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"A Versatile Soil Water Flux Meter"

C. DIRKSEN
Wageningen Agricultural University
Department of Hydrology & Soil Physics
Wageningen, The Netherlands

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A VERSATILE SOIL WATER FLUX METER

C. Dirksen[1]

SYNOPSIS

Soil water fluxes ranging from 0.11 cm/day to 1.43 cm/day were measured accurately in laboratory columns of sandy loam and Plainfield sand with a new type flux meter. Water is intercepted through a filter plate, fed through a fine metering valve with vernier handle and distributed back into the soil through another filter plate. The setting of the valve is changed until the total hydraulic head loss across the meter is equal to that measured over an equal distance of undisturbed soil nearby. In this way the flux through the meter is made equal to that through the soil, independent of the magnitude of the flux and soil type. This nearly eliminates the need for calibration. The flux through the meter is derived from the measured hydraulic head loss across the valve and a calibration curve which relates the flux per unit hydraulic head loss to the valve setting. This calibration is obtained very conveniently by means of a syringe pump and differential pressure transducer. This meter can be installed from a direction perpendicular to the direction of flow. This keeps the disturbance of soil and flow field to a minimum. A spring pushes the filter plates against undisturbed soil to minimize contact resistances. This device can also be used as an in-situ hydraulic conductivity meter.

INTRODUCTION

Devices that can measure directly volumetric flux of water in unsaturated soils are very helpful in almost any kind of study concerning the soil phase of the hydrologic cycle. Soil water fluxes

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[1]Soil Scientist; Contribution from the Corn Belt Branch, Soil and Water Conservation Research Division, Agricultural Research Service, USDA, Madison, Wisconsin, USA and the Wisconsin Agricultural Experiment Station.

can be derived from separate measurements of total potential gradients and hydraulic conductivities. However, methods for measuring hydraulic conductivity leave much to be desired, especially field methods. Direct measurement of rates of infiltration, drainage, evaporation, etc. is much to be preferred. Flux meters may actually prove to be better in-situ hydraulic conductivity meters than any existing devices.

A basic problem associated with flux measurements in unsaturated soils is that the fluxes will generally be different from the fluxes in the surrounding soil. The first reason for this is that hydraulic conductivities of soils vary with water content. If the conductivity of the meter is larger than that of the soil, flow will converge toward the meter and the measured flux will be too high; if it is smaller, flow will diverge from the meter and the measured flux will be too low. Existing flux meters have either a negligible resistance for flow (large conductivity), a fixed resistance or a semi-variable resistance. All cases require extensive calibration to determine the degree of convergence or divergence under various soil and water conditions.

The second reason is the disturbance of soil during installation. For instance, the flow field is seriously disturbed if vertical flow is measured with a meter located at the bottom of a refilled, vertical hole. Contact resistances between meter and soil also fall in this category. The effect of these disturbances is hard to evaluate without actual calibration in-situ, which is difficult and very time-consuming. The best approach seems to be to design meters such that these problems are minimized. This aspect has not received attention in any of the existing flux meters.

Flow of water through unsaturated soil can be described by Darcy's law:

$$q_s = - K(h) \text{grad } H \qquad (1)$$

where q_s is the volumetric flux of water (cm^3/cm^2 day) and K(h) is the hydraulic conductivity of the soil (cm/day). The hydraulic head H(cm water) is the sum of the pressure head h and the gravitational head z. If a flux meter is placed in a soil, then:

$$q_m = \kappa \ \Delta H \qquad (2)$$

where q_m is the volumetric flux of water through the meter and κ is the conductance (day^{-1}) of the section of the meter across which the hydraulic head differential ΔH is measured. The flux ratio f is defined as:

$$f = \frac{q_m}{q_s} \qquad (3)$$

By combining equations (2) and (3) the flux through the soil can be correlated with the measured hydraulic head loss ΔH:

$$q_s = (\kappa/f)\Delta H \qquad (4)$$

Cary has called κ/f "effective conductivity of the transducer" (Cary, 1968, symbol k/f) and "flow factor" (Cary, 1970, symbol k). The notation defined above will be used throughout this paper unless indicated otherwise.

We will first review previous work on soil water flux meters, with special emphasis on convergence and divergence. Then we will describe a new flux meter with a continuously variable resistance, which also has special features to reduce soil disturbance during installation and contact resistances. Finally, calibration results for this meter will be given and evaluated.

EXISTING FLUX METERS

The first flux meter was developed by Ivie and Richards (1937) and by Richards, et al. (1938). They intercepted the water by means of a filter plate, measured the rate of flow by means of drop counters and distributed the water back into the soil with another filter plate. Richards, et al. gave some data obtained with these meters buried about 4 to 5 inches underneath the soil surface.

