be measured with piezometers or tensiometers. The third aspect concerns the rate of flow. Very little work has been done in this area. Soil water fluxes have been measured in a number of ways, but often under abnormal, idealized conditions or at great expense (e.g., lysimeters). Simple, inexpensive devices for measuring soil water fluxes directly are just now beginning to be developed and still leave much to be desired.

In this paper we will evaluate these existing fluxmeters and then propose a new version which has many advantages over the others.

Before doing so, the flow of water in soils must be described in more detail.

FLOW OF WATER IN SOILS

Flow of water in saturated soils is laminar and can be described by Darcy's law:

$$q = -K\nabla H \qquad H = h + z \qquad (1)$$

where

q = flux cm³/cm²-day
K = hydraulic conductivity, cm/day
H = total hydraulic head, cm water
h = matric pressure head, cm water
z = gravitational head, cm water

Hydraulic conductivities of saturated soils are usually constant in time and vary from more than 1000 cm/day to less than 1 cm/day depending on the type of soil.

Under negative pressure head (suction) soils become unsaturated. The cross-sectional area available for flow decreases rapidly with pressure head while the tortuosity of the flow paths increases. As a result, the hydraulic conductivity K is a function of water content θ or matric pressure head h. The $K(\theta)$ relationship is unique for a given soil ranging over many orders of magnitude from the saturated value to zero when the soil is dry.

For vertical flow Eq. (1) can be written as:

$$q_z = -K(dh/dz) - K \qquad (2)$$

The first term represents the matric component, the second the gravitational component. In the case of evaporation the matric component is directed upward. During the initial stages of infiltration both components are directed downward. For later stages of infiltration and for drainage the matric component can often be neglected. The flux is then about equal to the hydraulic conductivity.

Maximum fluxes in unsaturated soils seldom exceed a few cm^3/cm^2, day. In saturated soils fluxes can be higher. Since the device of Byrne et al.[1,2] can measure these higher fluxes we will set the maximum flux to be measured by our device at about 5 cm^3/cm^2, day. Obviously, the lower limit of fluxes is zero. A practical limit can be taken as 0.01 cm^3/cm^2, day, which is smaller than the error in precipitation data. As for the desired accuracy of the measured fluxes, ±10 percent is acceptable in most instances. At the lower fluxes, larger errors can often be tolerated, since relatively small volumes of water are involved.

It is easier to talk about a fluxmeter in terms of its overall resistance rather than conductance. The resistance is the ratio between the total head loss across the device and the flux: $R = \Delta H/q$ days. For comparison, a column of soil of length L and hydraulic conductivity K has a resistance $R = L/K$ days.

EXISTING FLUXMETERS

Byrne et al.[1,2] derived the flux of water in soils from the asymmetry that it produces in the temperature field generated by a centrally located line or point source of heat. They state that such a sensor can readily measure a flow rate of 8.64 cm^3/cm^2, day. This sensor is restricted to such very high fluxes because it depends on the convective heat transfer by the water that flows past the sensor.

Smaller water fluxes can be measured by a device that intercepts the flow through a porous membrane on one side, allows the rate of flow to be measured directly or indirectly, and then distributes the water back into the soil on the other side. Such a device was proposed by Ivie[3] and by Richards et al.[4] They used a drop counter to measure the flow rate through the instrument.

The measured water flux will generally differ from the flux in the surrounding soil. This is caused, first, by the disturbance of the soil during installation. This is hard to evaluate without actual calibration in situ. The device must be so designed that this effect is kept to a minimum. This aspect has not received any attention in previous work. The second reason is that the effective conductivity of the device is usually different from that of the soil. If it is greater the flow lines will converge; if it is smaller they will diverge.

Cary[5] determined the flow rate through the meter by measuring the total head loss across a saturated porous plate of known conductivity, sandwiched between two outer porous filter plates. The total thickness of the meter was about 5 cm. In one version the ratio of the flux through the meter and that through the soil varied between f = 0.8 and f = 2.3; in another version it varied from f = 1.2 to f = 3.7. Cary used exceptionally high matric pressure head gradients and the maximum hydraulic conductivity was only 0.11 cm/day. He states that the effective conductivity of the transducer increased 2.5-fold, while the hydraulic conductivity of the soil decreased almost 20-fold. However, over half of the pressure head range the hydraulic conductivity decreased by a factor of 6.5 while the effective conductivity increased by a factor of 3.1.

Cary[6] also tested a device consisting of one porous disc mounted in the middle of a metal cylinder. The flux was determined by measuring the total head loss between two holes drilled through the plate. The cylinder had two purposes. The first was to make the soil with its changing hydraulic conductivity part of the meter so that the effective conductivity of the device changed with that of the soil. The second was to make the unit more sensitive to thermally induced water vapor flow. The transducer responded reasonably well to water flow associated with temperature differences. As for the first objective Cary found that he could predict the flux quite well with the help of an empirical "flow factor" which relates the flux through the soil to the total head loss between the holes for a particular soil. However, the ratio between the predicted flux and the observed flux which varies between 0.71 and 2.54, is really a measure of the deviation of the experimental data from a smooth curve, rather than the ratio f between the flux through the measuring device and that through the soil. The "flow factor" for the silty clay changed by a factor of almost 4 over the suction range of 50 to 200 cm water. Cary pointed out that this can be improved upon by increasing the cylinder length or the conductivity of the ceramic plate.

To increase the accuracy of existing fluxmeters, the following aspects particularly need consideration:

(1) Minimize convergence or divergence,

(2) Extend range of water fluxes and soil types,

(3) Reduce or preferably eliminate very tedious calibration procedures,

(4) Minimize disturbance of soil during installation and its effect on original flow pattern.

This paper shows that improvements are possible in all four categories if the total head loss is measured across a variable hydraulic resistance in the form of a fine metering valve with micrometer dial and the thickness of the flux meter is kept relatively large. First, however, the two basic types of flux meters discussed above will be analyzed in terms of their potential range of fluxes and accuracy.

FIXED HYDRAULIC RESISTANCE

A fluxmeter with fixed hydraulic resistance cannot follow the hydraulic resistance of the soil which is changing continually. Divergence can vary from none to infinite. In the latter case all flow goes around the device, which is then reduced to a (disturbed) potential gradient meter from which the flux cannot be derived. The possible degree of convergence is limited, and depends on the geometry of the device. The smaller the thickness to diameter ratio, the less the maximum possible convergence. The problem is similar to that for a heat flux meter. Philip[7] showed that for a thin circular plate with an effective conductivity K_m, diameter D, and thickness T, buried in soil with conductivity K_s, the ratio f of the flux through the meter and that through the soil is approximately equal to:

$$f = \frac{q_{meter}}{q_{soil}} = \left[1 - 1.92\,\frac{T}{D}\left(1 - \frac{K_s}{K_m}\right)\right]^{-1} \qquad (3)$$

In Fig. 1 the flux ratio f is plotted against R_m/R_s, which is equal to K_s/K_m, for three values of T/D. It shows that when T/D = 1/20, the flux ratio f varies between 1.10 and 0.90 over the range $0 < R_m/R_s < 2.2$. When T/D = 1/10, this range is reduced to $0.53 < R_m/R_s < 1.56$ and when T/D = 1/5, the range is only $0.77 < R_m/R_s < 1.28$. Thus, when T/D = 1/20 the flux rate can be measured

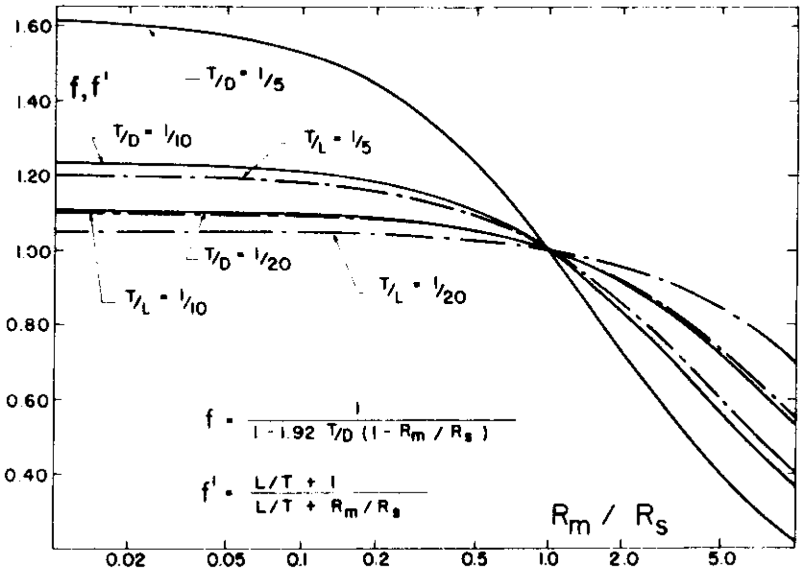

Fig. 1. Ratio f for fixed hydraulic resistance (_____) and ratio f' for fixed hydraulic resistance with cylinder (_____ . _____) vs R_m/R_s for T/D, T/L = 1/5, 1/10 and 1/20.

with a maximum error of 10 percent (provided the convergence factor is the largest source of error) as long as the resistance of the meter is no more than about twice the resistance of an equally thick column of surrounding soil. When T/D = 1/10, the maximum error is about 25 percent over the same range. There are limits to how thin a fluxmeter can be built, how small a resistance can be and still allow an accurate pressure measurement, etc. These considerations will be discussed later.

