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Field evaluation of passive capillary samplers for estimating groundwater recharge

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Abstract. Passive capillary samplers (PCAPS), which sample water from the vadose zone via a hanging water column in a fiberglass wick, have shown potential to provide superior estimates of soil water flux compared to alternative methods. The objectives of this study were to evaluate the performance of PCAPS under natural rain-fed conditions concerning (1) their operational characteristics and (2) their ability to estimate soil water flux. Forty-two PCAPS were installed in 21 commercial agricultural fields in Lane County, Oregon. Monthly measurements of soil water flux and precipitation were recorded at each site for the 4-year project duration. Of the 42 installed PCAPS, 12 samplers at six sites were inoperable or did not operate efficiently: 10 samplers were consistently below the water table, which overflowed the collection vessels rendering the samplers inoperable. Only two of the PCAPS exhibited technical failure resulting in unusually low collection efficiencies, thought to be due to a collapse of the collection vessel from oversuction during sample retrieval. On average, the 30 remaining PCAPS measured soil water flux 25% greater than that obtained from a water balance estimate. This discrepancy represents ~8% of the total annual precipitation and irrigation each site received. PCAPS collection efficiency was found to be significantly correlated ($R^2 = 0.75$) to the water balance yearly estimated recharge. The difference between PCAPS measured and water balance estimated percolation could be the result of inaccuracy in water balance evapotranspiration estimates and/or oversampling in the presence of high water tables. To estimate the mean yearly recharge at each site with a 30% bound on the mean at the 0.05 confidence level, eight PCAPS are required. This number corresponds closely to the results of *Brandi-Dohrn et al.* [1996a] and is thought to be due to intrinsic variability of percolation.

1. Introduction

There is a variety of sampling devices which may be used to monitor water and solute transport in the vadose zone. These include (1) soil core profile sampling, (2) vacuum extractors, and (3) lysimeters. The selection of an appropriate device depends on the project goals, the physical setting of the project, and the available financial resources.

The versatility and low cost of soil coring make it a valuable tool for measuring chemical composition in a given volume of soil. Minimal setup time and the ability to replicate measurements at different depths make soil coring useful for rapid assessment of contaminant spills. However, it is a destructive method that does not allow repetitive measurements at the same point, thus limiting its usefulness when monitoring changes with time. For precise measurements, a large number of samples are required [*Rice and Bowman*, 1988; *Cambardella et al.*, 1994]. Furthermore, since it measures resident concentration, solute flux concentration and amount, if required, must be determined independently of the soil core sampling procedure [*Parker and van Genuchten*, 1984; *Brandi-Dohrn et al.*, 1996a].

The use of porous ceramic suction cup samplers was introduced by *Briggs and McCall* [1904] and remains the U.S. Environmental Protection Agency standard for hazardous waste site characterization [*U.S. Environmental Protection Agency*, 1986]. Low cost and ease of installation and use has resulted in wide use of the suction cup sampler for leachate characterization. However, many problems associated with the use of this sampler have been documented. Central among these are that the sampler does not provide an estimate of solute flux and the soil volume sampled is not known [*England*, 1974]. Major sources of groundwater recharge such as fingered, preferential, and channeled flow [*Kung*, 1990; *Selker et al.*, 1992] may not be captured due to noncontinuous vacuum during the sampling period or the cross-sectional sampling area being too small [*Shaffer et al.*, 1979; *Barbee and Brown*, 1986; *Boll et al.*, 1991]. This may result in missed contaminant pulses during rainstorms or agrochemical application [*Barbee and Brown*, 1986; *Magid et al.*, 1992]. The soil solution sampled may be unrepresentative of actual leachate when the vacuum applied extracts soil solution at a higher seepage rate than the drainage rate under natural conditions [*Severson and Grigal*, 1976; *Tseng et al.*, 1995]. In most soils, water movement occurs at or near saturated conditions with soil water pressures close to zero. Owing to these pressures, a vacuum applied to a suction cup sampler >10 kPa may result in sampling soil solutions that are not subject to leaching [*Severson and Grigal*, 1976]. *Barbee and*

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Brown [1986] concluded that applying even small amounts of suction to extract a soil solution sample may cause significantly higher seepage rates, compared with rates under gravity drained conditions. Furthermore, since suction cup samplers predominantly sample resident instead of flux concentration, reported solute concentrations can be ± 100% of true recharge values [*Brandi-Dohrn et al.*, 1996b].

