Passive-wick water fluxmeters: theory and practice

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Abstract

Improvements in vadose-zone water-flux measurements are needed for a variety of reasons, including better water-use management for agriculture, for turf-grass (e.g., golf course) operations, and for monitoring the ground disposal of wastes from mining and other industries. For such purposes, we have developed and tested passive-wick water fluxmeters under a wide range of conditions, from non-vegetated desert settings in the USA to irrigated tea plantations in Sri Lanka and rain-fed squash plantations in the South Pacific. In desert settings, the drainage was found to depend upon the precipitation distribution, the surface soil and the type and amount of vegetation. In Washington State, USA, bare sands and gravels drained up to 60% of the annual precipitation while fine soils did not drain. In wetter environments, drainage was found to be closely linked to the rate and duration of precipitation events. Design calculations with a 2-D model show how divergence can be minimized for a wide range of soil conditions under expected transient fluxes. Model results show that for sands, the operational range of the water fluxmeter is from a few mm/yr to well above 10,000 mm/yr, for both steady state and transient conditions, while for silts and clays, the range is more limited and best operates in the range above a few hundred mm/yr. Passive-wick water fluxmeters provide a reliable, robust, and relatively inexpensive method to assess the quantity and quality of drainage waters over a wide range of conditions.

Key Words

Lysimeter, drainage, divergence, water balance, tipping bucket, capacitance sensor

Introduction

It is difficult to measure unsaturated (vadose zone) water flows for at least three reasons. First, vadose-zone flow rates are highly variable, ranging over four orders of magnitude, from a few mm per year to more than 10,000 mm/yr; second, the placement of water-flux sensors can disrupt the flow, causing either convergent or divergent flows with resultant inaccuracies in water-flux estimates; and third, there is no standard method currently available for measuring soil water flux. In this paper, we report the use of a passive-capillary wick lysimeter to measure water and solute fluxes in the vadose zone and show under what drainage rates and soil types the passive-wick system can effectively operate.

Theory

Estimates of the unsaturated water-flux density, J, are needed to quantify water and contaminant transfer within the vadose zone. The pore water velocity, *v*, is derived from the ratio of J to the soil water content, θ, and can be written as:

$$\boldsymbol{v = J / \theta} \qquad (1)$$

The water-flux density is not commonly measured directly but has often relied on secondary measurements of water content or water potential to estimate the water flux. The water-flux density, J, can be derived from water-potential gradients if the unsaturated hydraulic conductivity, K (ψ), is known. However, K (ψ) is seldom measured in the field and only tediously measured in the laboratory, often with great uncertainty. Estimates of J are best derived from direct measurements. One approach is to use lysimetry (Allen *et al.* 1991) where a quantity of soil water is captured in a buried container, and in some fashion, the volume is measured over a given period of time. A wide range of lysimeters has been employed, including pan lysimeters and wick lysimeters, each with its own advantages and disadvantages.

Pan (zero-tension) lysimeters

So called "pan" or zero-tension lysimeters are devices, typically in the shape of a pan, placed at depth below the ground surface to capture drainage water. They require that the pan be filled with coarse gravel or some other highly transmissive material so that the unit can easily intercept the drainage water and divert it to a collection device. The act of placing a gravel drain in the subsurface creates a flow boundary such that when outflow occurs, the soil water pressure becomes equal to atmospheric pressure (Richards 1950). The soil reaches field saturation at the interface between the soil and the gravel. When the pan or under-drain is placed in finer soil than the gravel in the pan, there is a tendency for water to divert around the lysimeter in response to water-potential gradients that exist in the soil at the interface and the soil surrounding the lysimeter. Just how much diversion depends on the flux rate, the textural contrast between gravel and soil, and the gradients in water potential that persist in and around the lysimeter. Pan lysimeters can be shown to operate reasonably well under very wet conditions in soils with large macro-pores, but are much less successful as the soil dries. Initially, pan lysimeters were used primarily to analyze water quality and seldom to quantify drainage rates. More recently, zero-tension lysimeters have been used to estimate drainage rates over a wide range of soil conditions (Chiu and Shackelford 2000; Zhu *et al.* 2002. van der Velde *et al.* 2003, 2004). Because of divergence, collection efficiencies less than 10% have been noted for pan lysimeters and gravel under-drains (Jemison and Fox 1992; Zhu *et al.* 2002), so diversion around zero-tension lysimeters can be a significant problem. Therefore, approaches other than using pan lysimeters have been sought to quantify drainage.

