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Soil Science Step-by-Step Field Analysis

Sally Logsdon, Dave Clay, Demie Moore, Teferi Tsegaye, editors

Natural resource manager, agronomist, land use consultant, educator, environmental consultant.... The lines are blurred, the questions are complicated, and soil science is required knowledge. *Soil Science: Step-by-Step Field Analysis* provides the knowledge for conducting specific activities related to improved natural resource management. Readers will learn both new procedures and tips for improved performance in the field, with a focus on usefulness for real-life applications.

Learning objectives:

- safety protocols for soil sampling
- soil profile description
- reducing sampling error for samples sent to a lab
- understanding variability of soil properties—pH, electrical conductivity, nutrient levels, and salinity—and how they affect crop growth
- site evaluation for specific end uses
- installing wells and piezometers, monitoring water table information
- surveying using simple or sophisticated equipment
- cleaning yield monitor data
- evaluation of overall soil quality
- identification of water repellency
- measuring soil density and water content, infiltration, temperature, and rainfall rate

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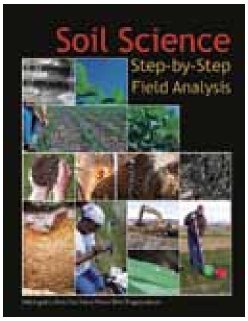

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Infiltration Rate, Hydraulic Conductivity, Preferential Flow

During rain or irrigation, incident water can either enter the soil, or run off. Infiltration operates as the partitioning "switch" at the soil surface. Infiltration rates that are smaller than the precipitation rate will eventually result in surface ponding of water, leading to the creation of run-off. Surface run-off water is not buffered or filtered by its passage through soil. Instead, its quality often deteriorates during its flow across the soil surface, especially if it picks up sediments, nutrients such as phosphorus (P) or nitrogen (N), pesticide residues, or fecal bacteria. This run-off water can rapidly transport these contaminants into surface water bodies, leading to environmental problems such as algal blooms or human health risks in rivers and lakes. Measurements of infiltration rates are needed to assess and manage these risks.

Another application of infiltration data is in the design of sustainable irrigation and effluent disposal schemes. Irrigation rates should be smaller than the infiltration rate at the soil surface and below the saturated hydraulic conductivity of the topsoil. This prevents run-off, surface sealing, and the degradation of the soil's aggregate structure.

The soil's hydraulic conductivity function is also a key input for many water and solute transport simulation models. These are used by scientists, land managers, and policy agents to assess the production responses and environmental impacts of land-use practices.

Often, however, the flow of infiltrating water through soil is not as uniform as our theories and models assume. Rather, a small fraction of the pore space, which is often connected, rapidly transports the majority of the infiltrating solution, with far-reaching consequences. Such flows occur, for example, thanks to macropores, which can originate from cracks, decayed root networks, and earthworm channels. Water and solutes often flow only through this preferential fraction of the soil's volume, bypassing the bulk of the soil's

Summary

The hydrology of our soils is controlled by the physical processes operating at the soil surface. We describe the new measurement techniques that are improving our vision of these processes. Tension infiltrometers can be used to determine the infiltration rate into soil and to measure the soil's near-saturated hydraulic properties. These properties reveal whether there is likely to be preferential, or bypass, flow through the soil. Tipping-bucket water flux meters can be used in the field at remote locations to provide a detailed temporal record, in real time, of the flow of water and transport of solutes moving through the surface soil. These observations, along with new modeling schemes, are increasing our ability to predict the hydrological functioning of surface soils.

Markus Deurer
Brent Clothier
Steve Green
Sustainable Land Use,
HortResearch
Palmerston North
New Zealand 4442
(bclothier@hortresearch.co.nz)

Glendon Gee
Battelle ETB 1349
P.O. Box 999, 3200 Q Ave.
Richland, WA 99352

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matrix. This behavior occurs because of the higher hydraulic conductivity, and greater continuity of the large macropores, compared with the pores in the rest of the soil matrix.

Preferential flow also regularly occurs if water-repellent zones develop in very dry soils. Such zones are either bypassed by water and solutes or traversed in the form of a few isolated "fingers".

When does preferential flow matter? It matters, for example, when assessing the leaching risk associated with surface-applied substances, such as pesticides and bacteria. This is especially true when the concentrations, however small, that reach the groundwater do actually matter in terms of water quality. Preferential flow can reduce the water use efficiency of irrigated crops and might reduce the efficiency of surface-applied substances such as fertilizers or herbicides. If the location of the source of the substance is within the soil matrix, as for example might be the case for mineralized nitrate, then the risk of groundwater contamination due to preferential flow is less because the mineralization occurs within the matrix, isolated and insulated from the bypassing flows. Preferential flow is most significant when the soil is either close to saturation or very dry. Large earthworm channels and pedogenic cracks can only conduct water if ponding occurs at the soil surface or the orifice of the macropore. Water repellency only develops in dry soils below a critical water content.