These showed diurnal fluctuations, often involving reversal of the direction of flow. They recognized that these "are exaggerated by, if not caused by, the temperature fluctuations in the soil". There was no independent check on how measured fluxes compared with actual fluxes.

All other attempts are quite recent. Byrne, et al. (1967, 1968) derived the water flux from the asymmetry in the temperature field generated by a line or point source of heat. They stated that such a sensor can readily measure a flow rate of 8.64 cm/day. This virtually limits its use to saturated soils. This sensor is restricted to such very high fluxes because it depends on convective heat transfer by water flowing past the sensor. To use this method for measuring much smaller, yet hydrologically significant fluxes in unsaturated soils would require concentration of flow from much larger cross-sectional areas.

Cary (1968) determined the flux by measuring ΔH across a saturated porous plate of known conductivity, sandwiched between two outer filter plates. The total thickness of the meter was about 5 cm. He tested two versions in laboratory columns of silt loam, using exceptionally high pressure head gradients. Whereas the highest flux was about 1.0 cm/day, the highest hydraulic conductivity of the soil was only 0.11 cm/day. The greater the pressure head gradient, the easier it is to make accurate flux measurements for the same hydraulic conductivity.

Cary states as his most important result that K/f (Cary notation k/f) changed by a factor of only about 2.5, whereas $K(h)$ decreased almost 20-fold. However, a closer look at the data shows that over the range of pressure head h from -3.6 to -25.5 cm Hg, $K(h)$ decreased about 6.5-fold while K/f decreased about 3.1 fold. This is only about a two-fold difference. From $h = -25.5$ to -51.2 cm Hg, K/f increased about 25%.

There does not seem to be a theoretical justification for this non-monotonic behavior of K/f. As h decreases the constant conductance of the center plate K becomes relatively larger with respect to K(h). Thus the flux ratio f should keep increasing and $\mathcal{K}/f$ should keep decreasing. This argument also shows that Cary's designation "effective conductivity of the transducer" for $\mathcal{K}/f$, is misleading, since it decreases as the relative flow through the meter increases.

With another type flux meter, Cary (1970, 1971) measured ΔH between two holes drilled through one saturated porous plate (about 2 cm thick) mounted inside a thin-walled metal cylinder. The purpose of the cylinder is to make the soil inside the cylinder effectively a part of the meter. Since K(h) of the soil inside the cylinder will change with K(h) outside the cylinder, the overall conductance of the meter will follow that of the surrounding soil. As a result, both convergence and divergence will be less than without the cylinder.

Cary gives calibration curves of $\mathcal{K}/f$ as a function of h for three different soils and uses these with equation (4) to"predict" the flux in the soil. The thus "predicted" steady fluxes, q_{pred}, differ from the observed fluxes in the soil, q_s, by a factor ranging from 0.66 to 2.54. This seems to indicate large differences between these calibration curves and the individual data upon which they are based. If one assumes that these differences represent actual variations in the flux through the meter and are not due to errors in ΔH or undetected changes in $\mathcal{K}$ then, for any of Cary's data points:

$$f = \frac{q_m}{q_s} = \frac{q_m}{q_{pred}} \times \frac{q_{pred}}{q_s}$$

$$= \frac{\mathcal{K}\Delta H}{(\mathcal{K}/f)_{h,soil}\Delta H} \times \frac{q_{pred}}{q_s}$$

$$= \frac{(\mathcal{K}/f)_{ideal}}{(\mathcal{K}/f)_{h,soil}} \times \frac{q_{pred}}{q_s} \qquad (5)$$

The first ratio can be obtained from Figure 3 and the second ratio from Table 1 of Cary (1970). The largest value of f is obtained for loamy sand at

$h = -200$ cm:

$$f \simeq \frac{0.11}{0.03} \times \frac{0.33}{0.13} \simeq 9$$

This is unbelievably high and must be due to error in ΔH or, more likely, a decrease in K. The largest deviation from $f = 1$ is expected under divergent conditions. For silty clay at $h = -81$ cm, equation (5) gives $f = 0.22$.

Again Cary reports non-monotonic behavior of K/f, this time for loamy sand. It is completely inconsistent with Cary's theoretical derivation [as summarized in his Figure 2; see also Dirksen (1972)] that K/f should decrease below the value for the other soils at large suction.

In summary, the flux through Cary's meters often differs by a factor of three or more from the flux through the soil. This information can probably only be obtained by calibration in the actual situation in which the meter is to be used. This is very tedious and time consuming and it is certainly desirable to have an instrument that does not require this.

