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Design and Calibration of Percolation Samplers for Measuring Polyacrylamide-Amended Furrow-Irrigation Effects on Drainage Water Quality

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ABSTRACT

Amending irrigation furrow inflows with polyacrylamide (PAM) at low concentrations (10 mg L^{-1}) reduces irrigation-induced erosion by 94% and increases infiltration by 15%, relative to untreated furrows. We hypothesized that PAM erosion-control technology would allow irrigation managers to increase furrow inflows to speed furrow-stream advance, produce a more uniform water distribution down field, and reduce the leaching hazard at the upper end (due to reduced infiltration opportunity time and/or shorter sets). We developed, tested, and installed instruments in a furrow irrigated Portneuf silt loam (Co-Si, mixed, mesic, Durixerollic Calciorthids with 1.6% slope) to investigate this premise. Soils were instrumented with repeating pulse multivibrator (CS-615) soil water sensors, thermocouples, tensiometers, and percolation soil water samplers at upper and lower ends of the furrows. Percolation samplers consisted of a 23-cm-deep, 20-cm-dia. stainless-steel beaker with a 17-cm-long, 4-cm-dia., 0.5 bar air-entry ceramic cup imbedded in a 5-cm-deep silica flour layer, slurried into the beaker bottom. Water was collected under suction (~1.4x ambient) via teflon tubes. Percolation sampler design and testing, field installation, and study experimental design are discussed.

Keywords. Irrigation management, Water quality, Furrow infiltration, Erosion control, Drainage

INTRODUCTION

PAM is a nontoxic and environmentally benign material and has been used extensively in health sensitive industries such as potable-water treatment and food processing (Barvenik, 1994). Lentz et al. (1992) and Lentz and Sojka (1994) demonstrated that the presence of 10 ppm PAM in advancing furrow irrigation streams reduces erosion and furrow soil losses by 94% and increases infiltration by 15%, relative to untreated furrows. PAM-use improves water quality of irrigation wastewater flows returning to natural surface waters. Irrigation runoff losses of total phosphorus (P), ortho-P, biochemical and chemical oxygen demand (Lentz et al., 1997), total nitrates (Bahr & Stieber, 1996), and certain pesticides (Agassi et al., 1995) are reduced by as much as 90% compared to untreated fields. The beneficial practice is economical and simple to apply, hence PAM field application (Lentz et al., 1995; Sojka & Lentz, 1997) is gaining rapid and wide acceptance among farmers in the irrigated western U.S. However, some state and federal environmental agencies have asked if the infiltration-enhancing PAM agricultural application might increase leaching of agricultural chemicals below the root zone beneath irrigated furrows.

Solute leaching losses are determined by measuring soil pore-liquid solute

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concentration and soil water flux. When both macropore and mesopore-flow occur in the soil profile, Wilson et al. (1995) recommended that two soil water samplers be used to collect both types of soil water. The chemistry of pore-liquid samples collected from porous suction samplers in structured soils may not be representative of draining water because macropore flow can bypass samplers (Steenhuis et al., 1995). Free drainage samplers collect macropore waters but not mesopore waters (Wilson & Dorrance, 1995).

Passive capillary-wick pore-liquid samplers collect both meso- and macropore waters from a well-defined area by applying tension supplied by a hanging water column (Holder et al., 1991). Hydraulic conductivity-pressure functions for soils and wicks are required to select type and length of wick needed to optimize wick sampler operation in particular soils (Knutson & Selker, 1994). Wick length requirements can result in samplers with large dimensions, making them difficult to place in soils with depth-restrictions. Vacuum extraction samplers are like wick samplers because they sample both macro- and mesopore waters from a known soil area. Both are often installed in horizontal tunnels carved into trenches to permit sample collection through an undisturbed soil profile. Vacuum samplers require a vacuum control system but sampler tensions can be adjusted for soil conditions. Vacuum samplers installed in relatively dry soils can be more compact than wick samplers designed for similar soil conditions.