FIXED HYDRAULIC RESISTANCE WITH CYLINDER

The convergence or divergence of a fluxmeter with a fixed hydraulic resistance can be decreased by including soil in the overall conductive path of the meter. Cary[6] mounted a single porous plate permanently in the middle of a thin-walled metal cylinder. In this configuration the chance for poor contact at the bottom of the plate is rather large and the soil above the plate is necessarily disturbed.

The porous plate could just as well be placed snugly on top or bottom of the cylinder. There is no need for a sealed fit since in unsaturated soil any space between cylinder and porous plate will drain empty at small suctions. The assumption that the hydraulic conductivity of the soil inside the cylinder is equal to that outside will be most valid under steady state conditions, and when the soil inside the cylinder is undisturbed. Essentially undisturbed soil can be obtained by first pushing the cylinder all the way in the soil and then placing the assembly on top of it.

Under transient conditions the most critical problem for any of these fluxmeters is to correctly measure fast moving wetting fronts (drying occurs much more gradually). The error in the amount of water involved during such an event could easily exceed the total amount of flow for several months of a drier period. It is likely that the fluxmeter would do much better under such conditions with the porous plate at the bottom of the cylinder, since the water

would tend to accumulate inside the cylinder above the porous plate and increase the overall effective conductivity of the meter. The cylinder could even be prefilled with a slightly coarser textured soil. This would increase the conductivity at the wet end and decrease it at the dry end and thus counteract convergence and divergence. This configuration would be the easiest to install and most favorable to prevent contact resistances.

If a porous plate of thickness T and resistance R_m is placed on top of a cylinder of length L in a soil with hydraulic conductivity K_s, then since $q = \Delta H/R$:

$$f = \left(\frac{\Delta H_m + \Delta H_{cyl}}{\Delta H_{soil}}\right)\left(\frac{R_{soil}}{R_m + R_{cyl}}\right) \quad (4)$$

If we assume that the hydraulic conductivity of the soil inside the cylinder equals K_s and relate the resistance of the soil to the thickness of the porous plate, that is $R_s = T/K_s$, then:

$$f' = \frac{R_{soil}}{R_m + R_{cyl}} = \frac{(L+T)/K_s}{R_m + L/K_s} = \frac{L/T + 1}{L/T + R_m/R_s} \quad (5)$$

In Fig. 1 f' is plotted against R_m/R_s for T/L = 1/5, 1/10 and 1/20. The reduced convergence and divergence with the cylinder is apparent. The curve of f' vs R_m/R_s for T/L = 1/10 virtually coincides with the f vs R_m/R_s curve for T/D = 1/20. To obtain f we must multiply f' by $\alpha = (\Delta H_m + \Delta H_{cyl})/\Delta H_{soil}$, which is dependent on the ratio D/(L + T) as well as R_m/R_s. We are not aware of an analytical or numerical solution of the problem for $D/L \geq 1$, which would give this information. For convergence $\alpha < 1$ and $f' > 1$, for divergence $\alpha > 1$ and $f' < 1$. Thus the deviations of f from unity are even smaller than those of f'.

VARIABLE HYDRAULIC RESISTANCE

Convergence or divergence can be prevented by matching the hydraulic resistance of fluxmeters with the continually changing resistance of the soil. This can be done easily by replacing the center porous plate of Cary's[5] three plate model by a solid barrier and conducting the flow through a fine-metering valve with micrometer handle. The setting of this valve must then be changed from time to time, depending on the rate of change of the flux and the desired accuracy, such that the total head loss across the fluxmeter remains equal to that across an equal length of undisturbed soil adjacent to the fluxmeter. For instance, during drainage under gravitational conditions, the resistance of the soil increases inversely proportional to the flux while the total head gradient in the soil remains unity. Under these conditions the resistance of the valve must be changed inversely proportional to the flux to keep the total head loss across the valve equal to the thickness of the meter. The flux can then be obtained from a calibration curve of the fine-metering valve relating flow rate per unit time per total head loss to setting of the micrometer dial. The total head loss across the valve must be corrected for the total head loss across the two outer filters, if this is significant.

The pressure drop in the soil can be measured with tensiometers located in the plane of top and bottom filter plates. They should be close enough to be representative of the conditions near the fluxmeter and far enough so that they are not influenced by convergence or divergence of flow when the resistances are not matched. Cary[5] found this to be true at distances greater than twice the diameter of the device.

There are many advantages to having a variable hydraulic resistance. By matching the resistance of the fluxmeter with that of the soil one creates an essentially uniform flow system, without divergence or convergence. Once the minimum and maximum soil hydraulic conductivity that can be matched have been determined, the meter should measure the correct flux within this range no matter what soil it is in. This reduces the need for calibration to a minimum. Calibration of the valve can be done in the laboratory, is simple and consumes relatively little time. It may be that after some experience has been gained, fluxmeters can be assembled that will measure correct soil water fluxes satisfactorily for any particular situation without further calibration.

Another advantage is that the range of fluxes is much greater. The available fine metering valves can cover fluxes from 0.01 to 10 cm^3/cm^2, day. There is some flexibility by choice of cross-sectional area of the meter and the type of valve. The Nupro "S" series fine metering valve and vernier handle (Nuclear Products Company, Cleveland, Ohio[8]) can measure from about 0.2 to 100 cm^3 per cm water head loss per day. The Gilmont M 7100 Micrometer Capillary Valve (Cole-Parmer Instrument & Equipment Co., Chicago, Ill.) covers a range of approximately 10 to 500 cm^3/cm water, day. Its range of 15 to 175 cm^3/cm water, day has a semi-logarithmic relationship between flow rate and dial setting which facilitates calibration appreciably. The range of soil water fluxes is limited on the low side by the accuracy of the valve calibrations for which better procedures still need to be worked out. The high fluxes are limited by the conductivity of the outside filters.

Fine metering valves can be easily flushed. The resistance of a porous plate tends to increase with time due to desaturation, plugging by microbes, etc. They cannot be restored or recalibrated that easily *in situ*. This advantage is somewhat offset by the greater susceptibility of the needle valves to any foreign matter, air, etc.

A disadvantage of the valves is that they are more expensive than porous ceramic plates. But this may be no longer true if the porous plates need machining. Also, a porous ceramic plate buried in the ground is kept at fairly constant temperature. Since the pressure drop across the valves is proportional to the viscosity of water it will be advantageous to keep them also at constant temperature. This is not easy to do in the field.

A NEW FLUXMETER

Probably the most important advantage of a variable resistance is that it makes the thickness of a fluxmeter of minor importance. A thicker meter is preferred because: (a) it has room for a number of very desirable features and (b) the greater pressure drop across the device allows for less expensive and/or more accurate pressure measurements. Figure 2 gives a radial cross section of a new fluxmeter about 5.5 cm thick that has been used with a fine metering valve.

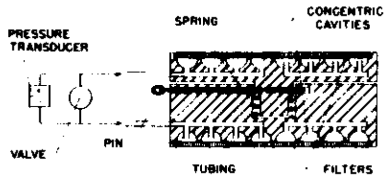

Fig. 2. Soil water flow rate meter. Radial cross section through plane of hydraulic lines. Right hand side of concentric cavities has outlet (not shown) used only during flushing.

Its features will be discussed in comparison with those of thin models.

All fluxmeters discussed so far can be installed only from the same direction in which the flux is to be measured. As a result, at least one of the filters is in contact with a column of disturbed soil. A thin device cannot be installed perpendicular to the direction of flow without risking large contact resistances (large pore space that drains at small suctions). By incorporating the spring and pin as described by Richards[9], the flow rate meter in Fig. 2 can be inserted perpendicular to the direction of flow. When the pin is pulled the spring pushes both filters against undisturbed soil. This increases greatly the reliability of the flux measurements. Contact may possibly be improved still further by covering both filters within a thin layer of soil before putting it in place.