Wick (fixed tension) lysimeters

Wick (fixed tension) lysimeters differ from zero-tension lysimeters in that they control water pressure (or tension) at the drainage interface. Basically, they maintain a fixed tension on the soil using an inert wicking material, such as fiberglass (Holder *et al.* 1991) or rock wool (Ben-Gal and Shani 2002). A hanging water column is created, and drainage water is pulled out of the lysimeter while the lower soil-boundary is maintained at a pressure less than atmospheric so the soil stays unsaturated. The degree of unsaturation depends upon the length of the wick, the flux rate, and the soil type (Holder *et al.* 1991; Boll *et al.* 1992, Knutson and Selker 1994; Rimmer *et al.* 1995; Zhu *et al.* 2002). Figure 1 is a schematic showing a wick-type lysimeter designed to act as a water fluxmeter (WFM). For wick-type lysimeters, divergence can be further minimized by placing an extension tube above the wick (Gee *et al.* 2002, 2003). The extension tube is filled with soil from the excavation of the hole into which the wick unit is placed. Where direct comparisons have been made, wick lysimeters clearly outperform pan lysimeters in their ability to capture drainage water (Zhu *et al.* 2002). In extensive field testing over several years, leachate collection efficiencies (LCEs), defined as measured drainage divided by estimated drainage (obtained from a mass balance of precipitation and evapotranspiration), have been shown to equal or exceed 100% for wick lysimeters (Louie *et al.* 2000; Zhu *et al.* 2002), while average LCE values for pan lysimeters were less than half that amount (i.e., 40%). Gee *et al.* (2002, 2003) have further modified the wick lysimeter to capture both the water and solute fluxes using a solution sampling scheme that simultaneously takes solution samples (for chemical analysis) at the same point and time that flux is monitored.

Other vadose-zone water-flux monitoring schemes

In addition to the more conventional lysimetry, there have been a number of other approaches to direct metering of soil-water flux. Ivie and Richards (1937) used an elaborate plumbing system consisting of two water-filled porous cups embedded in the soil and connected to water reservoirs and drop counters. As water moved upward or downward in the soil, pressure in the cups changed, forcing water into reservoirs where drops were counted and related to the flux. Using modern technology, a meter similar to the Ivie and Richards' unit has been tested, consisting of one or more ceramic plates connected to water-filled pressure transducers. Water flux through the Ivie and Richards-type flux meter in the modern setting is determined from the meter's conductance and the hydraulic head-loss across the meter (Cary 1968; Dirksen 1974; van Grinsven *et al.* 1988). This kind of a WFM has been even more recently modified using sophisticated electronic controls and sensing devices. In the latest version, pressure on a wetted porous-plate collection system is controlled by a vacuum system that is actuated by soil water-pressure sensors (i.e., tensiometers or heat dissipation units) placed in the soil adjacent to the collection container (Brye *et al.* 1999; Kosugi and Katsuyama 2004; Masarik *et al.* 2004). While these devices appear to keep tensions in the collection unit near that of the surrounding soil, thus minimizing divergence, they are far less robust and much more expensive than passive wick lysimeters since they require significantly more equipment, and operationally they are more labor intensive than wick units. In this paper, we investigate the use of wick lysimeters as drainage meters for a wide range of soil types and flux conditions. Specifically, we evaluate lysimeter performance for rates from 1 to 10,000 mm/yr (3.2×10^{-9} to 3.2×10^{-5} cm/s) for sand, loam, and clay soils.

Materials and Methods

Fluxmeter design

The meter is designed to use a funnel filled with soil. The soil captures flow from a predetermined area where it drains into the funnel neck occupied by a conductive material capable of applying a capillary suction (tension). In our meter, a fiberglass wick is used. Water flux is measured directly by placing a transducer at or near the distal end of the wick (Figure 1).