Soil wetting patterns beneath irrigated furrows can be measured nondestructively with neutron probes (Gardner, 1986), tensiometer systems (Cassel and Klute, 1986), electrical resistance blocks, and soil dielectric sensing systems, such as Time Domain Reflectometry (TDR) (White & Zegelin, 1995). Neutron probe measurements are precise but the system cannot be automated for simultaneous monitoring of numerous sites (Evett & Steiner, 1995). Resistance-block precision drifts with time and is poor at high water contents (White & Zegelin, 1995). A TDR system can be automated (Baker & Allmaras, 1990) and requires no calibration for our silt loam soils at water contents above $\theta = 0.05$, but hardware demands are extensive, making this the most expensive system considered. A newly available soil dialectric sensing system using repeating-pulse multivibrator sensors (RPM) requires less equipment and is less expensive than the TDR approach (no cable tester and fewer multiplexers). An RPM-based system can be automated but sensors must be calibrated for local soils (Bilskie et al., 1995).

Our objective was to develop a methodology and instrument network for a furrow irrigated field plot that would permit the comparison of PAM-managed vs. standard furrow irrigation effects on spatial soil water and drainage characteristics. Parameters of interest were solute concentrations and soil water flux and profile temperature and wetting patterns.

MATERIALS AND METHODS

Percolation Samplers

We chose vacuum extraction samplers to collect percolation water from treatment plots. They sample both meso- and macropore waters and permit measurement of downward water flux. Extraction vacuum pressure can be adjusted for ambient soil conditions to ensure valid sampling, and the extraction sampler's compact vertical size permitted their installation in depth-restricted soils. The sampler was constructed from a 23-cm-deep, 20-cm-diameter stainless-steel beaker. A 17-cm-long, 4-cm-diameter ceramic cup with 0.05 Mpa (0.5 bar) air-entry characteristic was fitted with a teflon plug containing two teflon compression fitting, male pipe adapters [3.2 mm (1/8") O.D. x 1.6 mm (1/16") PNT). The bottom positioned pipe adaptor was drilled out, permitting a 3.2 mm OD teflon collection tube to be inserted through it and terminate near the cup base. A second teflon tube connected to the upper fitting. The ceramic cup assembly was