Field Measurement Devices

We recommend tension infiltrometers (also known as disk permeameters; Perroux and White, 1988) to measure the infiltration rate and derive the unsaturated and saturated hydraulic conductivity properties of field soils. In addition, the use of tracer chemicals in infiltrometers can be used to identify the fraction of the soil's water content that can be classified as either **mobile** or **immobile** (Clothier et al., 1992), plus the exchange between these domains (Jaynes et al., 1995). Other devices can be used, and their strengths and weaknesses are described elsewhere (Clothier, 2001; Reynolds and Elrick, 2005).

To directly measure drainage fluxes and transport through soil and to estimate the degree of preferential flow in the field, we recommend the use of water-flux meters in combination with measurements of the soil's water content.

Tension Infiltrometry

Two forces control infiltration into and drainage through soil: **capillarity**, associated with the nooks and crannies of the soil's porous networks, and **gravity**, which attracts water downward toward the center of the earth. Flow in fine-textured soils is dominated by capillarity, and for coarse-textured soils the dominant force is gravity. **Sorptivity** is an integral measure of the soil's capillarity, and **hydraulic conductivity** is a measure of the ease with which water can pass through a soil under a given total potential gradient. Tension infiltrometers are devices that can be used to measure the soil's capillary and conductive properties (Fig. 1).

Several companies sell tension infiltrometers. Their cost ranges from $1500 to about $3000, depending on components and accessories (Table 1). Commercially available tension infiltrometers are sold pre-calibrated.

Table 1. Major suppliers of tension infiltrometers and tipping-bucket water-flux meters (TWFMs).[1]

Manufacturer	Address	Disk diameter Tension range
Tension infiltrometers		
Soil Measurement Systems	7090 N Oracle Road #178-170 Tucson, AZ 85704 USA Phone: 520-742-4471 http://www.soilmeasurement.com	8 and 20 cm 0 to −30 cm
Soilmoisture Equipment Corp.	P.O. Box 30025 Santa Barbara,CA 93105 USA Phone: 805-964-3525 http://www.soilmoisture.com	20 cm +2 to −25 cm
Decagon Devices	950 NE Nelson Court P.O. Box 835, Pullman, WA 99163 USA Phone: 1-800-755-2751 http://www.decagon.com	4.5 cm −0.5 to −6 cm
ICT International	P.O. Box 503 Armidale, NSW 2350 Australia Phone: +61 2-6772-6770 http://www.ictinternational.com.au	8 and 20 cm 0 to −30 cm
Eijkelkamp	Nijverheidstraat 30 6987 EM Giesbeek, The Netherlands Phone: +31 313-880200 http://www.eijkelkamp.com	20 cm 0 to −30 cm
SDEC France	Z.I. de la Gare 37310 Reignac sur Indre, France Phone: +33 2-479-41000 http://www.sdec-france.com	20 cm 0 to −30 cm
Water-flux meters		
Decagon Devices	950 NE Nelson Court, P.O. Box 835 Pullman, WA 99163 USA Phone: 1-800-755-2751 http://www.decagon.com	<60 cm <1 cm
Sledge Products	P.O. Box 727 Dayton, OR 97114 USA Phone: 503-868-7617 http://www.sledgesales.com	<60 cm <1 cm
HortResearch	Tennent Drive, Private Bag 11030 Palmerston North, New Zealand Phone: +64 6-356-8080 http://www.hortresearch.co.nz	Negotiated

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[1] Trade names are included for the benefit of the reader and do not imply endorsement of or preference for the product listed by the authors or SSSA.

Fig. 1. Schematic cross-sectional view of a tension infiltrometer showing its principles of operation. The infiltrometer is set at pressure head h_o, and both capillarity (multi-dimensionally) and gravity (vertically) draw water from the reservoir into the soil at flux density Q (mm h^{-1}).