One of the biggest obstacles to keeping the fluxmeters thin is presented by the outer filters. Besides being thin they must be strong, have a high permeability and a low air entry value. Obviously these properties conflict with each other. Filters can actually be too thin. When filters of 0.004 in. thickness with otherwise satisfactory properties were used, the meter was full of air in a short time. The reason is that an air bubble inside the meter with a diameter larger than the air-filled soil pores has a lower pressure than the soil atmosphere, Peck.[10] As a result, air diffuses through the liquid phase to the bubble, making it even larger. This, in turn, reduces the pressure, increases the rate of diffusion, etc. The rate of diffusion is inversely proportional to the square of the thickness of the filters.

A thicker fluxmeter has room for thicker filters and can tolerate larger resistances because of the larger corresponding total head loss in the soil. Micro-porous porcelain filter discs (Selas Flotronics, Spring House, Pa.) have a range of permeabilities of about 120 cm/day to 2 cm/day with air entry values from about 70 cm water to 1000 cm water, respectively. When adequately supported, lower permeability discs of 1/16-in. thickness were found to be satisfactory in terms of strength and the air diffusion problem, but 1/8-in. thickness is preferable and mandatory for the high permeability discs. Since, in general, in soils with high saturated conductivities fluxes of 0.01 cm^3/cm^2, day occur at still rather low suctions, while soils with still appreciable fluxes at high suctions have low saturated conductivities, the above ranges of filter disc permeabilities and air entry values are expected to provide enough flexibility to meet most conditions.

Air in the cavities is no problem as long as its rate of growth is negligible with respect to the measured flux and it can be kept away from the pressure measurement lines. In the thicker models this can be done by making the concentric cavities somewhat deeper and suspending short pieces of nylon tubing down from the pressure line into the cavities at the bottom. Similar short pieces of tubing are used at the top to facilitate flushing out any air accumulated against the top filter. Such a system worked for three months without flushing and showed no sign of air problems. The concentric cavities facilitate flushing and the ribs provide support for the filters. In thin models with a ceramic center plate the filters cannot be supported in this fashion and must be much stronger. In thick models the connections can be made much sturdier with large openings that facilitate flushing.

In thick models the filters can be sealed with "O" rings. This is more reliable than epoxy, which tends to snap loose or silicone rubber that tends to decrease the air entry value of ceramic. "O" rings allow easy replacement of filters that are broken or plugged. They also make it possible to convert fluxmeters for use in different soils with minimum effort and maximum flexibility. The resistance of the filters should be kept as high as possible so that the fluxmeter can be flushed out with the least disturbance of the surrounding soil. It may take days to obtain the original flux back in a dry soil that has been wetted up around the fluxmeter during flushing. One disadvantage of "O" rings is that the effective cross sectional area of the filters is smaller.

For the same flux the total head loss across a fluxmeter that is matched with the surrounding soil is proportional to its thickness. Under gravitational conditions it is equal to the thickness. A total head differential of 0.5 cm water can be measured accurately only with a differential pressure transducer, but 5 cm water may be measured reasonably accurately with a manometer. Manometers do not require electricity (a distinct advantage in the field) and are much cheaper than pressure transducers. Cost alone can be the overriding reason to use thick fluxmeters with manometers. However, the volumetric displacement per unit total head differential is much larger for manometers than for pressure transducers. As a result, pressure transducers follow transients much better and they can also be monitored easily. The higher total head loss across thick fluxmeters allow unknown contact resistances to be somewhat higher, before they affect the measured flow rate appreciably.

The one great disadvantage of thick fluxmeters is their much greater susceptibility to convergence or divergence. If the flux has changed appreciably between readings they will be much more in error than thin models. Usually fluxes in soils change gradually enough that they can be followed satisfactorily, but a fast moving wet front may not be measured adequately.

The performance of the new fluxmeter in Fig. 2 is illustrated by the data in the table below, which shows measured fluxes for various total head losses across the valve obtained by changing its setting. The meter was placed in a sandy loam column, 11-1/2 inches diameter and 13 inches long, through which a steady flux of 0.109 cm^3/cm^2, day was maintained under approximately unit gradient.

Interpolation of these data shows that the correct flux would have been measured at $\Delta H = 5.46$ cm water. The total head loss across an equivalent length of soil was equal to that within the accuracy of the measurements.

CALIBRATION IN SANDY LOAM COLUMN
Steady flow q = 0.109 cm/day
$\Delta H_{soil} \cong 5.5$ cm water

ΔH_{valve} cm water	Flux cm^3/cm^2, day
3.05	0.190
4.05	0.164
5.28	0.114
6.85	0.055

These data show that it is possible to match the resistance of the fine metering valve with that of the soil and measure the correct flow rate.

Laboratory calibrations of fluxmeters such as in Fig. 2 are still in progress and will soon be made in the field. Data such as those in the table give hope that these meters can be placed in any soil and will give correct fluxes without additional calibration as long as their resistance is accurately matched with that in the soil.

The range of fluxes that can be measured depends on the properties of the filters and these must be chosen carefully. To do so one must have some idea about the highest fluxes that can be expected and the suctions at which the fluxes become negligible. If pressure head gradients differ appreciably from unity this can be taken into account. In general, it is easier to measure fluxes accurately at higher hydraulic gradients.

If there are unknown contact resistances or if the soil has been disturbed too much during installation, the measured fluxes will not be the same as those in the undisturbed soil. Whatever fluxmeter one designs, this error can only be determined by calibration *in situ*. One calibration procedure for vertical flows is to wet up the soil over a large enough area to ensure one-dimensional flow over the meter. By covering the area with a plastic sheet to prevent precipitation and evaporation, the measured flux should be equal to the rate of loss of water in the soil profile above the top surface of the fluxmeter. This can be measured with neutron scattering equipment or by gravimetric sampling.

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Field Test of Soil Water Flux Meters

Christiaan Dirksen

SOIL water fluxes in a draining soil profile were measured with flux meters featuring variable hydraulic resistances. As the hydraulic conductivity of the soil changes, the meter resistance is adjusted such that the overall hydraulic head loss across the meter matches that measured with tensiometers in undisturbed soil nearby. The soil water flux is then equal to that through the meter and is derived from the calibration of the resistance. If this match is not quite perfect, the remaining small amount of divergence or convergence of flow is calculated with an empirical relationship, independent of the magnitude of the flux and the hydraulic properties of the soil. The soil water fluxes were measured in essentially undisturbed soil, since the meters were installed from a horizontal direction. Such installation is possible by using a compression spring that pushes thin filter plates against the top and bottom of undisturbed soil surfaces excavated to a certain size with a specially designed apparatus. A slanted pin used to constrain the spring permits the meter to be installed and retrieved repeatedly. Two flux meters of different sizes and with different hydraulic resistances were tested side by side in a field plot and gave consistent, satisfactory results.

INTRODUCTION

Most studies concerning the hydrologic water balance of a field require the water flux to be known in the soil or the atmosphere at one or more locations. Until a few years ago, devices other than lysimeters were not available for directly measuring soil water flux. Indirect techniques lacked accurate methods for measuring soil water conductivity or required elaborate atmospheric evapotranspirational measurements. As a consequence, such fluxes as deep percolation from irrigated fields and upward flow from a shallow water table have often been neglected.

Recent developments on soil water flux meters were reviewed and evaluated by Dirksen (1972). Since then Cary (1973) has used the asymmetry of the temperature around a heater wire caused by convective heat transport to measure the flow rate. Cary's meters can only be installed in the bottom of a pit and, therefore, like most lysimeters, can only measure the water flux through disturbed soil. The vacuum extractors proposed by Duke and Haise (1973) for measuring deep percolation do not have this drawback. However, it is doubtful whether they can be used to measure upward flow and they should not be used close to the surface, since they do not return the intercepted flow to the soil.

For the last several years I have been developing a soil water flux meter that has the following important features:

1 It has a variable hydraulic resistance that can be matched to the varying hydraulic resistance of the soil, thus eliminating divergence or convergence of flow. This eliminates the need for calibration for every new situation.

2 It can be installed perpendicular to the direction of flow so that the flux can be measured through undisturbed soil.

3 It returns the intercepted flow to the soil.

Design criteria and other considerations of this instrument have been described (Dirksen 1974). Laboratory tests (Dirksen 1972) showed that soil water fluxes ranging from 0.11 cm/day to 1.43 cm/day were measured with less than 10 percent error. This paper describes the procedures and results of a field test and gives the equations describing the operation of the flux meters.