A NEW APPROACH

The review given above indicates the need for a soil water flux meter which:

a. reduces or eliminates divergence or convergence of flow over a large range of soil and water conditions.

b. reduces and hopefully eventually eliminates the need for calibration.

c. minimizes disturbance of soil during installation and reduces the possibility of contact resistances between the apparatus and undisturbed soil.

A flow rate meter was designed with these considerations in mind. It is described in detail elsewhere (Dirksen, 1972).

Figure 1 gives a radial cross-section of the cylindrical meter. It consists essentially of two individually mounted filter plates, kept together with a pin under spring-load, similar to the salt sensor of Richards (1966). The device can be inserted into the soil from a direction perpendicular to the direction of flow to be measured, provided an access hole of the correct shape and size is obtained. After the device is placed in position the pin is pulled out and the spring pushes the two filter plates apart against undisturbed soil, hopefully without contact resistance. Even if the access hole is not refilled perfectly, most of the flow field is kept undisturbed.

Flow is intercepted by one filter, conducted through a fine metering valve with vernier handle, and distributed back into the soil through the other filter. The hydraulic head loss across the fine metering valve is measured and the setting of the valve changed, until the total hydraulic head loss across the meter is the same as that over an equal distance in the surrounding soil. Under those conditions there should be no divergence or convergence and the measured flow rate should be correct. The hydraulic head loss in the soil can be measured with two tensiometers located approximately in the planes of the filter plates. They should be placed close enough to the meter to be representative of the flow conditions around the meter and yet far enough so that they are not influenced by the setting of the valve. Two diameters of the meter appears to be a sufficient distance (Cary, 1968). Under transient conditions the valve must be changed from time to time to match the changing hydraulic conductivity of the soil. The flux through the valve can be derived from the measured hydraulic head loss across the valve and a calibration curve giving the flow rate per unit hydraulic head loss as a function of the valve setting. The following sections describe calibration results obtained with this type of flux meter in the laboratory.

CALIBRATION OF FINE METERING VALVE

To calibrate the fine metering valve, a known amount of water must flow through the valve for a known period of time under a known hydraulic head differential, ΔH. This must be repeated for each desired valve setting.

The amount of water can be determined accurately by weighing if special precaution is observed at beginning and end of the flow period, particularly at the very small flow rates. A syringe pump (Harvard Apparatus, Millis, Mass., Model 944)[1] is faster and more convenient. For each size syringe this pump has a 5000-fold range in flow rates in 12 reproducible, discrete steps. Thus the calibration of a single valve setting can easily be obtained with a number of fixed flow ratios.

The change in hydraulic head was measured with differential pressure transducers. Pressure transducers with the accuracy and sensitivity required for this type measurement usually have a volumetric displacement that is not negligible compared with the small flow volumes involved. For this reason the hydraulic head differential must first be returned to the original value if the amount of water is determined by weighing. The average voltage output of the pressure transducer can be determined by a voltage integrator. This is especially helpful with the syringe pump, since the plunger tends to jerk a little.

Figure 2 gives the calibration results of an "S" series fine metering valve with vernier handle (NUPRO Company, Cleveland, Ohio). The lower portion of the curve is duplicated on a larger scale. Distinction is made between results obtained by weighing and with the syringe pump. Many points are too close to show separately. The curves represent the best fit by eye through the data, with somewhat more weight given to the syringe pump data. Table 1 gives a series of results obtained with the syringe pump (these data were used in Table 2). The reproducibility is excellent. It demonstrates how

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1) Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

duplicate measurements can be obtained just by changing the speed of the syringe pump.

Results were not always as good, especially between different series of measurements. For instance, in another series of measurements with the syringe pump we found for S = 5.0, q_{cal} = 13.9 cm^3/cm water, day. This agrees closely with a duplicate set of measurements obtained by weighing, but is still smaller than another duplicate set by weighing which averaged q_{cal} = 14.5 cm^3/cm water, day. This suggests that the setting of the valve is not reproducible. However, when this was checked out on a short time scale, we found no significant difference in duplicate measurements whether the valve had been reset or not. These differences are probably caused by changes in the pressure transducer calibration, foreign material in the valve, possible desaturation of the valve, etc.

This particular valve failed to give satisfactory results for flow rates of the order of 0.05 cm/day and less. At these low valve settings the hydraulic head differential tends to increase with time. This can often be restored by flushing the valve with filtered de-aired, distilled water. We should be able to find other valves (or resistances) that will give more accurate results at these lower flow rates.

Once a satisfactory procedure for the calibration of the valve is obtained, it is relatively simple and fast. If valves can be procured which either all have the same calibration or for which the calibration is provided by the manufacturer, calibration can be eliminated entirely.