A zero tension lysimeter or pan sampler was designed and introduced by *Jordan* [1968]. Zero-tension pan samplers depend on gravitational drainage to supply soil solution to the sampling reservoir, thus sampling only from a soil matrix with pressure ≥0. The soil matrix must build up a capillary fringe prior to sample collection, resulting in a diversion of flow away from the sampler due to the lower pressure of the surrounding soil [*Jemison and Fox*, 1992]. *Jemison and Fox* [1992] found low collection efficiencies for zero-tension samplers, ranging from 45 to 58%.

The idea of developing a sampler capable of applying tension to the soil water and able to intercept a large flow area led to the introduction of the wick pan lysimeter, termed the Passive Capillary Sampler (PCAPS), by *Brown et al.* [1986]. Passive Capillary Samplers have proven to give superior results to existing soil water samplers in terms of efficiently collecting soil flux and chemical concentrations [*Brown et al.*, 1986; *Holder et al.*, 1991; *Boll et al.*, 1992; *Brandi-Dohrn et al.*, 1996a]. A wetted fiberglass wick acts as a hanging water column that develops suction in the soil water depending on the flux. To achieve a minimal disturbance of the native flow regime, the pressure at the top of the wick is matched to the expected pressure in the soil as a function of the flux by applying the design equation of *Knutson and Selker* [1994]. The length and diameter of the wick are adjusted to achieve the closest possible match for the expected pressure/flux conditions.

There have been a limited number of studies on the performance of PCAPS under field conditions. *Holder et al.* [1991] tested 0.09-m^2 PCAPS in three different textured soils; sand, silt loam, and clay. Since the tests were performed under saturated conditions, the results of the experiments cannot be considered representative of natural vadose zone flow conditions.

Boll et al. [1991] tested two PCAPS in a silt loam and found them to provide a significant improvement over zero-tension lysimeters. Under controlled conditions, the collection efficiency as measured with a water balance was 103% for the two PCAPS (coefficient of variation (CV) = 25 and 42%) compared to 27% for two zero-tension pan samplers (CV = 84 and 91%). Recovery of a Br^- tracer amounted to 63% in the PCAPS and to 6.5% in the zero-tension pan samplers, with the superior performance attributed to the ability of the PCAPS to sample soil water at low potentials prior to saturation.

Brandi-Dohrn et al. [1996a] installed 32 PCAPS at a depth of 1.2 m in an undisturbed silt loam soil. During a 244-day test period, the authors found the collection efficiency as measured with a water balance to be 80%. During a second 155-day test period, the collection efficiency as measured with a water balance was found to be 66%. The wick matching procedure of *Knutson and Selker* [1994] suggested the samplers would be expected to oversample on the silt loam soil found in this study. The authors attributed the undersampling to observed (but not quantified) runoff and poor air release from the collection bottles. The recovery of a Br^- tracer was low with an average of 29%, which was attributed to plant uptake and lateral water movement due to prominent lateral stratification.

The objectives of this study were to evaluate the performance of PCAPS under natural rain-fed conditions concerning (1) their operational characteristics and (2) their ability to estimate soil water flux.

2. Materials and Methods

2.1. Experimental Sites

The experiments were carried out at 21 separate sites located within a 30-km radius throughout northern Lane County, Oregon. Sixteen original sites were instrumented during the summer of 1993, with an additional five sites instrumented during the fall of 1995. The study includes replicated trials of the major cropping systems employed in the region including perennial rye grass seed, vegetable row crops, peppermint, tree fruits, organic vegetables, and blueberries. Sites were chosen with the cooperation of local farmers and based on 1992 agricultural commodity sales in Lane County.

2.2. Soil Description

There are eight soil types represented among the 21 sites. The classification is based on the description of the soil profiles obtained during sampler installation, Lane County soil survey information, and particle size analysis. The soil series, taxonomy, and geologic parent materials for each site are listed in Table 1. Soil cores were taken at each site from the 0- to 1-m depth layer and analyzed for bulk density. In situ field saturated hydraulic conductivity, K_{sat}, was measured using the well permeameter method [*Elrick and Reynolds*, 1992]. These basic soil properties are listed for each site in Table 2. The pressure-saturation relationship in each soil was obtained by pressure extraction fit to van Genuchten's model [*van Genuchten*, 1980]:

$$S_e = \frac{1}{[1 + (-\alpha h)^n]^m} \left(m = 1 - \frac{2}{n} \right) \tag{1}$$

with

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \tag{2}$$

where S_e is the normalized water content, θ is the volumetric water content, with the subscripts r and s denoting residual and saturated, h is the pressure (L), and α (L^{-1}), n and m are empirical parameters. The restriction $m = 1 - 2/n$ was used because it gave the best fit for the critical first 200 cm H_2O of pressure. Least squares fitting was carried out using the Retention Curve (RETC) code [*van Genuchten et al.*, 1991].