THEORY

When a flux meter is placed in unsaturated soil to measure the volumetric soil water flux, q_s (cm^3/cm^2, day) the flux, q_m, actually intercepted by the meter is described by

$$q_m = \kappa \, \Delta H_m / L, \quad \ldots\ldots\ldots\ldots [1]$$

where κ (cm/day) is the equivalent hydraulic conductivity of the meter, ΔH_m is the total hydraulic head loss (cm water) across the meter, and L is the height of the meter. The total head H is the sum of the pressure head, h, and the gravitational head, z,

$$H = h + z. \quad \ldots\ldots\ldots\ldots [2]$$

The flux of water in unsaturated soil is governed by Darcy's Law, which for the present purpose can be written as

$$q_s = k[h] \, \Delta H_s / L, \quad \ldots\ldots\ldots [3]$$

where ΔH_s is the total head loss across a length of soil equal to the height of the meter, and the brackets indicate the dependence of the soil hydraulic conductivity k on the pressure head h.

The dependence of k on h constitutes a major problem for successful soil water flux measurements. If κ can be adjusted with changes in K[h] such that ΔH_m remains equal to ΔH_s, then ideally the flow system is never disturbed. This situation is represented by

$$\kappa = k[h], \Delta H_m = \Delta H_s, q_m = q_s. \quad \ldots\ldots\ldots [4]$$

However, if k[h] increases with respect to κ, flow will diverge from the meter and ΔH_m will increase until the disturbed flow through and around the meter is again adjusted to the undisturbed flow in the soil nearby. Then

$$\kappa < k[h], \Delta H_m > \Delta H_s, q_m < q_s. \quad \ldots\ldots\ldots [5]$$

Conversely, convergence of flow is characterized by

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$$\kappa > k[h], \Delta H_m < \Delta H_s, q_m > q_s. \quad [6]$$

Analytical or numerical solutions are not available to determine the exact amount of convergence or divergence of flow. This must be determined experimentally for every new situation. It is much easier to vary κ with k[h] such that q_m equals q_s. This can be done by leading the flow through the meter through a variable hydraulic resistance, such as a fine-metering valve, and adjusting this resistance until $\Delta H_m = \Delta H_s$. If this resistance is calibrated, the flux through the meter, and thus the soil water flux, can be determined at the same time.

If the flow through the meter is led through a fine-metering valve, then the flow rate, Q_m (cm^3/day), through the meter is

$$Q_m = \text{Cal}[S]\ \Delta H_v \quad [7]$$

where Cal [S] is a calibration factor (cm^3/cm, day) of the valve, which depends on its setting, and ΔH_v is the total head loss across the valve. Any difference between ΔH_v and ΔH_m is due to additional resistances in the flow path through the meter such as filter plates and contact resistances. This difference should be minimized. As long as the cross-sectional area, A, and the height, L, of the meter remain the same, equation [7] can be written conveniently as

$$Q_m/A = q_m = K[S]\ \Delta H_v/L \quad [8]$$

where

$$K[S] = \text{Cal}[S]\ L/A. \quad [9]$$

Comparison of equations [3] and [8] shows that whenever the fine-metering valve is set such that $\Delta H_m = \Delta H_s$, and thus $q_m = q_s$, then

$$K[S] = k[h]\ \Delta H_s/\Delta H_v. \quad [10]$$

Thus, at any time, the perfect match between meter and soil will be at the valve setting for which K[S] is equal to the hydraulic conductivity of the soil, corrected for the ratio $\Delta H_s/\Delta H_v$.

If, for the flux meters described in this paper, ΔH_s and ΔH_m are not matched perfectly, the remaining convergence or divergence of flow can be calculated from

$$\frac{q_m - q_s}{q_s} = -1.7\ \frac{\Delta H_m - \Delta H_s}{\Delta H_s}. \quad [11]$$

This relationship was found empirically (Dirksen 1972, Fig. 3) for a 13-fold range in fluxes, upward as well as downward, in two different soils for values of $(\Delta H_m - \Delta H_s)/\Delta H_s$ between -0.54 and +0.31. Equation [11] should be valid within a limited range of this ratio, probably not extending much beyond the indicated values. The numerical coefficient in equation [11] is a ratio between two dimensionless quantities and will depend somewhat on the diameter-to-height ratio of the flux meter. Equation [11] can be solved for q_s:

$$q_s = q_m/(2.7 - 1.7\ \Delta H_m/\Delta H_s). \quad [12]$$

This equation makes use of the flux meter much more practical. Rather than having to match the meter to the soil at all times, it only needs to stay within the limits of the total head ratio for which equation [11] is valid.

The soil water flux, q_s, can be derived without measuring ΔH_s, if values of ΔH_m and q_m can be obtained for two different values of K[S] for which equation [11] is valid. The first set ΔH_{m1} and q_{m1} can be substituted into equation [12] and used to eliminate ΔH_s from equation [12] written for the second set ΔH_{m2} and q_{m2}. The result is

$$q_s = \frac{q_{m2}\ \Delta H_{m1} - q_{m1}\ \Delta H_{m2}}{2.7\ (\Delta H_{m1} - \Delta H_{m2})} \quad [13]$$

The corresponding value of ΔH_s can be calculated with equation [12].

Finally, once q_s and ΔH_s are obtained by equations [4], [12] or [13], the hydraulic conductivity of the soil can be calculated directly from equation [3]:

$$k[h] = q_s L/\Delta H_s. \quad [14]$$

Thus the soil water flux meter is at the same time a "soil hydraulic conductivity meter".

EXPERIMENTAL

Two flux meters were installed, side by side, about 2 feet apart, in a mulched plot at the University of Wisconsin Arboretum, Madison, Wisconsin, in the summer of 1972. They were placed about 60 cm deep in a layer of sandy clay loam, consisting of 20 percent clay, 26 percent silt and 54 percent sand. The soil profile is described by Van Rooyen and Hole (1971, p. 38). The flux meters were actually between soil layers containing as much as 40.5 percent clay, which caused total head gradients to be generally less than unity. The latter part of the summer and the fall of 1972 were so wet that the soil pit used to install and operate the flux meters was inundated several times by ground water.

Fig. 1 is a schematic radial cross section of a cylindrical flux meter. The meter contains two thin filter plates for intercepting or redistributing the soil water. The compression spring forces the filter plates apart, but is constrained during installation and retrieval by a slanted pin. The pin and shaft are a convenient handle. By turning the wing nut, the filter plates can be eased gradually against parallel, undisturbed soil surfaces. This permits a strong spring to be used without breaking the filter plates. Also, the slanted-pin makes it possible to compress the spring again and remove the meter from the access hole. The filter plates are supported by ribs that form concentric cavities. These cavities and the short sections of tubing at the top facilitate flushing out air bubbles. The sections of tubing at the bottom keep air bubbles away from hydraulic measuring lines.

Fig. 2 is a schematic diagram of the measuring apparatus and hydraulic switching valves used with the flux meter. The common ports (C,C) of the two 5-way switching valves are connected to opposite sides of a differential pressure transducer. Opposite sides of each concentric cavity are connected to different switching valves (TV, TC, BV, BC). One set of these connections (TV, BV) is permanently shunted by a fine-metering valve. One port of each valve is connected to a tensiometer (TT, BT) and the two remaining ports are connected together (Z,Z). The flow intercepted by the filter plate is led through the fine-metering valve. This valve has a micrometer handle and is calibrated so that the flow rate through it can be determined according to equations [7] or [8]. The valve is adjusted, so that the total hydraulic head loss across the meter remains approximately equal to that measured with the tensiometers over the same distance in undisturbed soil nearby. The soil water flux can then be derived with equations [4], [12], or [13]. The (Z,Z) configuration of the

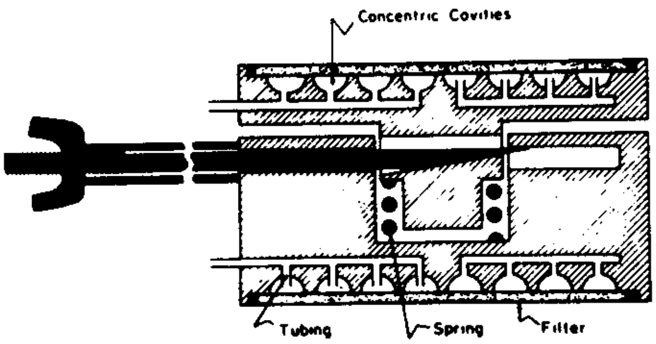

FIG. 1 Cross section of cylindrical soil water flux meter.