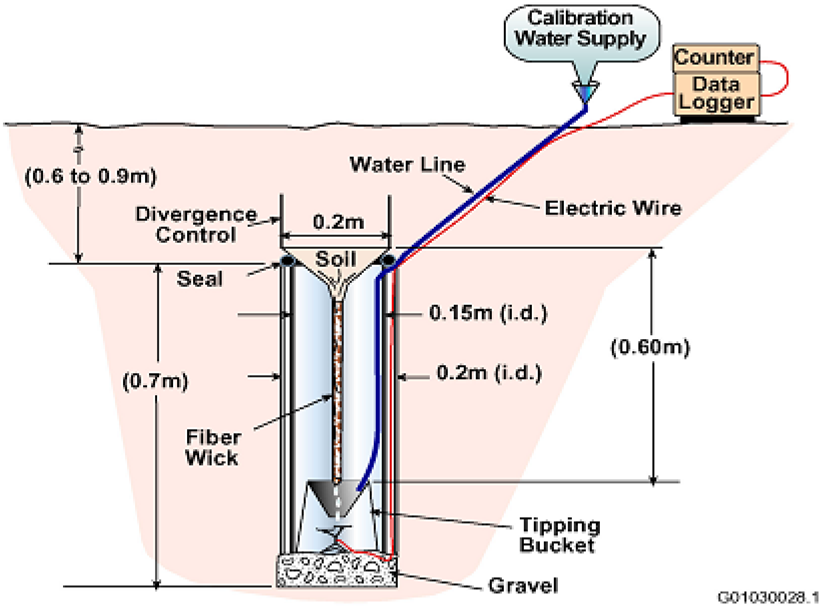

Figure 1. Schematic of a passive-wick WFM.

In the present design (Figure 1), the collector consists of a funnel (~21 cm i.d., 12.5 cm high). Our fluxmeter incorporates a divergence control mechanism. The divergence control consists simply of a pipe about the same diameter as the collector funnel that extends from the top of the upper funnel to a height of 60 cm. The height of the divergence controller depends on soil type and can be easily optimized. The restricted channel (funnel neck) is 2.5 cm in diameter and is filled with a fiberglass wick material. In some of our tests (Figure 2 b), we used two inter-twined fiberglass ropes (Pepperell Braiding Company, Pepperell, MA), each having a diameter of 12.7 mm.

In other tests (Figure 2c), we used larger diameter (2.5 cm) wick material (Amatex, Norristown, PA). The ropes were kiln dried at 400°C for 3 hr to remove glue and other organic materials, as recommended by Knutson *et al.* (1993). The top 15 cm of the wick material was separated into single strands, which were used to line the interior of the collector. To prevent soil from filtering through the funnel and the rope, a thin layer of diatomaceous earth was placed in the bottom of the funnel above the rope. The wick extended vertically ~50 cm below the collector bottom. For the tests reported here, the diameter of the diversion-control collector ranged from 20 to 21 cm. Correspondingly, the tested water-flux meters have a collector (soil-filled funnel and diversion pipe) with a surface area ranging between 314 cm^2 and 340 cm^2 while the restricted channel had a cross-sectional area of 5.1 cm^2. However, larger dimensions for wick and collector can be accommodated easily in the design. The Ksat of the wick is extremely high and under normal flow conditions (<10,000 mm/yr), offers little resistance to the overall flow in the water fluxmeter. Similarly, the diatomaceous earth material is highly conductive.