2.3. Climate

The climate of Lane County is classified as temperate oceanic, with mild wet winters and warm dry summers. During the cool wet months of November–April, temperatures average 6.6°C with an average monthly precipitation of 142 mm. In contrast, May–October temperatures average 15.8°C with an average monthly precipitation of 39 mm. Climatic data for the region have been recorded for the last 35 years at the Eugene airport. Unfortunately, no evaporation or solar radiation data are collected within Lane County. Little differences in the climate of the Willamette valley can be documented, so data from the U.S. Bureau of Reclamation Northwest Cooperative Agricultural Weather Network, AgriMet, station located in Corvallis, 50 km north of the test site nucleus, were used for the experiments.

Precipitation was measured with a nonrecording gauge at

Table 1. Experimental Sites, Soil Series, Soil Taxonomy, and Geologic Parent Materials

Site	Soil Series	Taxonomic Class	Parent Material
Blueberry 1	Cloquato silt loam	Cumulic Ultic Haploxerolls	recent alluvium
Blueberry 2	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Grass Seed 1	Coburg silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Orchard 1	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Orchard 2	Fluvents, nearly level		sediment deposits
Organic 1	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Organic 2	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint 1	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Peppermint 2	Chehalis silty clay loam	Cumulic Ultic Haploxerolls	recent alluvium
Peppermint 3	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Peppermint 4	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint 5	Coburg silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint 6	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Peppermint 7	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Peppermint 8	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row crop 1	Newberg fine sandy loam	Typic Haploxerolls	recent alluvium
Row crop 2	Newberg loam	Fluventic Haploxerolls	recent silty alluvium
Row crop 3	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row crop 4	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row crop 5	Malabon silty clay loam	Pachic Ultic Argixerolls	silty and clayey alluvium
Row crop 6	Newberg loam	Fluventic Haploxerolls	recent silty alluvium

the Eugene Weather Center. For the first year of the project, eight of the 16 initial sites were chosen for instrumentation with six nonrecording rain gauges on each site. After the first year of the project, all sites were instrumented with at least two nonrecording gauges. Measurements have been corrected by +2% to adjust for the systematic error introduced by the average wind speed of 0.8 m s^{-1} measured at the Eugene Weather Center [*Larson and Peck*, 1974].

Evapotranspiration, required for the water balance, was calculated by applying crop coefficients to daily reference evapotranspiration estimates. Alfalfa reference evapotranspiration was obtained from the U.S. Bureau of Reclamation where climate data from the Corvallis AgriMet station is used in conjunction with the 1982 Kimberly-Penman equation [*Wright*, 1982] to estimate daily reference evapotranspiration. The 1982 Kimberly-Penman equation is a theoretically based energy balance equation combining net radiation and advective energy transfer. The form of the 1982 Kimberly-Penman equation used in AgriMet crop modeling is as follows [*U. S. Bureau of Reclamation*, 1995]:

$$ET_r = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}6.43W_f(e_s - e_a), \quad (3)$$

where ET_r is the alfalfa reference evapotranspiration in MJ m^{-2} d^{-1}, Δ is the slope of the saturation vapor pressure-temperature curve in mb K^{-1}, γ is the psychometric constant in mb K^{-1}, R_n is the net radiation in MJ m^{-2} d^{-1}, G is the soil heat flux in MJ m^{-2} d^{-1}, 6.43 is the constant of proportionality

Table 2. Mean Bulk Density and Saturated Hydraulic Conductivity (K_{sat}) of Soils at Experimental Sites for 0- to 1-m Depth Layer and PCAPS Installation Parameters