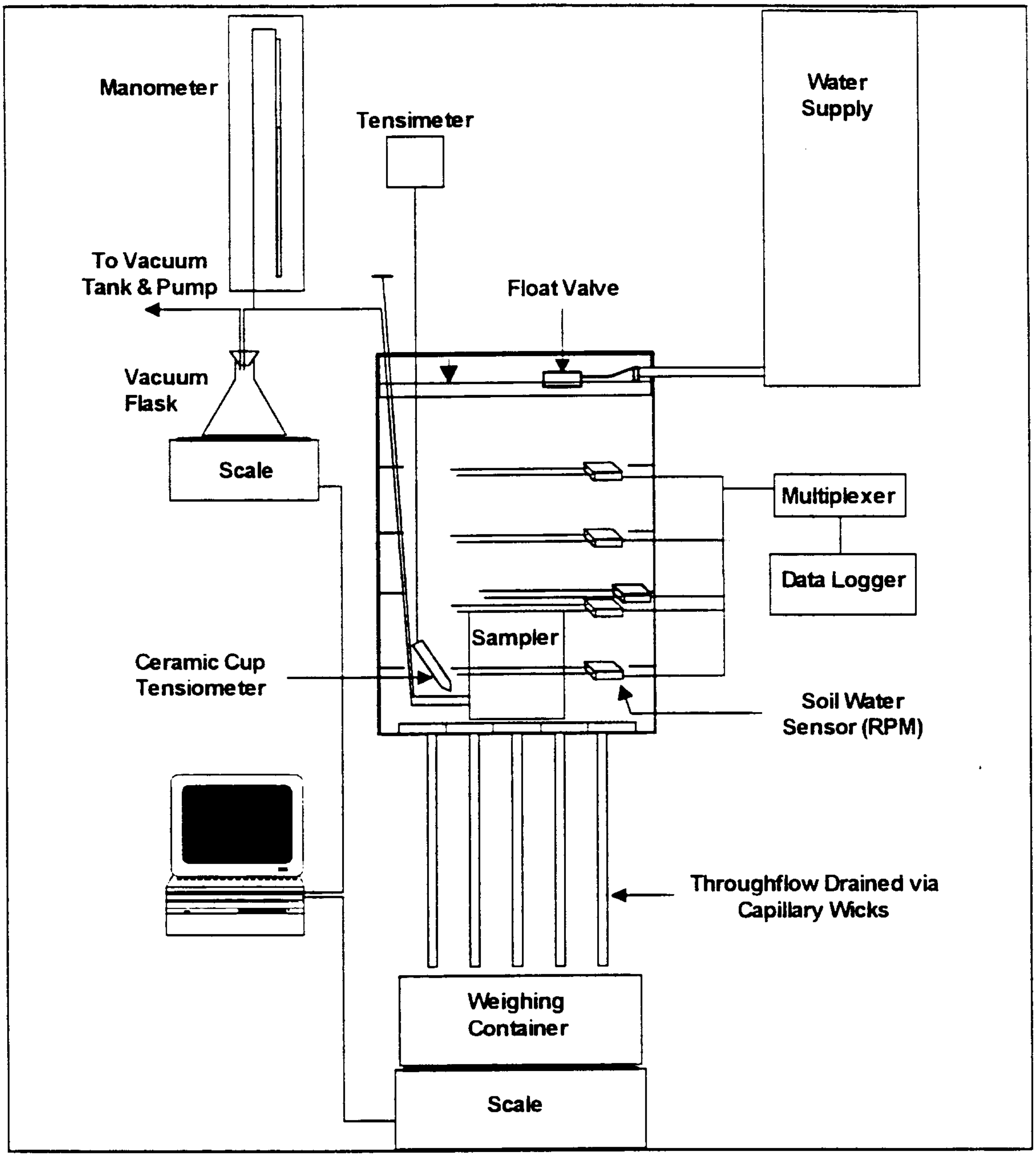

Fig. 1. Laboratory setup for determining percolation sampler adequacy over a range of extraction suctions. provided good soil contact.

placed in the bottom of the beaker and teflon tubes passed through holes drilled near the beaker base. A water/silica-flour (200 mesh screen) slurry was poured into the beaker, encasing the ceramic cup in a 5-cm-deep layer. The silca layer's flat upper surface provided good soil contact.

The depth of soil filling in the samplers (18 cm) was designed to obtain a valid percolation-water sample from the field soil over a range of applied suction (Corey et al., 1982). The objective was to collect percolating soil water without disturbing soil water stream lines, ie. causing their convergence or divergence at the top of the sampler. To test this premise, we inserted a percolation sampler in a column of flood irrigated soil and compared sample volume to barrel throughflow over a range of sampler extraction suctions.

A 0.58-m-diameter, 0.81-m-deep plastic barrel filled to 0.74 m with Portneuf silt loam (Co-si, mixed, mesic, Durixerollic Calciorthid) subsoil was instrumented with percolation sampler, ceramic-cup tensiometer, RPM soil water sensors and thermocouples (Fig. 1). Five 2.54-cm-diameter, 67-cm-long glass fiber wicks were inserted through the barrel bottom to duplicate natural drainage conditions. A 13-cm-long terminal section of each wick was unravelled and spread out within the barrel. Soil was sieved through a 5-mm screen and slurried into the barrel in four portions.

A percolation sampler was centered in the barrel with its top at 0.45 m soil depth. Five RPM soil water sensors were calibrated (Mutziger et al., 1997) for the soil, three were inserted horizontally on-center at 0.13, 0.28, and 0.42 m depth, and two were inserted horizontally off-center at 0.42 and 0.57 m depths. Copper-Constantan thermocouples were also placed at the four depths. Edge flow deflectors were attached along the barrel circumference at four locations in the soil column at depths slightly above soil water sensors (Fig. 1). A ceramic cup tensiometer was placed off-center at 0.57 m depth. A range of extraction suctions was applied to the percolation sampler. Sample-drainage-rate and soil-drainage-rate (throughflow) were measured over 20-50 min periods.