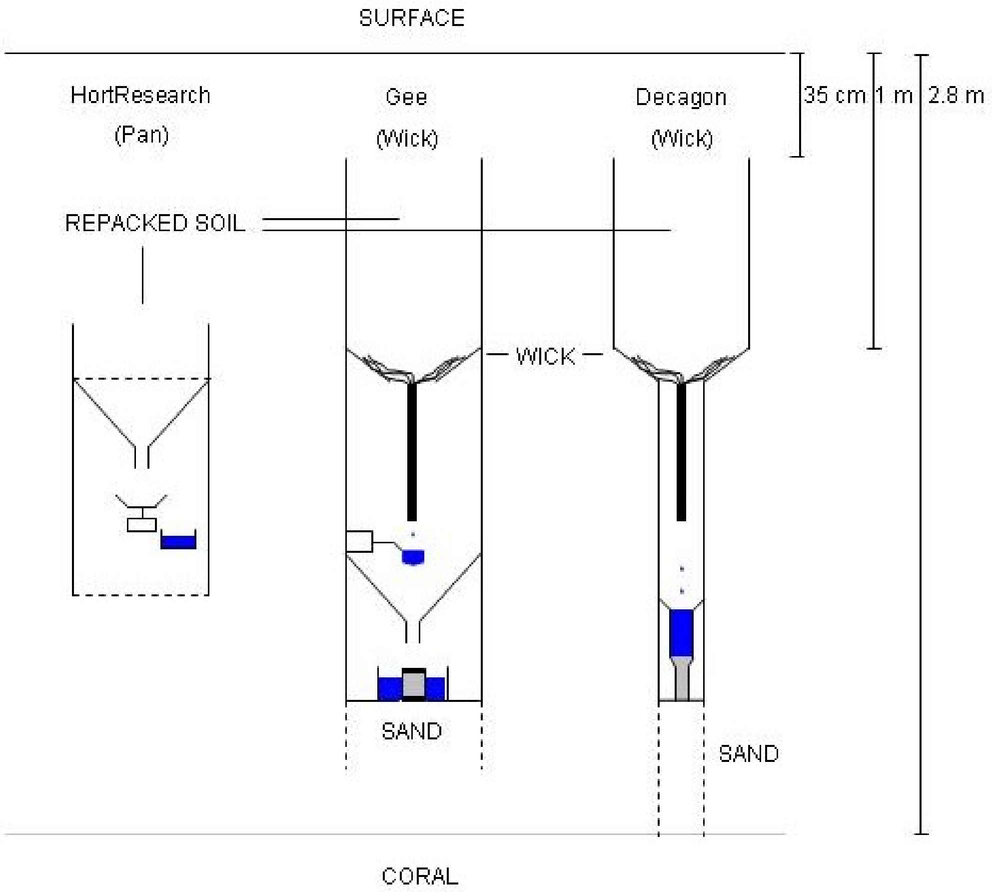

Figure 2. Schematic of three WFMs tested in the same field in Tongatapu, Tonga. 2a) pan-type, 2b) wick type-tipping bucket; and 2c) wick type-capacitance sensor (after van der Velde 2003). Cups shown at the bottom of each WFM represent the collection zones for water samples. The Gee Wick unit uses a tipping spoon, while the Decagon Unit uses an auto-siphon and capacitance probe detector.

Water was collected from the wick in two ways. The first used a miniature rain gauge (Rain-O-Matic, Pronamic Co. Ltd, Sikeborg, Denmark) that consists of a reed switch and a small plastic spoon to which a magnet is attached (Figure 2b). The tipping spoon is positioned in a 10.2-cm-dia. PVC plastic tube designed to isolate the wick from the surrounding soil. As the spoon fills and empties, the magnet moves past the reed switch, causing an electrical pulse to be counted on an event recorder. Because the tipping spoon is enclosed, there is no evaporation from it, and even when the soil drains and dries, the humidity near the tipping spoon typically remains at ~100%. All exposed components of the buried gauge are potted and sealed so that they do not rust in such a wet environment (Gee *et al.* 2002). A number of these tipping spoon units have been in the ground and operational now for over three years. For the tipping spoon design, an application rate of 0.3 mL/min was about the upper limit of the range of interest (i.e., ~5000 mm/yr). The lower range of interest is less than 1 mm/yr, which is achievable because the resolution of one tip is equivalent to ~0.15 mm water. The second collection method (Figure 2c) uses an ECHO-type capacitance probe (Decagon Devices, Pullman, WA) in a manner similar to that reported by Masarik *et al.* (2004) with the following modifications. The capacitance probe is placed in the center of a water reservoir (~60 mL capacity), and as the water fills the reservoir, corresponding capacitance changes are recorded. As capacity is approached, an auto-siphon discharges the reservoir (~40 mL), and the process is repeated. Data loggers can be programmed to capture either the discharge or the stage as indicted by the changing capacitance reading of the probe (van der Velde *et al.* 2004). In one test, we compared the results of three types of fluxmeters, pan (Figure 2a), wick with tipping spoon (Figure 2b) and wick with capacitance sensor (Figure 2c).