CALIBRATION OF FLUX METER

A flux meter (diameter 10.8 cm, heigh 5.32 cm) was tested in a 33 cm high and 29 cm diameter column of sandy loam soil under two more or less steady downward fluxes. The total potential gradient was about unity. The soil column, valve and pressure transducer were all inside a constant temperature cabinet, maintained at 20°C. The results are summarized in Table 2, in chronological order.

The upper five lines of Table 2 summarize the results for the first flux. Columns (1) and (2) show that the rate of inflow and outflow both approached 0.109 cm/day. While these rates prevailed, the setting of the fine metering valve was maintained at S = 2.0, 2.5, 3.5, 3.0, and 2.5 respectively. The corresponding settings of the fine metering valve are shown in column (3). For each setting the hydraulic head loss ΔH across the valve was measured and is given in column (4). The flux through the valve, and thus through the meter, is shown in column (5). This flux is the product of ΔH across the valve and the appropriate calibration value from figure 2, divided by the cross-sectional area of the meter (91.8 cm^2). Before the meter was placed in the soil, the permeability of the two filter plates was determined. Accordingly, ΔH across both plates was equal to 0.2 times the flux through the meter, which, in this case, was only about 0.02 cm. Column (6) gives the total ΔH across valve and filter plates. Values of ΔH measured in the soil and corrected for a distance of 5.32 cm, are listed in column (7). The meter works correctly if the average of columns (1) and (2) is equal to column (5) and, at the same time, column (6) is equal to column (7).

At S = 2.0, total ΔH was larger than ΔH in the soil and consequently, the flux through the meter was too low. At S = 2.5, total ΔH was virtually the same as ΔH in the soil and the average of inflow and outflow was equal to the flux through the meter. Thus the correct flux (no convergence or divergence) was measured by matching the total ΔH across the meter with that in the soil. The third and fourth line of Table 2 show that when the valve was opened further the measured flux was too high. At S = 3.5, the lower ΔH across the valve affected ΔH in the soil indicating that the tensiometers were not located quite far enough away from the meter under those circumstances. When the meter was returned to S = 2.5, ΔH in the soil increased to 5.71 cm, indicating a decrease in hydraulic conductivity. To measure the correct flux under these conditions would have required a valve setting slightly less than S = 2.5.

The next three lines of Table 2 similarly summarize the results for a nearly steady flux of about 1.43 cm/day. For both S = 5.0 and S = 5.5 the measured flux was too low. At S = 6.0, ΔH across the valve was 6.22 cm and the corresponding flux through the valve 1.43 cm/day. For this flux ΔH across the filter plates was 0.2 x 1.43 = 0.29 cm, making total ΔH only 6.51 cm. Thus the valve measured exactly the average flux through the column, but total ΔH was 0.44 cm smaller than ΔH in the soil. The most plausible explanation for this discrepancy is that contact resistances between the filter plates and soil accounted for 0.44 cm head loss. Therefore, all three values of total ΔH were increased by 0.44 cm, as indicated by the asterisk. There was no indication of contact resistances at the 13-fold lower flux. This is possible since the ΔH would amount to only about 0.03 cm.

Column (8) of Table 2 gives the difference between total ΔH and ΔH in the soil as a fraction of ΔH in the soil. Similarly, column (9) gives the flux through the meter minus the average of inflow and outflow, divided by that average. These ratios are plotted in Figure 3. This shows that the data are mutually consistent and surprisingly, the relationship is pretty much linear: a 6% deviation in total ΔH gives a 10% deviation in the measured flux in the opposite direction. The corrected values in column (8) for S = 5.0 and S = 5.5 are consistent with the results for the lower flux, supporting the assumption that contact resistances existed at the higher flux. Without this assumption the measured flux would have been approximately 11% too low. This corresponds very nearly to the situation for S = 5.5 in Table 2, and is still an acceptable error.

In an earlier experiment the meter was tested in a 20 cm high column of Plainfield sand. Water was supplied at the bottom and evaporated from the top at nearly steady rate. Data obtained with the water supply level at 64 cm below the soil surface are summarized in the last four lines of Table 2. The two higher evaporative fluxes (columns (1) and (2) combined) were obtained while an air blower was directed at the soil surface. Note that the total potential gradient in the soil is only about 0.4 cm/cm, directed upwards. In this case ΔH across the filter plates was 0.175 times the flux through the valve. Columns (8) and (9) indicate that at S = 10.0 total ΔH was 54% too low and the measured flux 82% too high. At S = 7.0, total ΔH was 17% too low and the measured flux 26% too high. The two lower fluxes were obtained by removing the blower. Since the level of water supply remained the same, the hydraulic conductivity around the meter must have remained virtually the same. Thus the same degree of convergence is expected for the same valve setting with or without blower. The last two lines of Table 2 show that this was indeed the case: the measured fluxes were now about 81% and 25% too high. During the lower flow rates tensiometer measurements were not obtained in the soil due to experimental problems. Although no measurements were obtained with total ΔH equal to ΔH in the soil, these data nevertheless show that the flux meter was functioning properly. The two sets of ratios obtained at the higher fluxes were plotted on Figure 3. They are consistent with the data obtained in the sandy loam.