Soil Water Sensors

When its two wave guides are imbedded in soil, the pulse period generated by a Campbell Scientific[2] repeating-pulse multivibrator sensor (CS-615) varies with the soil's dielectric constant and hence its volumetric water content. This signal can be directly measured by a period measuring function of a datalogger (Bilskie et al., 1995). Soil water RPM sensors were calibrated for soils in which they were inserted. Soils from appropriate depths were sampled. The following soil parameters were measured to study their effects on sensor calibration: electrical conductivity (EC) of the saturation paste extracts; pH of saturated pastes; and bulk soil EC with a TDR probe (Dalton, 1992). Specific water volumes were added to crushed soils prior to packing into 10-cm-diameter, 36-cm-deep PVC columns. Columns were filled with several lifts of soils and tamped to a bulk density of 1.35 Mg m^{-3}. The signal generated by RPM-sensors placed in soil columns were measured at several water contents and soil temperatures.

Experimental Design

The 179-m-long, 48-m-wide, 0.87 ha experimental plot was located 2.4 km southwest of Kimberly, ID. The field had, and continues to be used for a long-term PAM application study. Field subplots had been treated with polymer each year beginning in 1992. Plant rows and furrows were spaced 0.76 m apart and were 179 m long, with 1.5% slope. The plot layout was a randomized block design with three blocks and three replications. Two PAM treatments and a control were included in the plot layout, but only the control and one of the PAM treatments was monitored in this study.

The polymer treatment applied 10 ppm PAM as a concentrated stock solution to initial irrigation inflows and curtailed treatment once runoff began. Untreated water was used to finish the irrigation. Inflows for control furrows were set at a rate typical for the region and were unchanged during the set. PAM furrow inflows were three times those of controls to take full advantage of the polymer's anti-erosive and infiltration-enhancing properties, while reducing advance times. The PAM triple-rate inflows were cutback to

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[2] Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the USDA-Agricultural Research Service and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

untreated furrow rates once runoff began and after PAM application had ceased. Each treatment replicate consisted of two wheel-trafficked furrows alternating with two nontrafficked furrows. Only wheel-trafficked furrows were irrigated.

A monitoring site was located 30 m from the upper and lower ends of a furrow in each treatment replicate for a total of twelve sites. Each site included 1) three soil water percolation samplers; 2) four soil water sensors positioned beneath the furrow and two placed across from these first four in the adjacent plant row; and 3) in two of the three replicates, thermocouples were installed with the soil water sensors to measure soil temperature (to account for temperature effect on the RPM sensor signal).

Field Installation

Field installation of percolation samplers, and RPM and thermocouple sensors was accomplished by inserting devices horizontally through the sidewall of an access pit (Fig. 2). A backhoe trench was dug 0.2 m away from, and parallel to, the monitored irrigation furrow. Three horizontal cavities were excavated into the pit sidewall. A specially designed tool was used to cut a circular slot 20 cm in diameter and 5-10 cm deep into the cavity ceiling. Soil was tamped into the the samplers and a 2-3-cm layer of slurried soil placed on its surface to make good contact with the cavity-ceiling soil as the sampler was pushed upward into the carved slot. Cinder block and cedar wedges were used to firmly press and hold samplers against the soil mass. Sampler tops were set at 1.2 m depth.

The RPM soil water sensors and thermocouples were placed at 0.3 m, 0.6 m, 0.9 m, and 1.3 m depths. At each location a soil core sample was taken near the sidewall for bulk density determination. The RPM was inserted and in some cases a thermocouple was buried in soil near the RPM base. Sensor leads and sampler tubing were run along the sidewall to a vertical, slotted 5-cm-diameter PVC pipe and finally to a horizontal pipe at 0.3 m depth. This buried pipe conveyed the lines 3 m down furrow, and across the field (perpendicular to furrows) to one of five buried risers located along the top or bottom field positions. Subsoil was replaced and saturated with water to settle. The soil was allowed to drain for at least 24 hours before the topsoil (upper 20 cm) was replaced and water-settled if necessary. Risers were constructed of two 30-cm-long, 30-cm-diameter PVC pipes. One vertical pipe section was buried 30 cm below the soil surface at the riser location. The second 30-cm section was attached to the first via a flange. The top of the upper riser projected approximately 7 cm above the soil surface. Sensor leads and sampling tubes were coiled inside this lower riser section during field tillage operations. Prior to field operations, the upper riser section was removed, a cover placed over the lower riser, and the entire assembly buried. After tillage the lower riser was uncovered and the upper section replaced.