Numerical simulations

Flow was simulated using the STOMP (**S**ubsurface **T**ransport **O**ver **M**ultiple **P**hases) simulator (White and Oostrom 2004), which is designed to solve a variety of nonlinear, multiple-phase, multi-dimensional flow and transport problems for unsaturated porous media. A cylindrical coordinate system was used, and only one slice of the cylinder was used in the simulation. The simulation domain was subdivided into a grid with variable spacing steps (Δx and Δz). The minimum value of Δx was 1 mm, which was at two locations where the bottom of the funnel and the wall of the WFM reside. The minimum value of Δz was 2 mm, which was where the funnel was located. The modeling domain was 1 m horizontally and 2 m vertically and was discretized into 104 × 128 nodes.

Both steady state and transient simulations were carried out. For the steady-state simulations, the upper boundary conditions were set as a constant flux of 1, 10, 100, 1000, and 10,000 mm/yr. The lower boundary outside the WFM was set as a unit gradient condition and that inside the WFM at the bottom of the funnel was set as a constant head of 60 cm. The wall of the WFM was treated as being impermeable. The differences between steady-state and transient simulations were that for the transient cases, the upper boundary conditions were set as variable flux, and the lower boundary at the bottom of the funnel was set as a constant head of either 60 or 100 cm. Simulations were carried out for soils with different textures—a sand, silt loam, and clay. The hydraulic parameters are summarized in Table 1.

Table 1. Soil hydraulic properties (van Genuchten [1980]-type parameterization).

Soil	K_s ($m\ s^{-1}$)	α (m^{-1})	n	θ_s ($m^3\ m^{-3}$)	θ_r ($m^3\ m^{-3}$)
sand	2.92×10^{-4}	8.05	4.81	0.310	0.093
silt loam	1.10×10^{-5}	1.78	1.34	0.500	0.000
clay	3.19×10^{-5}	5.00	1.45	0.590	0.447

Field tests

Field tests have been conducted with the passive wick lysimeters at a variety of locations throughout the world. These include sites near Richland, Washington, USA, under a cool-desert setting and in humid sites, including a tea plantation in Sri Lanka and a squash plantation in Tongatapu, Tonga (South Sea Islands). We report data from these three locations to illustrate the breadth of application of the passive wick lysimeters for monitoring vadose-zone drainage. At the USA and Sri Lanka sites, devices similar to those shown in Figure 1 were deployed and have been operational in various locations for more than 2 years. At the Tongan site, the three types of WFMs (pan, wick-with tipping bucket, and wick-with capacitance probe sensors) shown in Figure 2 were tested. The complete analysis of the Tongan drainage data set can be found elsewhere (van der Velde *et al.* 2004).

Results and discussion

Model results

For the flux analysis, we calculated the flux efficiency ratio (J_m/J_a), which is the ratio of the measured flux, J_m, to the actual flux, J_a, where the actual flux is the applied steady-state flux incident on the flux meter. Values of the flux ratio greater than 1 indicate convergence and less than 1 indicate divergence. Using the STOMP simulator and the soil characteristics for the three soils tested, we calculated flux ratios for WFMs placed in the three soils. Figure 3 shows the calculated flux ratio as a function of divergence barrier height for flux meters installed in three soils. The simulations suggest that in coarse soils, the wick unit should operate satisfactorily over the tested steady-state flux range (1 to 10,000 mm/yr). In contrast, the silt loam and the clay soil preformed best only at the higher fluxes, suggesting that finer soils may exhibit divergence at lower flux rates. Simulations using transient fluxes (not shown) suggest that flux efficiency ratios with transients increase compared to steady-state values.