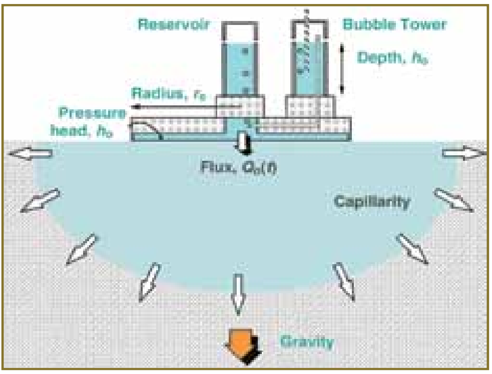


Fig. 2. The use of tension infiltrometers in the field. (A) Preparation of the contact sand as the infiltration surface atop the undisturbed soil. (B) Measurement of the infiltration rate at the surface. (C) Multiple and simultaneous measurement of infiltration rates at several depths in a soil profile.

Preparation

It is best to assemble the infiltrometer before field use by filling it with water to check for possible leaks. If air enters the reservoir, water will leak out because the infiltrometer has not "held" the suction (or pressure head) set by the air-entry tube at depth h_0 in the bubble tower (Fig. 1). Leaks can occur because the nylon cloth that covers the base of the infiltrometer disk can be easily punctured with little holes. If this occurs, then the nylon cloth will need to be replaced. Companies that sell infiltrometers supply procedures for how to test systematically for leakages and how to fix them (e.g., http://www.soilmeasurement.com/tension_infil.html). It is convenient to transport the water-filled infiltrometer to the field in a bucket and then set the air-entry tube to h_o and place the infiltrometer in a retort stand, off the ground, to await placement onto the specially prepared surface. Again, check for air leaks before placement onto the soil. Level the measurement surface and remove all protruding plant stalks, roots, or other debris. For all but sandy soils, cover the measurement surface with a thin (2–3 mm) layer of contact sand (Fig. 2A).

Mini-disk-infiltrometers, a single tubular assembly that combines the bubble-tower and reservoir into one unit, are available for easy and robust use in circumstances where a quick assessment of the soil's hydraulic properties is sought (http://www.decagon.com/environmental/infiltrometer). These have the advantage of portability. Because they use little water, they can be used in remote locations. They only sample a small volume of the soil, however, so more replications will be required to obtain confident results.

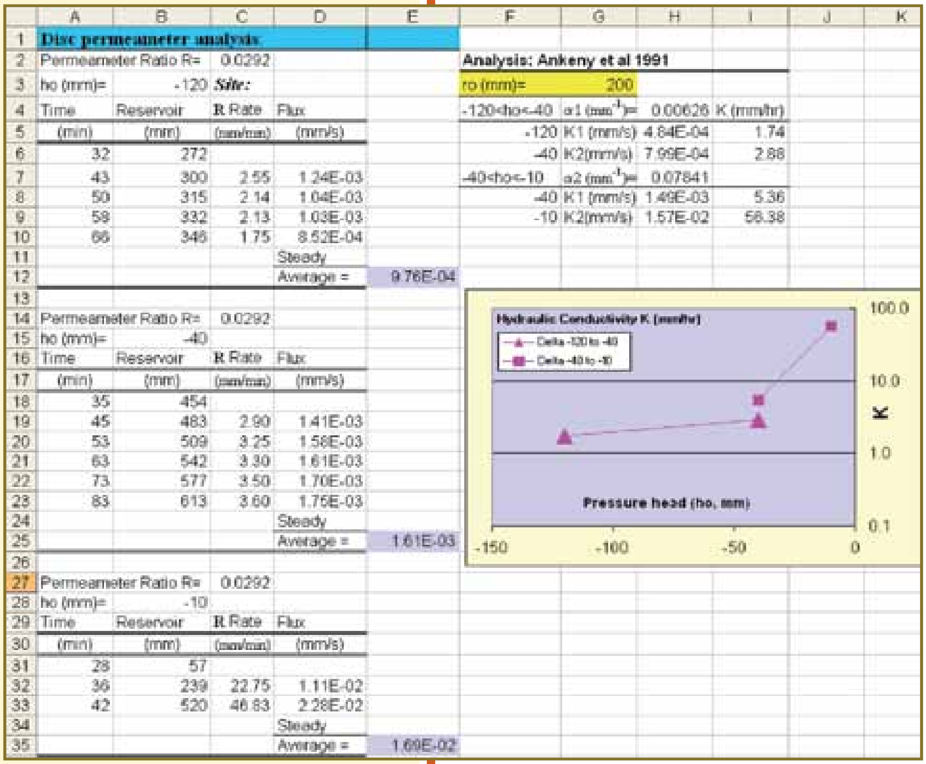
Here we describe the use of tension infiltrometers, which analyze flow measurements from at least two pressure heads h_o to resolve the two components that control infiltration into soil: capillarity and gravity (Fig. 1) (Ankeny et al., 1991).