The field vacuum extraction system employed a precision vacuum pump with < 133 pa, 110 L min^{-1} capacity and vacuum tank. The tank was connected by vacuum tube to a gas dryer, and then to a polyethylene tube main line that ran the length of the field. Other polyethylene tubes branched off the mainline and ran across the field at upper and lower field positions to manifolds at each riser. Each manifold supplied 1-L vacuum flasks connected to individual samplers. A Bourdon-tube pressure switch with 0-1 Mpa vacuum range and vacuum gauge were used to adjust system vacuum. Individual vacuum controls will be added to separate branch lines if necessary.

Soil RPM sensors were linked to a datalogger through a 4-line relay multiplexer, and thermocouples were connected to the same 21X via a separate 2-line relay multiplexer.

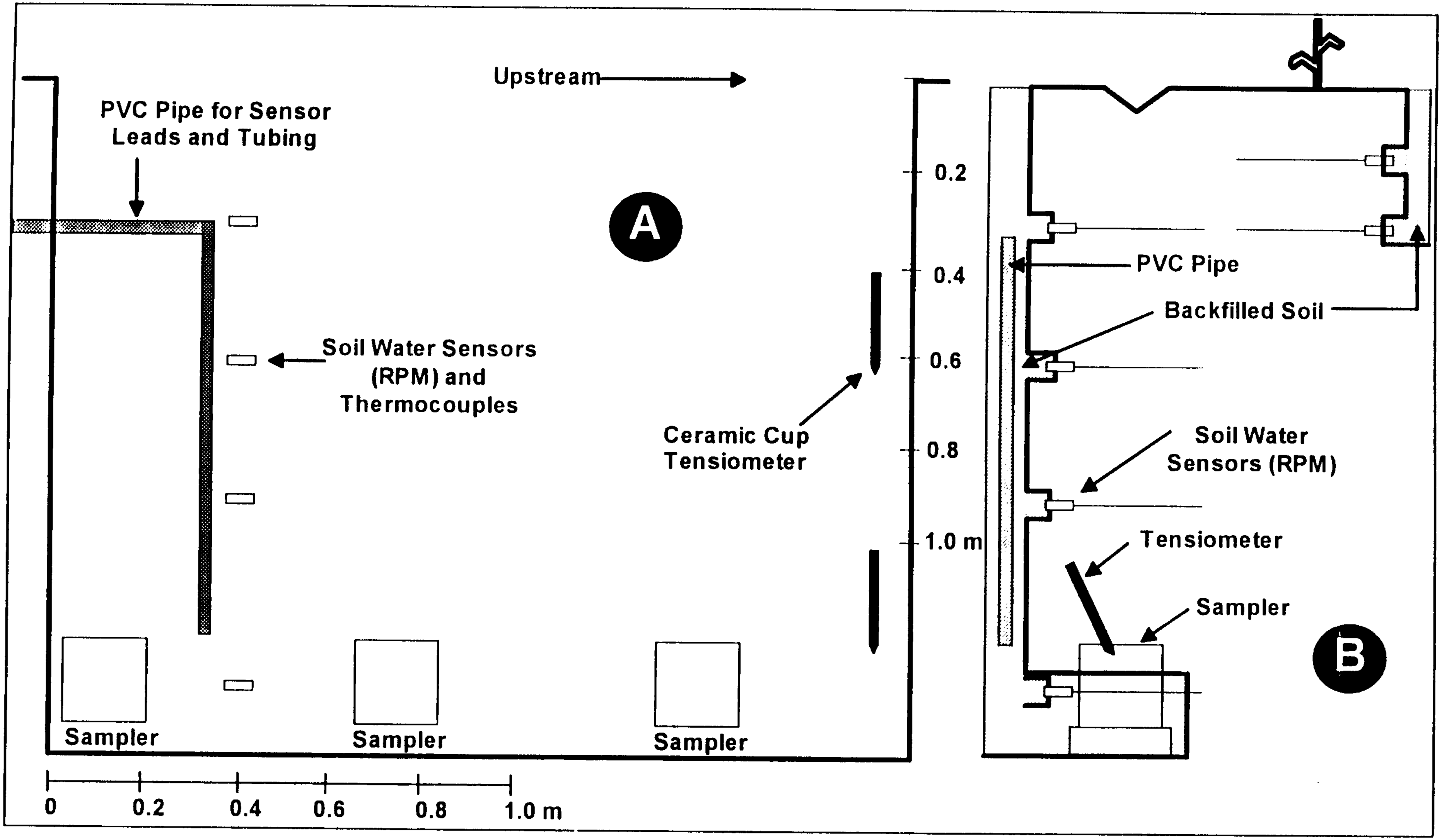

Fig. 2. Placement of percolation samplers and sensors at each field site as viewed parallel (A) and perpendicular (B) to direction of furrow

RESULTS AND DISCUSSION

Percolation Sampler Operation

Soil column measurements were made at soil water contents of 32-44% and soil tensions, 4.5-6.0 kPa, representing conditions under which greatest water flux occurs in the field. Sampler extraction suction was normalized by expressing it as a fraction of the ambient soil tension. This value was termed the *extractor-soil-suction ratio*. The sampler drainage fraction was computed as the sample-drainage-rate divided by total barrel throughflow-rate. The sampler area fraction was the ratio of percolation sampler area divided by the total barrel throughflow area, or 0.12. We assumed that soil water flux through the barrel's packed soil was uniform. Hence the sampler measured percolation rates accurately when the sampler drainage fraction equaled the sampler area fraction (0.12).