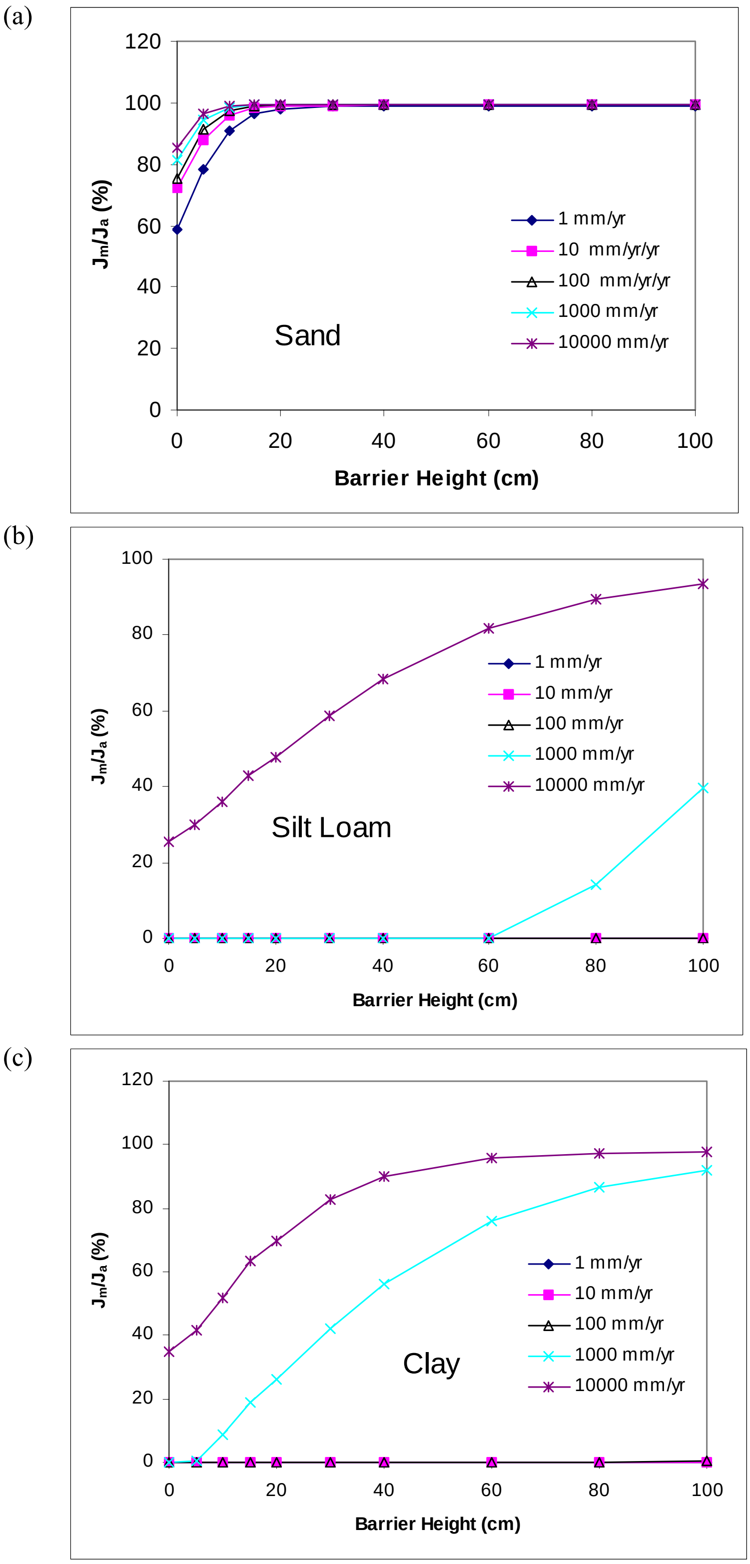

Figure 3. Water flux efficiency ratios (J_m/J_a) for 3a) sand, 3b) silt loam, and 3c) clay soils under a variety of steady-flux conditions and diversion barrier heights.

Field results

Figure 4 shows water-flux data for a desert site in Washington State, USA. The total precipitation for the test period (Apr. 2002 through July 2004) was 448 mm. Drainage from the gravel surface was > 50% of total precipitation, but was 0% for the 1 m-thick silt loam soil. Note that under these low drainage conditions, divergence around the silt loam was eliminated by extending the divergence barrier to the soil surface. The data indicate that drainage is related to surface texture and that low rates of drainage (<100 mm/yr) can be measured readily with the wick fluxmeters. Data previously reported for a tea plantation in Sri Lanka show that reasonable results also can be obtained for humid sites with coarse soils (Gee *et al.*

2004). At the Sri Lanka Site, the drainage collection efficiency, computed as the ratio of the measured drainage to that estimated from monthly precipitation less evapotranspiration, was about 0.7 compared to 1 for the sandy soils in Washington State. Preliminary results from Tonga suggest that in highly conductive volcanic clay soils the collection efficiency can be much higher and may exceed 1 (van der Velde *et al.* 2003, 2004). Observations in Tonga indicate that high rainfall conditions over short periods of time on highly permeable soils create temporarily saturated soils and induce convergent flows that affect overall drainage estimates. Reducing the wick or divergent barrier length is an option for such soils.