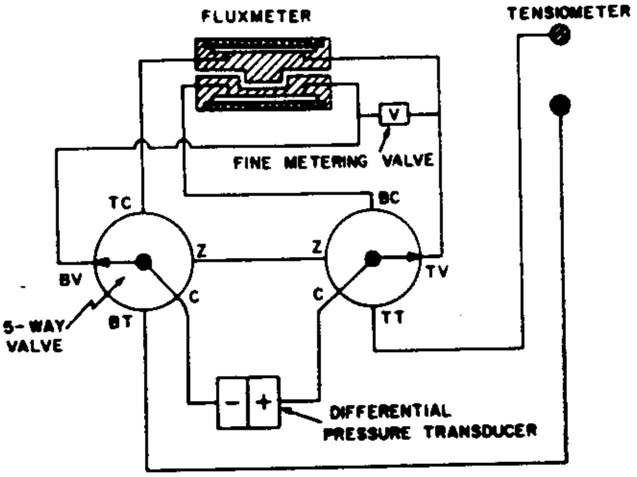

FIG. 2 Diagram of hydraulic system for soil water flux meter.

switching valves is used to check and adjust the zero of the pressure transducer. The hydraulic head loss across the fine-metering valve can be measured with both a positive deflection (TV-BV) and a negative deflection (BC-TC) of the pressure tranducer. Averaging these two values increases the reliability and accuracy of the measurements. The hydraulic lines and cavities can be checked for the presence of air by measuring through the cavities, TV-TC and BC-BV. If they do not read ZERO, the cavities need to be flushed by temporarily disconnecting the pressure transducer and connecting a water source and sink to the common ports C. Finally, the head differential between the two tensiometers can be measured with the same pressure transducer by switching to TT-BT. This allows accurate matching of the meter with the surrounding soil. Fig. 3 shows a flux meter connected to the differential pressure transducer, fine-metering valve, and switching valves, just before it was installed in the field.

Access holes for the meters were dug with a specially designed apparatus, shown in Fig. 4. First, a rectangular guide is driven into the vertical wall of a soil pit with two sliding weights or a hydraulic jack, and the soil inside is removed by hand. A plate is bolted to the guide and stakes or braces are used to stabilize the guide. A rotating cutter is then gradually driven into the soil beyond the guide by turning the hand wheel. The cutter has six blades that protrude beyond the end of a shaft. The shaft has extended surfaces that slide snugly inside the guide. The cutter is driven by a variable-speed electric motor via a slip coupling and a chain and sprockets located inside the shaft. When the end of the shaft underneath the cutter hits the end of the excavated hole, the cutter is removed from the hole, the hole is cleaned out, and the cutter is used upside down until the shaft again hits the end of the excavated hole, this time at the top. The procedure is repeated cutting about 2 inches per stroke alternately from the top and from the bottom. The cutting blades are slightly higher than half the excavated hole to ensure a clean cut. When the soil is not too wet, the excavated loose soil is easily removed with a vacuum cleaner. When the soil is wet enough to stick to the blades, one must take care to prevent the loose soil from gouging the lower excavated surface. This may require removing the cutter from the guide an additional time or two during a cycle to clean the blades.

Fig. 5 shows a plaster of Paris cast of an excavated hole. The top surface is flat and smooth. The flux meters are the same width as the excavated holes, but the height of the completely compressed meters is about 3 mm smaller. The alternating operation of the cutter is apparent from the demarcation in the cast. The final two cuts can easily be made to blend into each other by running an adjustable nut on the shaft of the hand wheel against a stop.

Before the plate and guide are removed from the soil, a steel frame (partially visible in Fig. 4) is bolted to the plate for drilling the access holes for the tensiometers. This frame contains two parallel guides located exactly at the depths of the top and bottom filter plates of the flux meter, about 25 cm away from the center of the meter. The guides closely fit rather large diameter rods (1.91 cm) to assure that the holes remain parallel. First, 1.91 cm diameter holes are drilled up to the location of the tensiometers, about 35 cm into the soil. Holes slightly smaller in diameter than the tensiometers are then drilled beyond that point over the length of the tensiometers. Both drills are visible in

FIG. 3 Soil water flux meter just before installation.

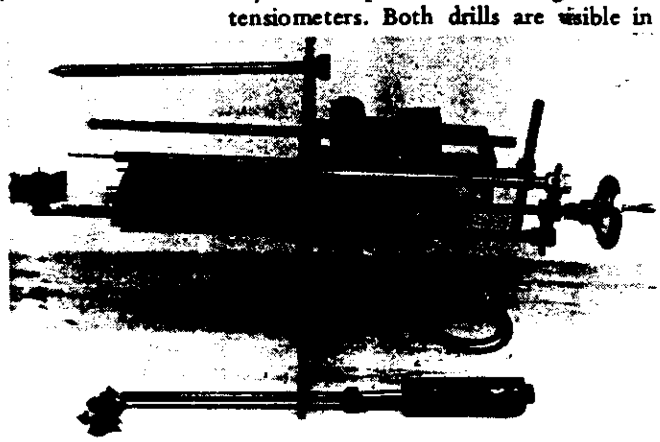

FIG. 4 Apparatus for digging access holes for soil water flux meters.

FIG. 5 Plaster of Paris cast of access hole obtained with digging apparatus.

Fig. 4. The tensiometers used here were about 8 cm long and 0.5 cm thick.

The access holes are sealed off with insulation material, but are not refilled with soil, since it is virtually impossible to repack the soil consistently. By leaving the access holes open, one should eventually gain enough information to determine how much the flux should be corrected, if any. A flux meter can be installed and retrieved repeatedly at the same location or one flux meter can be used at different locations. Finally, the access hole can conveniently be used as a relatively constant temperature space for the fine-metering valve, pressure transducer and other small temperature-sensitive measuring devices.

The two meters used had total cross-sectional areas of 90.66 cm^2 and 53.95 cm^2, respectively. Both meters were 6.35 cm high when in place, expanded against the undisturbed soil surfaces. The ends of the meters were placed about 45 cm in from the vertical wall of the pit. The large meter was used with an 18-turn Micromite fine-metering valve (Hoke, Inc., Cresskill, N. J.)*; the small meter was used with a 7-turn S-series fine-metering valve (Nupro Co., Cleveland, Ohio). Hydraulic head differentials were measured with PACE model P7D ± 0.1 psi differential pressure transducers, driven by Model CD 10 carrier-demodulators (Whittaker Corp., Instrument Systems Division, Chatsworth, CA.). The voltage output was measured and recorded with portable single-channel recorders (Model T 171 B, Esterline Angus, Indianapolis, Indiana). The recorders were operated directly from a 12-volt car battery, while the carrier-demodulators were operated with a vibrator inverter (Terado Model 50-197, St. Paul, Minnesota), which in turn operated from a 12-volt car battery. This system consumed very little power and ran several days from two 12-volt batteries. By working with three batteries and by substituting a charged battery every 1 to 2 days, the system could be run indefinitely.

*Trade and company names are included for the reader's benefit and do not imply endorsement or preferential treatment of the products listed by the U. S. Department of Agriculture.

The flux meters described here can measure soil water fluxes in the tensiometer range of pressure heads. The maximum flux that can be measured is estimated at several cm/day and is limited by the permeability of the filter plates and any head losses across remaining contact resistances. Minimum fluxes are determined mainly by the calibration of the fine-metering valves. It is impractical, because of the time and effort involved, to maintain reliable calibration values for fluxes smaller than 0.05 cm/day. For this reason, attempts are presently being made to determine the flux without constricting the flow.

RESULTS

The large meter was installed on July 20. The summer was very dry until July 17, and very wet thereafter. Until July 28, this meter measured upward flows smaller than the calibration range of the valves. On July 28, the flow direction reversed after a rain of about 1.8 cm and a total rainfall, since July 17, of 8.6 cm. The small meter was installed on July 27 and measured downward flows only. A flow rate of about 0.1 cm/day was obtained soon after installation. No further measurements were made until August 15. During that time interval, total additional rainfall was 8.7 cm, 2.3 of which was measured on the morning of August 15. No further rain fell until August 24, when a storm of about 8.4 cm flooded the pit.