A plot of the sampler drainage fraction vs extractor-soil-suction ratio (Fig. 3) fit an exponential function ($P < 0.001$). The sampler drainage fraction ratio changed relatively slowly as the extraction-soil-suction ratio increased from 1 to 1.5 but increased more steeply at higher suction ratio values. The percolation samplers operate accurately at extractor-soil suction ratios between 1.43 and 1.57. This amplitude was within the range of values calculated from theoretical considerations by Corey et al. (1982). The good fit of an exponential function to these data (Eq. 1) suggested that the relationship might be used to correct percolation values obtained from samplers for which extractor-soil-suction ratios were suboptimal. For Eq. 1, Y = sampler drainage fraction; x = extractor-soil-suction ratio; $a = 0.0074$; $b = 0.000155$; and $c = -0.227$.

$$Y = a + be^{(-x/c)} \tag{1}$$

CS-615 Calibrations

Calibration of the first CS-615 models delivered was complicated by subtle abnormalities in some sensors that interfered with their operation, especially when inserted within 30 cm of another CS-615 in soils having high bulk soil ECs and water contents. These faultly sensors were replaced with a revised model that was less problematic. The calibrations provided by the manufacturer were not accurate for sensors installed in Portneuf soil horizons.

Extensive testing of several CS-615 soil water sensors revealed that the period length of the RPM signal varied with water content, bulk-soil EC, and temperature (Mutziger et al., 1997). We found that saturated soil pH was highly correlated to bulk-soil EC for our soils and was more easily measured than the latter. For example, multiple regression analysis of data ($n = 148$) from a single sensor produced a first-order multiple regression function that described the entire data set well ($P = 0.0001$, $R^2 = 0.978$). The calibration function is given in Eq. 2:

$$\theta_v = -0.749 - 0.00422(T) + 0.419(PRD) + 0.069(pH) \tag{2}$$

where T = temperature (°C) of soil surrounding the sensor wave guides; PRD = signal period length (ms); and pH = pH of soil saturated paste.