A tension infiltrometer can measure the infiltration rate into a soil at pressure heads between 0 and −300 mm, depending on the device. The pressure head is set by adjusting the air-entry tube in the bubble tower (Fig. 1). The distance from the bottom of the tube to the water level within the bubble tower, h_o, is the tension, or pressure head, at which the water infiltrates from the disk into the soil at rate Q (mm h^{-1}) (Fig. 1). Make sure there are no air bubbles sitting above the membrane. If so, then get rid of them by tilting and rotating the infiltrometer in such a way that the air bubbles escape up into the reservoir.

Measurement at a Single Depth

Set the disk firmly on the contact sand with a slow, forceful downward motion. Do not twist the infiltrometer because that could dislodge the membrane from its assembly or puncture the membrane. The entire disk needs to be in contact with the contact sand. Use your finger and draw a small trench around the disk to ensure that infiltration occurs in the area of contact sand that is the same radius as the disk, r_o (Fig. 1 and 2). Capillary forces dominate the early phase of flow, and then the geometry and dominance of gravity forces establish the phase of steady-state infiltration (Fig. 3). The infiltration rates are measured by recording the water level in the water reservoir versus the time (Fig. 3). The water reservoir is the larger of the two towers on the infiltrometer (Fig. 1). Either record the water level in the reservoir at preset times, such as every minute at the start and later every 10 min, or measure the times at preset changes of the water level, such as at every 5-mm decrease of the water level. Some infiltrometers use a differential-pressure transducer in the water tower that is connected to a data logger so the readings can be automated.

Fig. 3. A spreadsheet example using the Ankeny et al. (1991) method to calculate piecewise the hydraulic conductivity function near saturation for h_o values of −120, −40, and −10 mm. The infiltrometer was of radius 200 mm, and the ratio of the reservoir's cross-sectional area to the area of the infiltration disk was 0.0292.



	A	B	C	D	E	F	G	H	I	J	K
1	**Disc permeameter analysis**										
2	Permeameter Ratio R=		0.0292			**Analysis: Ankeny et al 1991**					
3	ho (mm)=	-120	***Site:***			ro (mm)=	200				
4	Time	Reservoir	R Rate	Flux		-120<ho<-40	α1 (mm⁻¹)=	0.00626	K (mm/hr)		
5	(min)	(mm)	(mm/min)	(mm/s)		-120	K1 (mm/s)	4.64E-04	1.74		
6	32	272				-40	K2(mm/s)	7.99E-04	2.88		
7	43	300	2.55	1.24E-03		-40<ho<-10	α2 (mm⁻¹)=	0.07841			
8	50	315	2.14	1.04E-03		-40	K1 (mm/s)	1.49E-03	5.36		
9	58	332	2.13	1.03E-03		-10	K2(mm/s)	1.57E-02	56.38		
10	66	346	1.75	8.52E-04							
11				Steady							
12				Average =	9.76E-04						
13											
14	Permeameter Ratio R=		0.0292								
15	ho (mm)=	-40									
16	Time	Reservoir	R Rate	Flux							
17	(min)	(mm)	(mm/min)	(mm/s)							
18	35	454									
19	45	483	2.90	1.41E-03							
20	53	509	3.25	1.58E-03							
21	63	542	3.30	1.61E-03							
22	73	577	3.50	1.70E-03							
23	83	613	3.60	1.75E-03							
24				Steady							
25				Average =	1.61E-03						
26											
27	Permeameter Ratio R=		0.0292								
28	ho (mm)=	-10									
29	Time	Reservoir	R Rate	Flux							
30	(min)	(mm)	(mm/min)	(mm/s)							
31	28	57									
32	36	239	22.75	1.11E-02							
33	42	520	46.83	2.28E-02							
34				Steady							
35				Average =	1.69E-02						

Measurement at Multiple Depths

To measure the infiltration rates at several depths in the soil profile it is best to dig a soil pit first. Flat, horizontal surfaces can be carefully excavated in the shape of a staircase (Fig. 2C). Make sure that the steps are large enough to replicate the measurements. If the contact sand is very slightly pre-wetted, it makes it easier to spread, and stops it falling down macropores, which would otherwise create "wicks" that would enhance infiltration.

Notes

In general, the duration and frequency of measurement of the infiltration rate depends on the value of the pressure head h_o, the soil type, and the wetness of the soil. For example, if one wants to derive the hydraulic conductivity at a specific tension, then it is necessary to wait until a steady-state infiltration rate is reached. This may well take more than an hour, especially at smaller heads, say h_o less than −100 mm, when the flow is more unsaturated.