Conclusions

The use of passive-wick WFMs provides a way to readily quantify drainage where such data have been difficult to obtain in the past. Theoretically, water flux rates in the range from 1 to 10,000 mm/yr can be easily measured with passive-wick fluxmeters. In practice, optimizing performance depends on the soil type and the climatic conditions. Coarse soils are readily suited to monitoring with wick-type fluxmeters. However, careful design is required for fine-textured soils to minimize divergence, which could lead to underestimates of actual drainage rates. In contrast, rainfall intensity and duration must be considered in designing fluxmeters for humid sites where highly permeable soils could cause convergent flow and overestimate drainage rates. In spite of the these limitations, the ability to better measure water flux holds great promise for agriculture, golf courses, and mining operations, where improved water-balance measurement can lead to water-use efficiencies and resultant economic and environmental rewards.

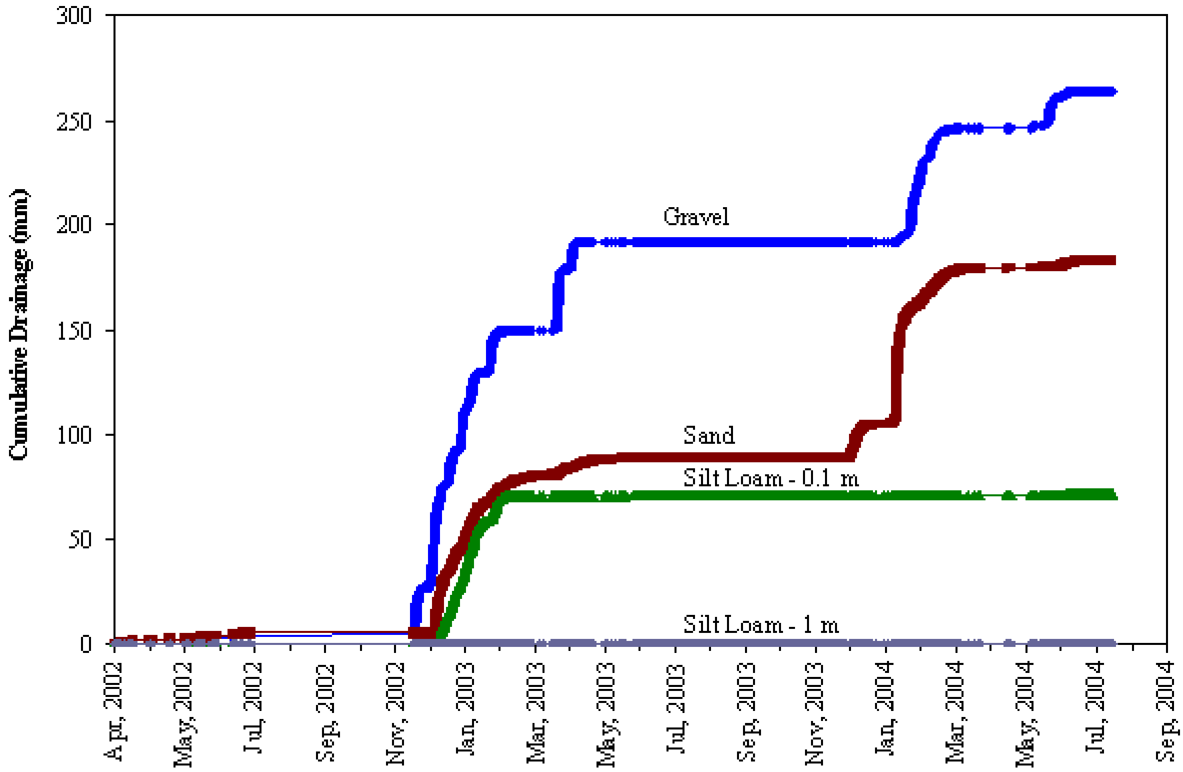

Figure 4. WFM records of drainage for a gravel, sand, and 0.1 m and 1 m silt-loam soil over sand at a semi-arid site in Richland, WA (USA).

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