Preliminary Field Tests

Field instrumentation was installed in the summer of 1996 and two preliminary irrigations were done that fall to test the monitoring system. The soil water sensing system

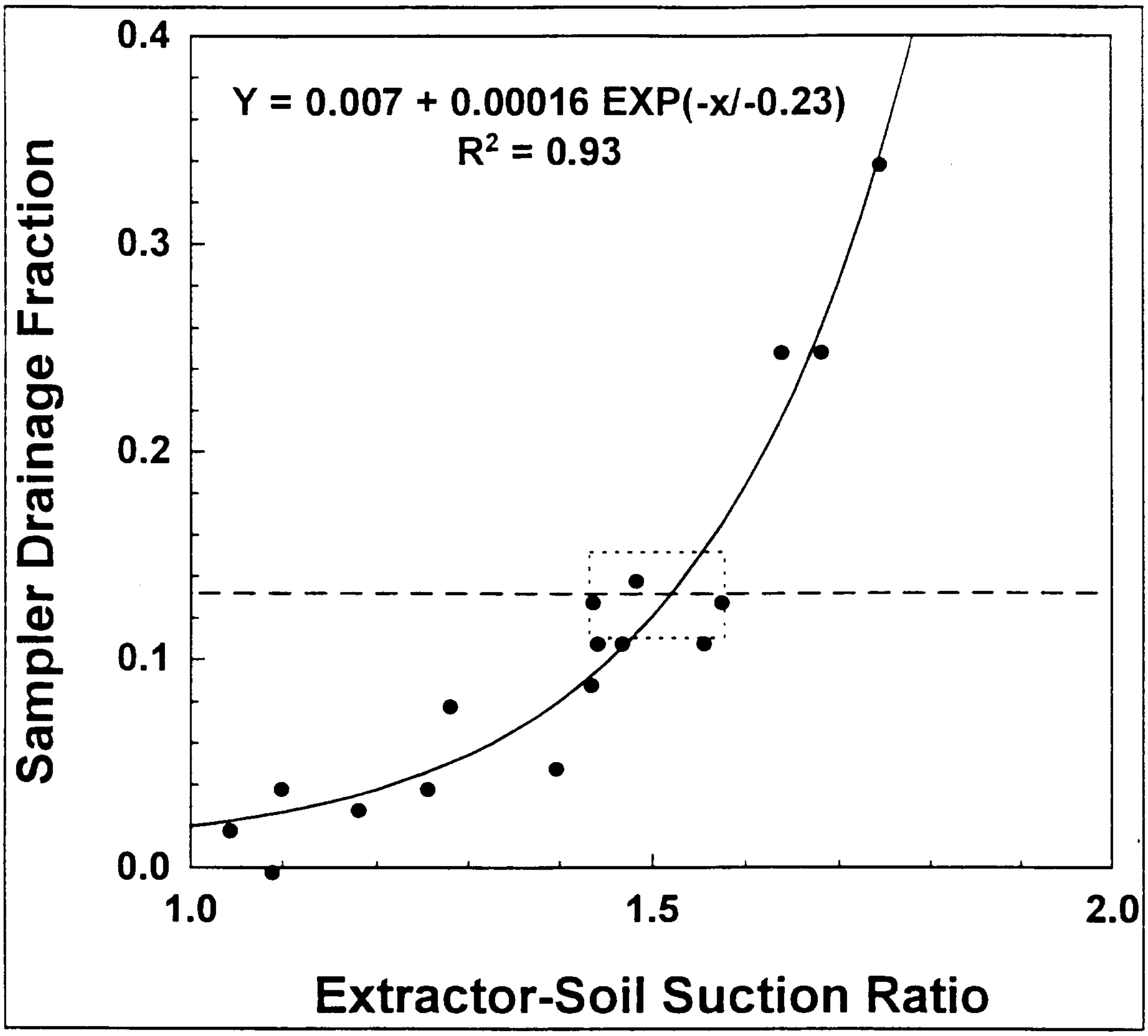

Fig. 3. Plot of sampler drainage fraction vs. extraction-soil ratio for soil water percolation sampler.

functioned at startup, but was damaged shortly after, possibly as the result of a lightning strike. This required repairs that could only be done in the following spring. The total percolation sampler volume collected at each monitored furrow ranged from 0-60% of net furrow infiltration value. This variability probably resulted from effects of 1) treatment effects, 2) spatial variability, especially of macropore flow, 3) anomalous preferential flow through the recently refilled access pits, and 4) misalignment of furrows over percolation samplers. Errors caused by the latter two have been minimized in 1997. Soil in access pits has settled more thoroughly over a unusually wet winter, and furrows have been more accurately positioned.

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