Between August 15 and August 24 the soil profile drained. During this period the response of the flux meters to various settings of the valves was rapid and consistent with previous findings. This is illustrated by the measurements with the small meter on August 15, summarized in Table 1. Reasonably steady values of the total head loss across the valve, ΔH_v, were measured at valve settings S = 3.0, 2.5, and 2.0, respectively. The calibration factor K[S] for these settings, as defined by equation [9], is given in the second column. The flux, q_m, through the meter follows directly from equation [8]. Based on the measured hydraulic conductivity of the filter plates, the head loss across both filter plates was equal to 0.25 q_m (cm). For this day that amounts to only about 0.1 cm. Contact resistances must be neglected at this point. The digging apparatus was made especially to minimize contact resistances. The results indicate that, compared with previous attempts when access holes were dug by hand, this problem was largely solved. However, the present data do not allow an evaluation of any remaining contact resistances. In the future, contact resistances will be taken into account automatically by incorporating a small tensiometer in the center of each of the filter plates. Without contact resistances, the total head loss across the meter, ΔH_m, is the sum of that across the valve and that across the filter plates and is listed in Table 1. The total head loss in the soil nearby at that time was measured at ΔH_s = 5.8 cm. The setting S = 3.0 shows virtually the same value of ΔH_m and, therefore, the value q_m = 0.37 cm/day is a good estimate of the soil water flux, q_s, if the value ΔH_s = 5.8 cm is correct. This will be discussed later. The setting S = 2.5 is too restrictive, showing a high ΔH_m and a low q_m. However, values of q_s can still be calculated with equation [12] and are listed in the last column of Table 1. This shows reasonably good agreement between the measurements at the first two valve settings. For S = 2.0, ΔH_m deviates from ΔH_s too much for equation [12] to be used. The denominator becomes very small and q_s unrealistically large. This is consistent with the value of $(\Delta H_m - \Delta H_s)/\Delta H_s$ = +0.42, which is well outside the range for which equation [11] was tested.

TABLE 1. SOIL WATER FLUX MEASUREMENTS FOR AUGUST 15, 1972.

S	K[S] cm/day	ΔH_v, cm	q_m cm/day	ΔH_m, cm	q_s cm/day
3.0	0.40	5.8	0.37	5.9	0.38
2.5	0.25	6.5	0.26	6.6	0.33
2.0	0.18	8.2	0.23	8.3	- - -

Steady values of ΔH_v close to ΔH_s were obtained in a matter of minutes after changing the valve settings. The same value of ΔH_v was measured with the 5-way switching valves at BC-TC as at TV-BV. However, the tensiometric measurements of ΔH_s made with the same pressure transducers behaved altogether differently. The value ΔH_s = 5.8 cm, measured on August 15, represents a fairly steady value after the pit had been open for awhile, but this was an exception. On the following days, the first measured values of ΔH_s were usually low (5 to 6 cm), but soon after they would rise as high as 12 cm. This is attributed to temperature changes, accentuated by air developing in the tensiometer lines, and will be discussed again. The measured values of ΔH_s were the largest source of error in the values of q_s derived with equation [12]. Thus, it is desirable to calculate q_s with equation [13], which does not require measured values of ΔH_s. The values of ΔH_m and q_m for S = 3.0 and 2.5 in Table 1, when substituted into equation [13], give a soil water flux of 0.48 cm/day. The corresponding total head loss in the soil is ΔH_s = 5.1 cm. This corresponds to the value ΔH_s = 5.0 cm at which the measurement started immediately after opening the pit on August 15. A set of tensiometers with mercury manometers close to the flux meter, used in the same plot as part of another experiment, also indicated that the total head loss in the soil at the depth of the flux meters fluctuated around 5 cm at 8:00 a.m. each morning. Thus the values q_s = 0.48 cm/day and ΔH_s = 5.1 cm, obtained with equation [13], appear to fit the available data best. With the distance between the two tensiometers being L = 6.35 cm, it follows then from equation [14] that the best estimate for the hydraulic conductivity of the soil at that day is k = 0.60 cm/day. Equation [13] did not always produce values of q_s and ΔH_s that agreed well with other data. Therefore equation [13] should be used with caution and values of q_s are probably best based on accurately measured values of ΔH_s.

The tensiometer measurements were unsatisfactory because of the large diurnal temperature fluctuations as compared with the relatively steady soil temperatures. Later, when the pit was kept closed for a few days, its temperature ranged only between 19.5 C and 21 C. However, the pit had to be opened to make readings, adjust valves, replace batteries, etc. This exposed the fine-metering valve, tensiometer lines, and pressure tranducers to much higher temperatures. Obviously, these instruments need to be insulated. The temperature of the fine-metering valve should be monitored since the hydraulic head loss across the valve is directly proportional to the viscosity of water. For instance, after the pit had been open for awhile on August 15 in hot weather, a second set of values ΔH_v = 5.2 cm and ΔH_v = 5.9 cm was measured for S = 3.0 and S = 2.5, respectively. The valve was calibrated at 20 C, which must have been close to the valve temperature immediately after opening the pit. The temperature in the field rose to well over 32 C. Since the fine-metering valves were not insulated, the calibration values, and thus the values of q_s, should probably be increased about 20 percent. This would bring them close to the previously obtained values.

Independent data are not available to check the accuracy of the measured fluxes. In view of this, and the problems just described, this field test provides only a qualitative test of the flux meters. A match between ΔH_m and ΔH_s was not obtained on August 15 with the large meter. However, a particular valve setting gave a value of ΔH_v too high to use equation [12], which indicated that the flux was about the same as the 0.48 cm/day obtained with the small meter. Both meters gave fluxes of about 0.20 cm/day on August 17 and about 0.10 cm/day on August 19. This is as expected in a draining soil profile without additional rainfall. Thus the two meters appeared to give reasonable results that were mutually consistent, despite the fact that they had different cross-sectional areas and fine-metering valves. After the pit flooded on August 24, the meters were removed from the access holes. They came out nearly clean.

In October, the large meter was placed back in the same hole. The fine-metering valve was replaced by four different ceramic hydraulic resistances, which could be switched into the line in any parallel configuration. This was done because the calibrations of the fine-metering valves vary with time and it takes considerable time to check them regularly. During a 24-hr period, the measured total head loss across a ceramic resistance varied only about 0.1 cm out of 5.0 cm. Also, the tensiometer measurements were now quite stable, in contrast with their behavior during the summer. This supports the view that temperature fluctuations caused the earlier problems, since the surface temperature and pit temperature were now about equal. A nearly perfect match was obtained between ΔH_m and ΔH_s during this period, corresponding with a flux of about 0.05 cm/day. This was about 8 days after the last significant rainfall.

The large flux meter was taken out once more to line the pit and build an instrument cabinet. When reinstalled, it measured essentially the same flux as before. This is as expected in view of the low flux and no additional precipitation. The significant point is that the meter could be installed and retrieved without any apparent influence on the measurements. The flux meters were drained and let in place throughout the winter to be used the next spring. However, during the winter the pit caved in, and the site was abandoned. The flux meters were dug out and were still in good condition.

SUMMARY AND CONCLUSIONS

This field test represents an attempt to measure soil water fluxes directly in essentially undisturbed soil. This was accomplished by excavating access holes perpendicularly to the direction of flow with a specially designed apparatus. Filter plates were pressed against undisturbed soil by a spring. Fluxes were measured by adjusting the overall hydraulic head loss across the meters, with a variable hydraulic resistance, to that in the soil nearby. Two flux meters gave realistic results that were generally in good agreement with each other. They reacted rapidly to different hydraulic resistance values consistent with earlier laboratory tests. This is in sharp contrast with an earlier attempt in which the access holes were dug by hand resulting in a complete failure.

To obtain better quantitative results, the influence of diurnal temperature variations on the measuring apparatus needs to be eliminated. Also, it appears desirable to separate the two functions of the variable hydraulic resistance. It can still be used to regulate the head loss across the meter and attempts are being made at present to do this automatically. The flux is better determined without constricting the flow. This can be done with a heater wire as described by Cary (1973) or in a few other ways that are now being explored. Finally, the total hydraulic head loss across the meters, including the effect of contact resistances, should be measured directly. This can easily be done by embedding a small tensiometer in the center of the filter plates.

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Automated In Situ Measurement of Unsaturated Soil Water Flux

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ABSTRACT

A device is presented which, based on new operation principles, intercepts unsaturated soil water fluxes within an error of 10% and can yield samples for subsequent chemical analysis and calculation of convective solute fluxes. Operation is controlled by a microprocessor which automatically adjusts the vacuum imposed on a porous filter cloth such that identical matric potentials are maintained just above the cloth and at the same depth in the neighboring soil. Contact resistances and internal resistance of the device are implicitly corrected by adjustment of suction. Laboratory and field tests in a loamy sand under steady and transient flow conditions showed that cumulative water fluxes could be measured within 10% of those calculated from storage changes, and from numerical and analytical flow models.