As a rule of thumb, at least three to four consecutive readings should show about the same infiltration rate, namely **steady state**. Once a measurement at a specific pressure head is finished, the air-entry tube in the bubble tower can be adjusted to the next tension. Care must be taken that the contact between the disk and the soil remains intact or is re-established. Before the next measurement, make sure there is still enough water left in the reservoir to finish the next measurement sequence.

Typically start with the lowest, that is the most negative, pressure head. Depending on the soil and the pressure head being applied, it might take some time before you can see the infiltration start, as indicated by air bubbling into the reservoir. If it takes too long, especially in heavy-textured soils, you might then decide to reduce the pressure head. If the infiltration still does not start, then it could be that the disk does not have good contact with the soil or, that the soil is hydrophobic (Tillman et al., 1989).

We recommend measuring the infiltration rates at three or four pressure heads. The infiltrations measured between the low-tension pairs of, say typically −150 mm and −80 mm, would describe the conductivity of the soil's matrix, and the results from the higher-tension pair of about −20 mm and −10 mm can provide a measure of the conductivity of the macropores (Fig. 3).

Interpretation and Use of the Data

Several hydraulic and solute-transport properties can be derived from tension infiltrometry, and these can be based on a variety of methods. Here, we list the most important of these properties and refer the reader to some helpful references. This information is also contained, in part, in the manuals or spreadsheets that accompany commercially available infiltrometers, such as that provided by Soil Measurement System on http://www.soilmeasurement.com/tension_infil.html.

Hydraulic properties that can be derived from tension infiltrometry include:

- **Hydraulic Conductivity.** A variety of methods are available, most of which rely on solving Wooding's equation (Wooding, 1968) for a circular surface disk-source of water maintained at head h_o. See Clothier (2001), Hopmans et al. (2007), Logsdon and Jaynes (1993), and Reynolds and Elrick (2005).
- **Sorptivity.** Sorptivity is a measure of the soil's capillarity. Depending on the method used for sorptivity determination, knowledge of the water content at the start and the end of an infiltration measurement period at a specific tension is needed. We recommend taking a sample directly adjacent to the infiltration disk at the start to determine the antecedent conditions, and from just below the contact sand at the end of the measurement to measure the water content at head h_o. See Clothier (2001), Hopmans et al. (2007), and Reynolds and Elrick (2005).
- **Flow-Weighted Mean Pore Diameter.** From knowledge of the soil's conductivity and capillarity it is possible to infer the size of pore that would account for the flow characteristics observed as the infiltration rate changes with pressure head. In general, the more the conductivity changes between successive heads, the larger the size of the "average" pore. See Clothier (2001), Reynolds and Elrick (2005), and White and Sully (1987).
- **Mobile and Immobile Fractions.** By placing tracer chemicals in the reservoir of the infiltrometer, and then sampling the soil beneath the infiltrometer to determine the final resident-concentration of tracer, it is possible to determine the fraction of the soil's pores that were involved in the infiltration of the solution from the infiltrometer—the so-called mobile water content. By repeating this sequentially using multiple tracers, it is possible to determine the solute-exchange rate between this fraction, and the so-called immobile fraction of the soil's water. These ratios, plus the inter-domain exchange coefficient, are useful parameters in the dual-domain modeling of preferential flow. See Clothier (2001) and Jaynes et al., (1995).
- **Hydrophobicity.** If glass tension infiltrometers filled with a solution of 95% ethanol are used, then a measure of the soil's sorptivity for ethanol can be obtained. If this result is compared with the sorptivity from permeameters filled with water, then the ratio of the sorptivities should scale in relation to the different surface tensions of ethanol and water, namely 1:1.95. If the soil were hydrophobic, then this ratio would be larger, as the water sorptivity will be less than expected. This can be used as a measure of the water repellency of the soil. Do not use ethanol in acrylic infiltrometers as it causes them to disintegrate. See Clothier et al. (2000) and Tillman et al. (1989).

Fig. 4. The use of water-flux meters in the field. (Upper) Installation of a water-flux meter under potatoes. (Lower) A water-flux meter under pasture. The protruding tubes are for the calibration of the tipping spoon (light-colored tube) and the extraction of the soil solution (darker tube). Additionally, a CS616 soil moisture sensor was installed to measure the soil's water content (see the chapter on bulk density in this volume, Logsdon et al., 2008).