The data in Table 2 and Figure 3 were obtained with two different soils, two different types experiments (one involving upward flow and the other downward flow) and over a 13-fold range in flux. Admittedly, this is still rather limited, especially as to soil types and soil water suctions. However, they support the view that, if the total hydraulic head loss across the meter is matched perfectly with that in the soil, this meter should measure the correct flux, within its limits of fluxes and soil water suctions, no matter what soil it is in (Dirksen, 1972).

It should be possible to measure higher fluxes as long as the resistance of the filter plates does not exceed that of the soil and the hydraulic head losses remain large enough to be measured. Lower rates, however, are at the moment uncertain. The present valve does not function satisfactorily at much lower fluxes, but we should be able to find a solution to that problem. However, the response of the flow system may be too sluggish to allow much manipulation of the valve. These difficulties became apparent while attempting for two and one half months to measure a flux of about 0.01 cm/day in the sandy loam column. This proved virtually impossible, in part due to difficulties associated with maintaining such a low steady flux over extended periods of time.

Figure 3 is not required to measure the correct flux. It will normally not be available since it requires unnecessary calibration. However, the relationship between the two dimensionless ratios is likely to be dependent only on the height to diameter ratio of the meter. If it is available, the total head loss across the meter does not have to be matched exactly with that in the soil. As long as they are made approximately the same, the correct flux can be calculated. This may prove very helpful, for instance, if after an experiment is completed, an analysis of the data indicates that contact resistances may have existed between meter and soil. Fluxes can then easily be corrected.

Whenever the total hydraulic head loss across the meter is matched with that in the soil, the flux in the soil is known as well as the total potential gradient. Thus, using Darcy's law, the hydraulic conductivity at the average pressure head near the flux meter can be calculated. The flux meter can be used, therefore, as a device to measure hydraulic conductivity in-situ. In fact, the data reported here suggest that it is more accurate than any other method proposed so far. It certainly is much simpler and cheaper than using lysimeters, sprinkling infiltrometers, etc.

INSTALLATION

The meters were installed in the laboratory at the time of packing without pin and spring. Springs were used when these flux meters were tested in the field. They responded properly to changes in valve settings but the actually measured values were much too small. This was due to contact resistances. Parts of the bottom filter plates had remained clean, despite soil slurries that were put at the bottom of the holes as well as on the top filter plates before installation, in an attempt to obtain good contact. Instead, it most likely made the overall resistance of the flow path through the meter much larger than that through the surrounding soil, even without poor contact.

We have only recently begun to investigate how to install these meters in the field. It is very hard, indeed, to dig by hand near the bottom of a pit a small, elongated hole with perfectly flat parallel surfaces at the right distance and with a cylindrical end wall. We are building and hope to test soon an apparatus that will automatically dig out such a hole with cutting edges rotated by an electric motor, while gradually being guided into the soil. Contact could then yet be improved by wetting up the adjacent soil with water supplied through the meter itself. It has also been suggested [1] to fill up the gaps around the meter by "grouting" with a silt type of soil.

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Table 1. Some calibration results of fine metering valve with syringe pump.

S	Pump Setting	Average ΔH	q_{cal}
-	$\frac{cm^3}{day}$	cm	$\frac{cm^3}{cm, day}$
5.0	116.5	9.04	12.93
5.0	58.2	4.51	12.94
5.5	116.5	6.92	16.88
5.5	58.2	3.51	16.61
6.0	116.5	5.54	21.10
6.0	116.5	5.50	21.25
6.0	233	11.10	21.07

Table 2. Calibration results of flux meter in laboratory columns.