UNSATURATED soil water flux densities must be estimated for any study which includes water balance or chemical budgets in the unsaturated zone (Ingestad, 1987; Jordan, 1982; Van Breemen et al., 1987). Unsaturated convective chemical fluxes can be calculated from unsaturated soil water flux densities and concentrations in soil solution (Wagenet, 1986; Van Grinsven et al., 1987). Unsaturated soil water flux densities can be obtained indirectly either by simulation or by integration of a time series of water content and matric potential measurements. Few methods are available for direct measurement of the unsaturated soil water flux (Wagenet, 1986).

Two general principles are used for flux measurement. The first principle involves measurement of the displacement of a thermal field due to convective heat transport by soil water (Byrne et al., 1967, 1968). This method can only measure rather large flux densities and has not been thoroughly tested in the field. The second principle involves intercepting part or all of the soil water flux and determining its magnitude by measuring the hydraulic head loss across a known hydraulic resistance (Cary, 1968, 1970). Since the hydraulic resistance of the meter cannot be matched to that in the undisturbed neighboring soil, the soil water flux streamlines will converge to or diverge from the fluxmeter. Correct flux densities can only be derived with extensive in situ calibrations for each combination of soil type and fluxmeter.

Dirksen (1972, 1974) improved this type of fluxmeter by using fine-metering valves with micrometer dials as known variable hydraulic resistances and by installing the meter perpendicular to the flow direction. By matching the head loss across the meter with that measured with two tensiometers across an equal length of soil nearby within ± 10%, the measured flux density through the meter could be corrected for convergence and divergence of flow. Unfortunately, the calibration of the fine-metering valve proved to be a problem due to unpredictable effects of air dissolution, precipitation of solutes and bacterial growth on the resistance of the very narrow opening. This problem was later eliminated by using the fine-metering valve only to match the hydraulic resistances of meter and soil. The flux through the meter was derived from the convective heat transport in an unconstricted part of the hydraulic path (Cary, 1973). Small head losses across the meter and soil need to be measured within ± 10 Pa (Dirksen, 1972; 1974). This accuracy was difficult to obtain due to the sensitivity of pressure transducer measurements to temperature variations, which inevitably occurred when taking readings and changing valve settings.

The fluxmeter described in this paper eliminates some of the previous problems by performing all control manipulations remotely and automatically with the help of a microprocessor. The method combines features of the methods by Dirksen (1974) and by Duke and Haise (1973). Soil water flow is intercepted by a porous plate, in which the suction is automatically adjusted to maintain identical matric potentials above the plate and in the surrounding undisturbed soil. A major new feature is that the fluxmeter no longer is a passive element through which soil water must find its way solely driven by the prevailing soil hydraulic gradient. Instead, soil water can be sucked into the fluxmeter, irrespective of larger hydraulic resistances in the path through the meter than through the soil. This makes the device insensitive to air bubbles, which unavoidably will occur in filter cloth and tubing (Peck, 1969), and which are disastrous in passive measuring systems such as that used by Dirksen (1972, 1974).

H.W.G. Booltink, N. van Breemen, N. Bongers, and N. Waringa, Dep. of Soil Science and Plant Nutrition; J.J.M. van Grinsven and C. Dirksen, Dep. of Soil Science and Geology. Contribution from the Dep. of Soil Science and Geology and Soil Science and Plant Nutrition, Agricultural Univ., Wageningen, The Netherlands. Received 16 Oct. 1987. *Corresponding author.

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Table 1. Hydraulic conductivity and water content at 0.25, 2.5, 5 and 10 kPa suction, for soils in laboratory and field experiments.

Suction, kPa	0.25	2.5	5.0	10
		Water content (cm³ cm⁻³)		
Lab soil	0.35	0.22	0.20	0.15
Field soil	0.36	0.26	0.23	0.21
		Conductivity (cm d⁻¹)		
Lab soil	20.0	2.0	1.0	0.8

The water extracted by the fluxmeter can be used for subsequent chemical analysis and calculation of the local convective unsaturated chemical flux density.

MATERIAL AND METHODS

Description of the Fluxmeter

The fluxmeter is schematically presented in Fig. 1 as part of a field setup. The flux plate consists of a round polyacrylic filter cloth [Gelman, Versapor 200, (Gelman Sciences, Inc.) a pore size of 0.2 μm, area of 79 cm²] supported by a polyacrylate body. A thin tensiometer (P_1, diameter 0.7 cm) is installed, together with the plate, in disturbed soil 0.5 cm above the plate. At the same level in the undisturbed soil, two tensiometers (diameter 1.8 cm) are installed at both sides of the plate, with a joined outlet (P_2). P_1 and P_2 are connected with tygon tubing to a differential pressure transducer (Honeywell Bull Microswitch 160 PC, Micro Switch, Freeport, IL). All tensiometer tubing was installed horizontally to avoid hydraulic head differences along the length of the tubing. The suction is applied by means of a pump connected to a buffer container. Adjustment of the suction inside the plate starts by bringing the buffer container to a suction of approximately 50 kPa. The differential transducer is read at preset time intervals (6–3 min). When the suction difference between P_1 and P_2 exceeds 100 Pa, either the valve to atmospheric air or the buffer container is opened for a short period, decreasing or increasing the suction in the collecting bottle and the flux plate.

Description of Laboratory Setup

Experiments were carried out under steady-state flow conditions. The flux plate and the tensiometers P_1 and P_2 were installed in a packed soil column (50-cm high, 45 cm in diameter) of loamy sand (Table 1). Tubing from the flux plate to the collecting bottle was 3 cm in diameter, air filled and slanting; the intercepted water flowed by gravity in a thin film to the collecting bottle. The suction in the collecting bottle thus acted directly on the filter cloth. The soil was homogeneously packed at field capacity in layers of 5 cm. The flux plate and tensiometers P_1 and P_2 were installed at 20 cm below the soil surface during filling, so contact resistances were small. Additional tensiometers were installed at 10-cm depth intervals to verify steady-state flow. The matric potential at the bottom of the soil column was controlled by a hanging water column. At the bottom of the soil column a filter cloth (Gelman, Versapor 1200, pore size 1.2 μm) prevented air entry. The surface flux was applied with a dripping device consisting of a 5-cm high closed vessel, with the same diameter as the soil column, and perforated at the bottom by 150 hypodermic needles. Puddling was prevented by a layer of gravel on the soil surface. The surface flux density was regulated by a pulse pump. Matric potentials and suction in the collecting bottle were measured with a pressure transducer. The volumetric outflow of the fluxmeter and of the column were recorded manually.

Field Test

The flux plate was installed in an undisturbed loamy sand profile (Table 1) at the 20-cm depth through a horizontal tunnel from an adjacent soil pit. In contrast to the laboratory setup, tubing was thin (1-mm diameter), water filled and horizontal, to avoid problems with installing a wide slanting tube in undisturbed soil. The frequent adjustment of the suction in the collecting bottle proved to be adequate for compensating variable hydraulic resistance in the tubing due to air bubbles. Hydraulic contact between soil and plate was secured by using a spring-loaded support. The plate was covered with loose soil (containing P_1) before installation. Tensiometers were installed in duplicate at 10-cm intervals down to a depth of 50 cm. The matric potential at P_2, the matric potential difference between P_1 and P_2, and the total amount of collected water were measured continuously by means of a Hewlett Packard-75 computer/Hewlett Packard-3421A datalogger combination. Also the air temperature near the datalogger next to the soil pit was recorded. Additional tensiometers were recorded manually at intervals of 30 to 60 min during daytime.