Water-Flux Meters

Water-flux meters are devices that have only been developed recently, and currently only a few companies sell them. These include Decagon of Pullman, WA (http://www.decagon.com/) and Sledge Products of Dayton, OR, USA (www.sledgesales.com) (Table 1). It is fairly easy to build them, and the cost for the materials for a single flux meter is about $500 (Table 1). Different designs exist. We will focus on the tipping-bucket water-flux meter (TWFM).

Water-flux meters are devices that are used to monitor and better understand solute transport in unsaturated soils. In our experience, water-flux meters can only be installed above the highest level of the water table. Otherwise, they will rise with the water table. A typical application for the water-flux meter is monitoring of pesticide and nutrient leaching from an agricultural field (Fig. 4). In this case, we would recommend installing the flux meters just below the plow layer. Another application could be to monitor the leaching of dissolved organic carbon from the topsoil of a grazed pasture (Fig. 4). Here, the top column would end at the soil surface. The TWFM typically consists of three assemblies (Fig. 5):

The Convergence Ring. The first part is a convergence ring with the same diameter as the funnel (~0.2 m) to prevent the sideways movement of water and solutes away from the sampling device (Part 2 in Fig. 5B). This tube can enclose repacked soil, or preferably it can also be used to collect undisturbed cores that are "bolted" directly onto the other two assemblies before installation in the field. For coarse-sandy soils, the convergence ring should have a length of about 0.15 m (6 inches) to prevent flow away from the collection unit. For finer-textured soils, and for sites with small water fluxes, a length of 0.6 m (24 inches), or more, is recommended (Gee et al., 2002). This convergence ring can be sharpened at the bottom and carefully "pounded" or hydraulically pressed into the soil to the desired depth of measurement. This is best done when the soil is close to field capacity. The cylinder containing the undisturbed soil is then excavated, and the base carefully smoothed to ensure a good hydraulic connection with the collection unit. Alternatively, the soil can be refilled and repacked in the tube layer by layer so that the depth profile and bulk density of the soil in the tube is similar to the surrounding soil.

The Funnel, the Wick, and the Tipping Spoon. The second part of the TWFM contains the funnel (Part 4 in Fig. 5B), a wick (Part 5 in Fig. 5B), plus a tipping spoon (Part 8 in Fig. 5B), or drop-counting mechanism. The wick comprises two intertwined fiberglass ropes (Pepperell Braiding Company, Pepperell, Massachusetts, USA), each with a diameter of 12.7 mm (0.5 inches). The wick has to be "cooked" at 400°C (more than 750°F) for at least 3 hours to remove any organic residues that might make the wick hydrophobic (Knutson et al., 1993). The wick is then inserted through the neck of the funnel. More information on the hydraulic properties of the wick can be found elsewhere (Knutson and Selker, 1994). About 0.15 m (6 inches) of the wick is left above the funnel neck. This part of the wick is then unbraided into its individual strands, and then these are spread across the funnel top. To prevent soil from entering the funnel, a thin layer of diatomaceous earth is placed on top of the unbraided strands of wick. The convergence ring containing the soil is then "bolted" on top of the funnel. We recommend gluing both parts together, as well as inserting screws horizontally to provide sufficient strength should the TWFMs need to be removed from the soil.