Column Flow in	Column Flow out	S	ΔH_{valve}	q_m	ΔH_{total}	ΔH_{soil}	$\frac{\Delta H_{total}-\Delta H_{soil}}{\Delta H_{soil}}$	$\frac{q_m-q_{av}}{q_{av}}$
$\frac{cm}{day}$		-	cm	$\frac{cm}{day}$	cm	cm	-	-
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Sandy Loam								
.114	.137	2.0	6.85	0.056	6.87	5.25	+0.31	-0.50
.112	.119	2.5	5.28	0.115	5.30	5.25	+0.01	-0.01
.112	.116	3.5	3.05	0.189	3.07	5.07	-0.40	+0.66
.110	.109	3.0	4.05	0.159	4.07	5.25	-0.23	+0.39
.109	.109	2.5	5.35	0.117	5.37	5.71	-0.06	+0.07
1.50	1.46	5.0	7.90	1.11	8.65*	7.37	+0.13*	-0.23
1.49	1.44	5.5	7.06	1.29	7.81*	7.42	+0.05*	-0.12
1.44	1.43	6.0	6.22	1.43	6.95*	6.95	0.00*	0.00
Plainfield Sand								
0.585		10.0	.82	1.07	1.01	2.2	-0.54	+0.82
0.536		7.0	1.54	0.67	1.66	2.0	-0.17	+0.26
0.174		-7.0	.50	0.22	.54	-	-	+0.25
0.163		-10.0	.23	0.30	.28	-	-	+0.81

*Corrected for contact resistance, $\Delta H = 0.44$ cm

FIGURE TITLES

Fig. 1. Soil water flux meter. Radial cross section through plane of hydraulic lines to fine metering valve. The meter can be placed in position from a direction perpendicular to the direction of flow. After the pin is pulled out, the spring pushes the filters against undisturbed soil.

Fig. 2. Calibration curve of fine metering valve, relating the flow rate per unit hydraulic head loss to the valve setting. Data were obtained by weighing and with a syringe pump.

Fig. 3. Deviation of the measured flux from the flux in the surrounding soil as a function of the deviation of the total hydraulic head loss across the meter from that in the surrounding soil, both relative to the values in the surrounding soil. The numbers with the data points indicate the average flux in the surrounding soil in cm/day.