Two similar experiments were carried out with the field setup described above, the first (I) during fall 1986 and the other (II) in spring 1987. In both experiments soil was initially wetted to near saturation by applying 22 mm and 24 mm water, respectively. After irrigation, the plot was covered by plastic to prevent evaporation. Monitoring was car-

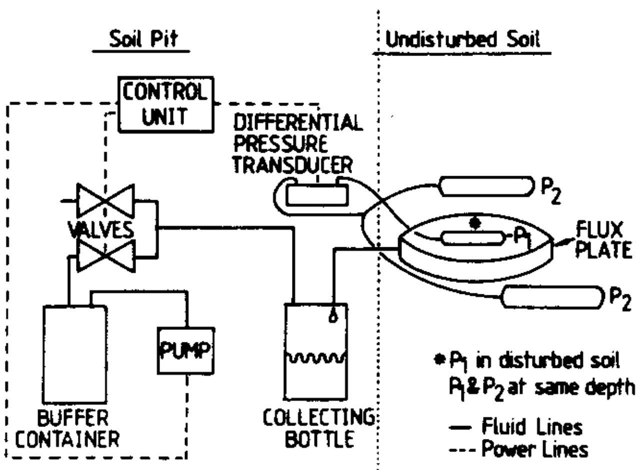

Fig. 1. Schematic diagram of flux meter components in assembly of field experiment.

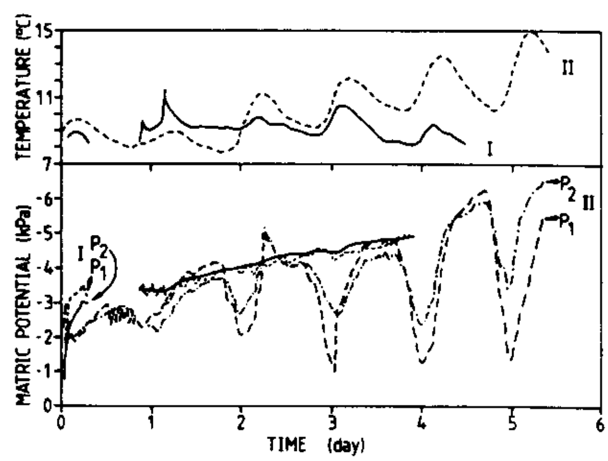

Fig. 2. Air temperature, and matric potential 0.5 cm above the fluxmeter and at the same depth in undisturbed soil during field experiment (I) in fall 1986 and (II) in spring 1987.

ried out during 4 (I) and 6 (II) d. Twice daily soil cores were sampled for gravimetric water content. The collecting bottle was a 80-cm long and 3.5-cm wide tube. In the first experiment the increase of water volume in the tube was determined from the increase of hydraulic head which was measured by means of a pressure transducer at the bottom of the tube. In the second experiment the volume increase was derived from the increase of electrical capacitance, measured by means of two opposite copper plates along the length of the tube. Soil water fluxes obtained with the fluxmeter were compared with fluxes calculated from storage changes derived from tensiometer data, the water retention curves and gravimetric water contents.

RESULTS AND DISCUSSION

In a steady-state laboratory experiment with a surface flux density of 9.2 mm d^{-1} and a matric potential of -5 kPa at the bottom of the column, linear regression of cumulative flux with time over 4.3 d gave a flux density 9.0 mm d^{-1} ($r^2 = 0.967$, $n = 33$) for the fluxmeter, as compared to 8.9 ($r^2 = 0.99$, $n = 33$) mm d^{-1} for column outflow. The applied surface flux density was rather high compared to normal field values, but lower fluxes could not be controlled accurately. Suction differences between P_1 and P_2 seldom exceeded 0.2 kPa. The suction applied to the filter plate was generally between P_1 and P_2, which confirms that contact resistance between plate and soil and the resistance of the filter cloth in the packed column were small.

Matric potential at P_1 and P_2 and air temperature during the two field experiments are shown in Fig. 2. In Experiment I soil was wetted to -1 kPa, in Experiment II to -2 kPa. In both experiments the average potential difference between P_1 and P_2 was small: -51 ± 199 Pa ($n = 805$) for Experiment I, and -183 ± 722 Pa ($n = 317$) for Experiment II. In Experiment II the recorded matric potential had a strong diurnal fluctuation, which was clearly associated with temperature. Although air temperature near the data logger did not fluctuate more than 5 °C, the temperature in the pit, where transducers and tubing were stored, probably fluctuated more strongly due to absorption of sunlight by the black plastic cover. In spite of this marked variation of the recorded suction, the average difference between P_1 and P_2 was small, although larger and more variable than in Experiment I. Cumulative measured flux densities and flux densities obtained from measured storage changes are shown in Fig. 3 for both experiments. At the end of monitoring, the difference between alternative flux density measurements did not exceed 5%. Apparently temperature fluctuations did not affect the accuracy of the flux measurement.

Cumulative flux density measured for field tests (II) was compared with two analytical solutions for vertical nonsteady drainage by Jackson and Whisler (1970)

$$(Q/Q_\infty)/(1 - Q/Q_\infty) = \tau \quad [1]$$

$$(0.03\, Q/Q_\infty)/(1 - Q/Q_\infty)^2 - 0.9 \ln(1 - Q/Q_\infty) = \tau \quad [2]$$

where Q is cumulative flux density (cm^{3}cm^{-2}), Q_∞ is Q at infinite time, q_o is the initial flux density, $\tau = q_o\, t/Q_\infty$ and t is time (d). Both solutions predict the general shape of nonsteady drainage with time, without requiring a conductivity and water retention function, and are calibrated by using the initial measured flux density. Equation [1] assumes capillaries of equal radii, Equation [2] capillaries of variable radii. The comparison for Experiment II (Fig. 4) shows that the measured cumulative flux density did fall in between the two analytical solutions.

Our fluxmeter measured cumulative flux densities in the field within 10% of the true value, which is similar to the accuracy obtained by existing fluxmeters or by numerical simulation. Installation and operation are easier than for existing fluxmeters (Dirksen, 1972, 1974; Duke and Haise, 1973), however, and no time series of water content and water potential are needed to calibrate and validate simulation models (Van Grinsven et al., 1987). Tests were carried out under high downward flow conditions in loamy sand. By inversion of the flux plate, our fluxmeter is also suitable to intercept upward flow. When using the fluxmeter in coarser or finer soil material under low flow conditions, the response of tensiometers will be more sluggish and flux measurement will be less accurate. Less accurate performance in dry soil is not a serious limitation since water transport and convective solute transport during high downward flow conditions (flux > 1 mm d^{-1}) often dominate annual fluxes. If matric potential varies strongly on a short distance, e.g. in very heterogeneous soils or in case of

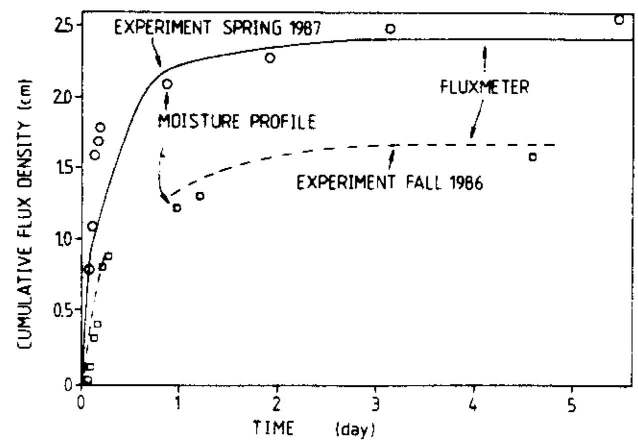

Fig. 3. Cumulative soil water flux density for field experiments as measured by fluxmeter and calculated from soil water changes.

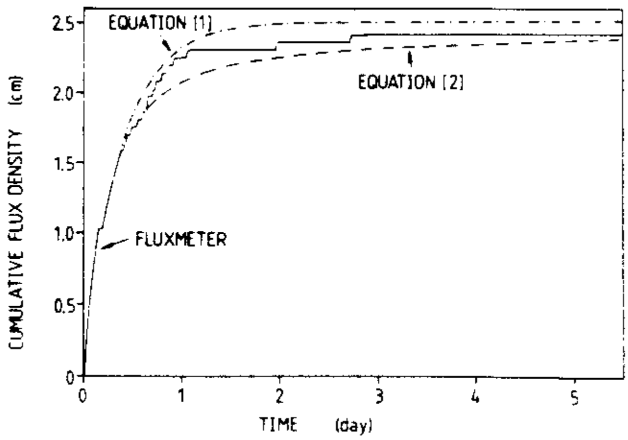

Fig. 4. Cumulative soil water flux density for second field experiment as measured by fluxmeter and calculated by two analytical solutions of Jackson and Whisler (1970).

macropore flow, flux measurement by control of the difference of matric potential between P_2 and P_2 is not possible. If the scale of spatial variability is larger than the dimensions of the fluxmeter setup (≈ 300 cm^2 for our prototype), the intercepted flux is not representative for the area. Theoretically, the principle of our flux measurement can be used to intercept fluxes over larger areas, similar to experiments by Montgomery et al. (1987).

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