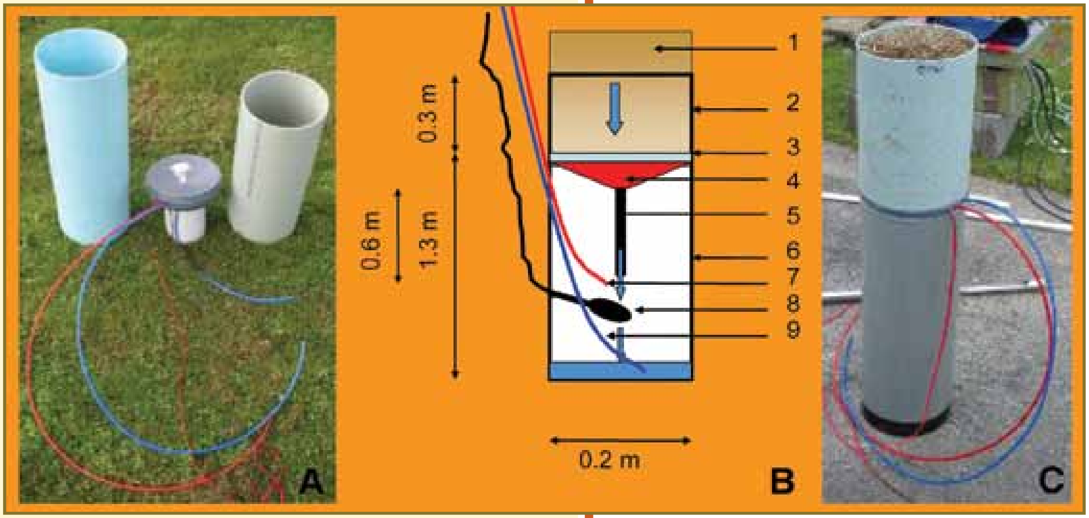


Fig. 5. A tipping-bucket water-flux meter (TWFM). (A) The three different assemblies of a TWFM from left to right: collector; funnel, wick, and tipping spoon unit; and column to prevent flow divergence. (B) Schematic cutaway view of a water-flux meter: 1) soil, 2) flow divergence ring, 3) layer of diatomaceous earth, 4) funnel, 5) fiberglass wick, 6) collector, 7) tube for calibration of tipping spoon, 8) tipping spoon with connection to data logger, 9) tube to extract the soil solution from collector. (C) Fully assembled water-flux meter ready for installation.

The length of the wick, l_o, akin to h_o for the tension infiltrometer, which extends vertically below the funnel establishes the suction head, l_o, that will be applied to the bottom of the soil column (Part 2 in Fig. 5B). The length of the wick below the base of the soil column is the suction head created there, namely l_o. A wick length of between 0.6 and 1.0 m (24–39 inches) is often recommended (Gee et al., 2002), although this can be shortened if, for example, TWFMs are sought to mimic tile drains. Because the suction head, l_o, is constant, during the course of the year, such a set wick length might lead to over-sampling during the wet season, or under-sampling during the dry season (Mertens et al., 2007). Unfortunately, a seasonal change in wick length is not practically feasible at this time.

The tipping spoon needs be calibrated after the installation of the TWFM in the field because the installation might lead to the TWFM being aligned somewhat off-vertical. A known volume of water is injected down the calibration tube that ends just above the tipping spoon (Part 7 in Fig. 5B). One spoon tip is about 5 mL. For example, if we assume a cross-sectional area of 314 cm^2 for a 200-mm-diameter convergence ring, then we achieve a resolution in the drainage depth-equivalent of 0.15 mm.

The tipping spoon (Rain-O-Matic, Pronamic Co. Ltd., Sikeborg, Denmark) can easily be automated by connecting it to a data logger with a pulse counter. Continuous monitoring of the water flux, at high temporal resolution, is possible, and if the data logger is connected to a modem, this can be done remotely, while allowing interrogation in real time. Note that the commercial unit of Sledge Products has two tipping spoons in series, for redundant measurement capability.

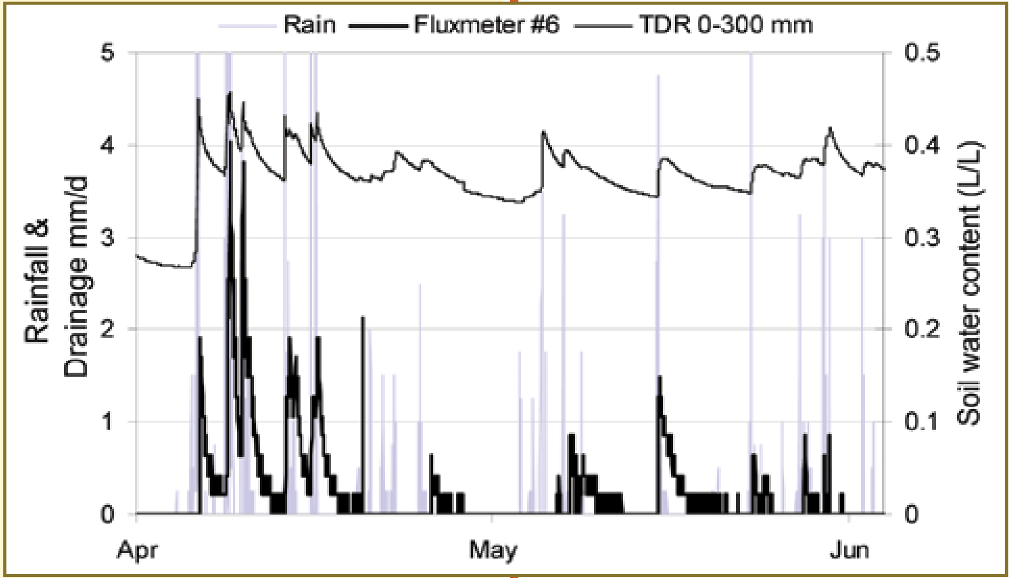
The Collector. The third part of the TWFM is the collector (Part 6 in Fig. 5B). The other two parts are simply glued, and preferably screwed on top of the collector. The length of the bottom column depends on the wick length, and on the intended collector capacity to store solution. A length of about 1.2 to 1.5 m (4–5 feet) is usually sufficient. The bottom column also contains another tube (Part 9 in Fig. 5B), which ends at the bottom of the collector. This is used to extract the soil solution (Gee et al., 2003; Van der Velde et al., 2005). Once all three parts are assembled, the TWFM is ready to be installed in the field.