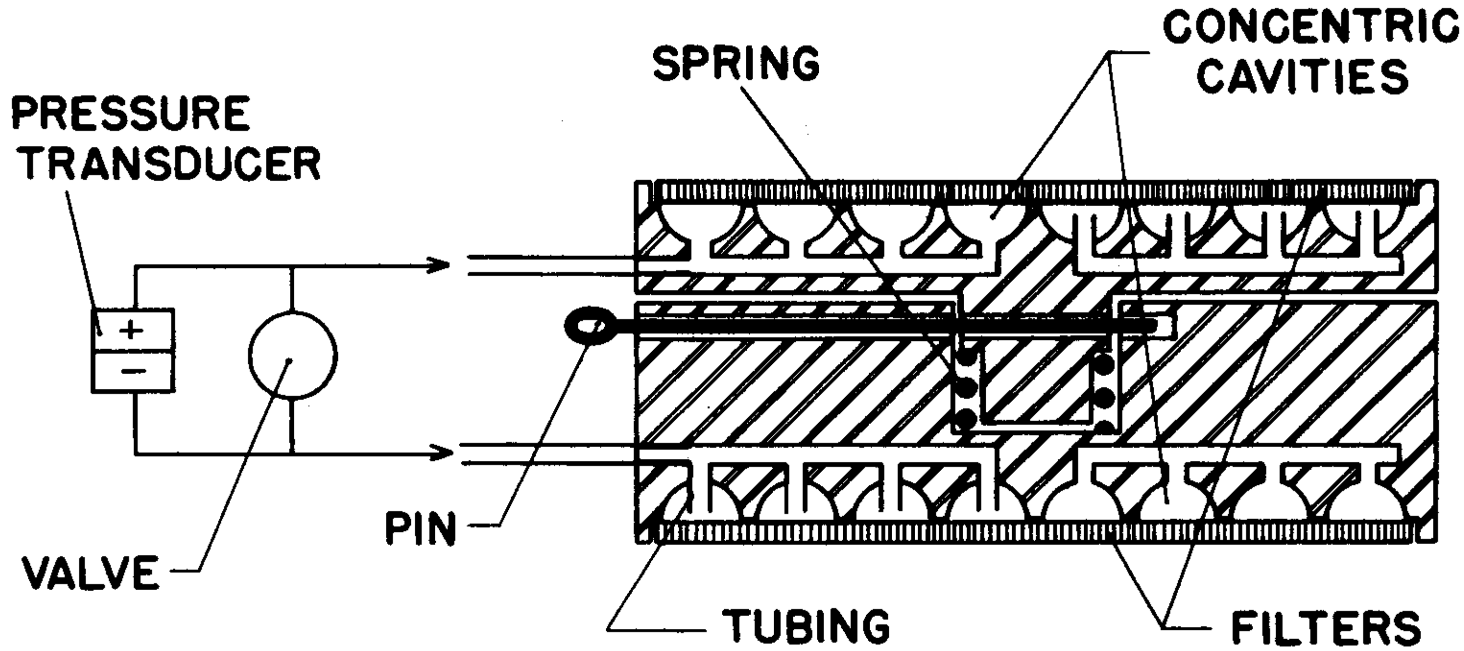
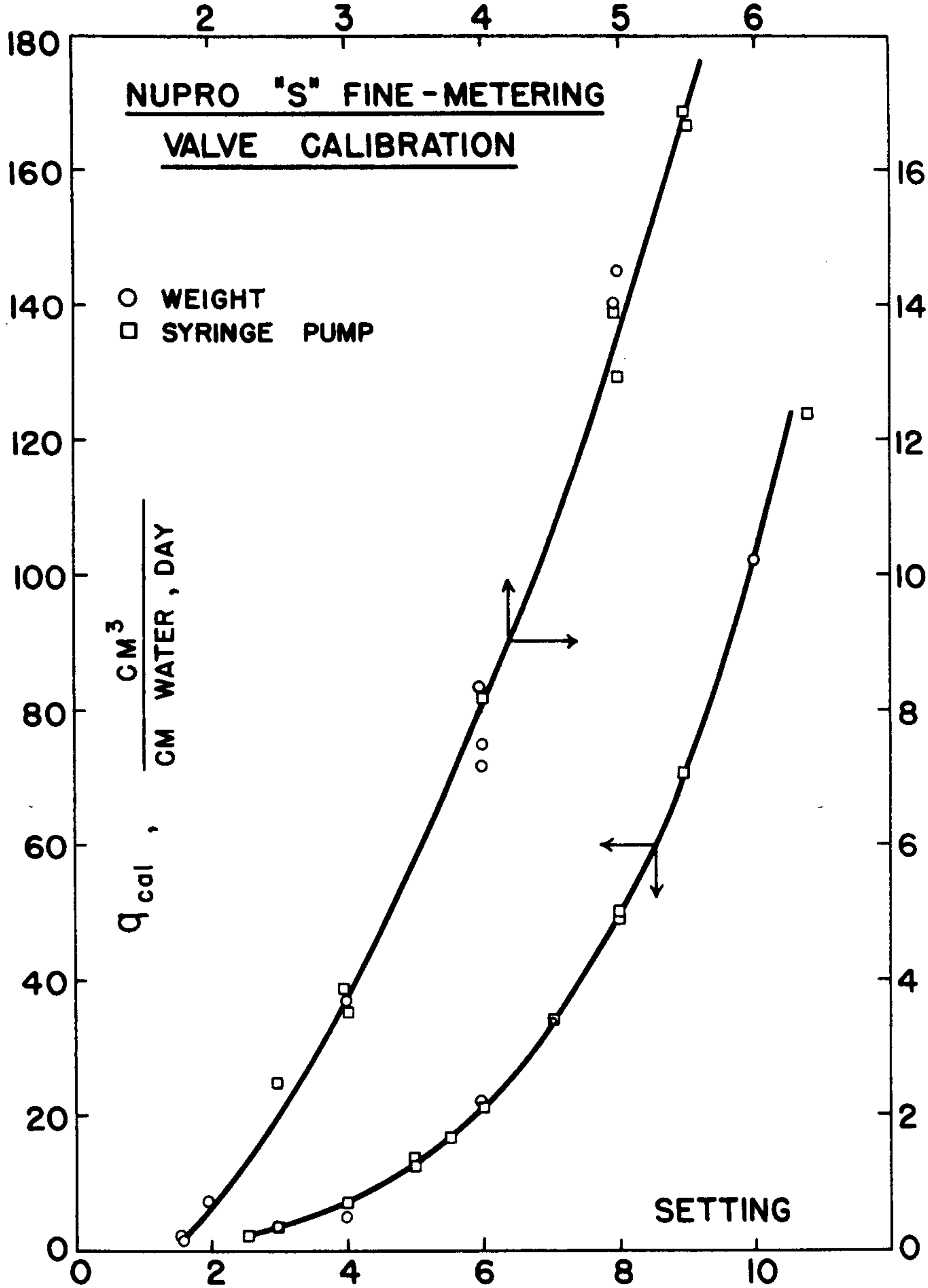
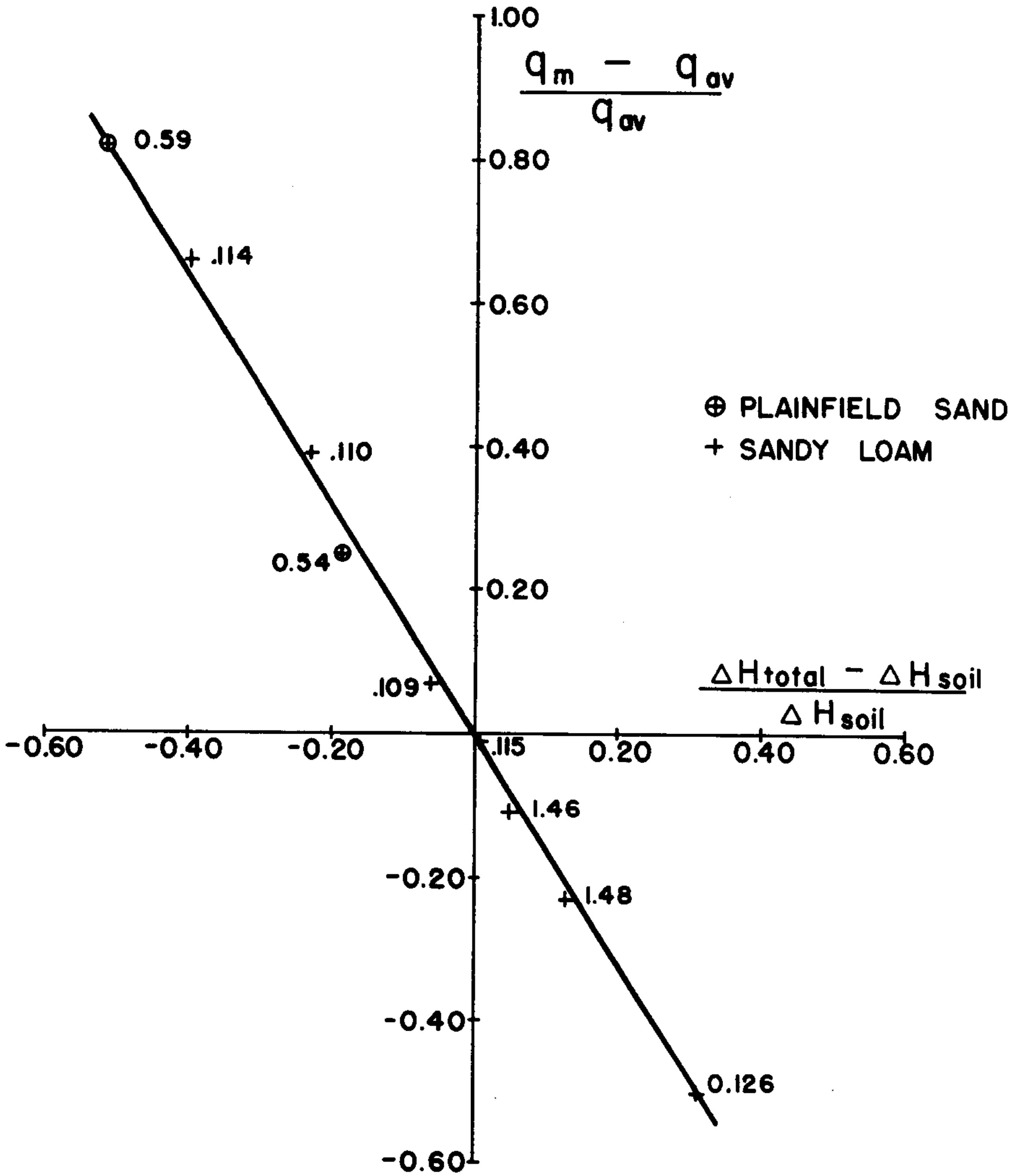

PRESSURE TRANSDUCER
+
−
VALVE
PIN
SPRING
CONCENTRIC CAVITIES
TUBING
FILTERS

Fig. 1



NUPRO "S" FINE-METERING VALVE CALIBRATION
WEIGHT
SYRINGE PUMP
q_{cal}, $\frac{CM^3}{CM\ WATER,\ DAY}$
SETTING
0
2
4
6
8
10
20
40
60
80
100
120
140
160
180
12
14
16
2
3
4
5
6

Fig. 3



1.00
$\frac{q_m - q_{av}}{q_{av}}$
0.59
0.80
.114
0.60
⊕ PLAINFIELD SAND
+ SANDY LOAM
.110
0.40
0.54
0.20
$\frac{\Delta H_{total} - \Delta H_{soil}}{\Delta H_{soil}}$
.109
-0.60
-0.40
-0.20
.115
0.20
0.40
0.60
1.46
-0.20
1.48
-0.40
0.126
-0.60