Installation and Use in the Field

A borehole with a diameter slightly larger than the TWFM is augered to the required depth. This depth depends on the intended depth of measurement and the overall length of the TWFM. To insert the TWFM into the hole we recommend drilling two holes at the top of the convergence ring (Part 2 in Fig. 5B) and inserting a rope through them. When first augering the hole we advise to carefully separate the soil above the water-flux meter into layers of about 0.1 m (4 inches) because the soil above the TWFM needs to be replaced and repacked in the same order and at the same bulk density as the surrounding soil. The respective soil material can be stored in the right order, for example, in a series of color-coded buckets, before replacement. In some cases, the convergence ring (Part 2 in Fig. 5B) can be aligned with the soil surface, as is the case with the TWFM in Fig. 5C.

The water flux in the meter can be continuously recorded with a data logger (Fig. 6). Therefore, the amount of soil solution that can be extracted from the flux meter is always known. Thus, it is possible to collect a soil solution that is weighted by a known cumulative water flux. Depending on the application, a sampling after every 10 mm of water flux can be made, or it can be performed after a given time-interval, or even following a "call-out" after a known volume of drainage has been remotely detected. With TWFM, plus associated measurements of rainfall, and the soil's water content by time domain reflectometry (TDR), it is possible to obtain temporally detailed information about the soil's hydrological functioning at remote locations, in real time.

Fig. 6. Measurement of rainfall, drainage, and soil water content from the field setup shown in Fig. 5. The data were logged at the remote location and downloaded via modem. Local field staff removed water samples for the collector at various times.



Water-flux meters can be used to monitor and better understand solute transport in various ways. At the field scale, due to the high spatial variability of hydraulic properties, we recommend the installation of many water-flux meters to derive the average solute transport. The results can be used, for example, to calculate the amount of applied fertilizer that leaches below the root zone.

Interpretation and Use of the Data

An estimation of how preferential processes affect solute transport in a cropped field, even with TWFM data collected over a long time period with a high degree of detail (Fig. 6), cannot be derived using TWFMs alone. To complement these measurements, we recommend using a numerical solute-transport model, such as SPASMO (Rosen et al., 2004) or HYDRUS (Šimùnek et al., 2003), to achieve a more comprehensive understanding. The combination of measurements and modeling enhances the understanding of infiltration, drainage, and preferential-flow processes. For example, solute transport can first be simulated with a model assuming no preferential flow. These model results can then be compared with the data from the TWFMs.

If solutes were transported downward much more quickly, or with much less water, than simulated, then the flow must have been preferential. To run these models requires the following additional information, and parameters: the initial solution concentrations in the soil, the amount and basic properties of solutes applied, crop uptake, some basic soil hydraulic properties, and meteorological data.

- The initial solution concentration in the soil can be obtained by soil sampling before the start of the experiment.
- The basic soil properties can be measured or can be derived from soil maps using pedotransfer functions (Nemes and Rawls, 2004).
- Meteorological data can be obtained from a nearby weather station or from synthetic weather generators.
- A simple means of calibrating the simulation model is by checking whether the model can reproduce the key measurements as a function of time (Fig. 6). In addition, a tensiometer could be easily installed near a TWFM and connected to the same data logger. Placing a tensiometer both inside and outside the convergence tube, both at the mid height of the tube, can provide a way to estimate the effect of water flow around, or into, the flux meter.
- For conditions where dry soil or large amounts of plant water extraction are expected, it may be possible to use heat-dissipation probes, such as those produced by Campbell Scientific (http://www.campbellsci.com/soil-water-potential), instead of tensiometers for monitoring soil water potential.

Conclusions

New devices and electronic technologies have resulted in advances in our ability to parameterize the hydraulic characteristics of soil, and to observe and monitor its hydrological functioning. These measurement devices have resulted in knowledge and understanding that will ensure the continued productive capacities of our soil, promote the efficient use of input resources, and protect receiving environments.

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