	Bulk Density		K_{sat}			
Site	Mean, Mg m^{-3}	n	Mean, cm hr^{-1}	n	Wick Type	PCAPS Depth, m
Blueberry 1	1.49	3	0.76	3	medium-density	0.80
Blueberry 2	1.42	3	0.59	3	high-density	0.80
Grass Seed 1	1.49	3	1.36	3	high-density	0.92
Orchard 1	1.42	3	10.3	3	medium-density	0.92
Orchard 2	n/a	n/a	9.29	3	high-density	0.65
Organic 1	1.05	7	1.73	3	medium-density	0.92
Organic 2	1.26	7	3.46	3	high-density	0.80
Peppermint 1	1.26	7	0.58	3	medium-density	0.80
Peppermint 2	1.36	3	3	3	high-density	0.92
Peppermint 3	1.21	9	1.45	3	high-density	0.92
Peppermint 4	1.21	6	1.45	3	high-density	0.92
Peppermint 5	1.31	6	0.065	3	high-density	0.92
Peppermint 6	1.35	9	1.92	3	high-density	1.00
Peppermint 7	1.31	7	2.13	3	high-density	1.00
Peppermint 8	1.27	7	1.46	3	high-density	1.00
Row crop 1	1.42	3	8.04	3	medium-density	0.92
Row crop 2	1.27	6	0.27	3	high-density	0.90
Row crop 3	1.23	6	1.49	3	high-density	0.92
Row crop 4	1.32	6	0.25	3	high-density	0.92
Row crop 5	1.35	6	1.92	3	high-density	1.00
Row crop 6	1.31	4	2.13	3	high-density	1.00

Table 3. Summer Crop History of Experimental Sites

Site	1994	1995	1996	1997
Blueberry 1	blueberry	blueberry	blueberry	blueberry
Blueberry 2	blueberry	blueberry	blueberry	blueberry
Grass Seed 1	rye grass	rye grass	rye grass	rye grass
Orchard 1	apple	apple	apple	apple
Orchard 2	peach	peach	peach	peach
Organic 1	mixed veg.	mixed veg.	mixed veg.	mixed veg.
Organic 2	Foenugreek seed	lemon balm	lemon balm	Lemon balm
Peppermint 1	peppermint	peppermint	peppermint	peppermint
Peppermint 2	peppermint	peppermint	peppermint	peppermint
Peppermint 3	peppermint	peppermint	peppermint	peppermint
Peppermint 4	peppermint	peppermint	peppermint	peppermint
Peppermint 5	rye grass	peppermint	peppermint	peppermint
Peppermint 6			peppermint	peppermint
Peppermint 7			peppermint	peppermint
Peppermint 8			peppermint	peppermint
Row Crop 1	sweet corn	sweet corn	carrots	raddish seed
Row Crop 2	red beets	sweet corn	green beans	sweet corn
Row Crop 3	beet seed	wheat	sweet corn	green beans
Row Crop 4	sweet corn	sweet corn	green beans	green beans
Row Crop 5			sweet corn	sweet corn
Row Crop 6			green beans	carrots

Blanks correspond to preinstallation years. Veg., vegetables.

in MJ m^{-2} d^{-1} kPa^{-1}, W_f is the dimensionless wind function, and $(e_s - e_a)$ is the mean daily vapor pressure deficit in kPa. Compared to lysimeter measured evapotranspiration at 11 locations throughout the Unites States, the 1982 Kimberly-Penman equation has been found to overestimate alfalfa reference evapotranspiration by an average of 7% [*Jensen et al.*, 1990]. In the same study, the popular Penman-Monteith equation was found to overestimate alfalfa reference evapotranspiration by an average of 1% [*Jensen et al.*, 1990]. Although the Penman-Monteith equation would likely give a slightly better estimate of reference evapotranspiration, the 1982 Kimberly-Penman equation was selected because of its use at the nearby Corvallis AgriMet station and implementation throughout the northwest.

Crop coefficients taken from *Smesrud et al.* [1998] were multiplied by daily alfalfa reference evapotranspiration to estimate daily crop evapotranspiration. For crop coefficients based on grass reference evapotranspiration, the Food and Agricultural Organization (FAO) grass crop coefficient [*Doorenbos and Pruitt*, 1977] was applied in conjunction with the alfalfa reference crop coefficient. During months when the soil surface was bare, a crop coefficient for evaporation based on the number of days between significant rainfall events was computed and applied [*El Kayal*, 1983; *Ryan and Cuenca*, 1984]:

For $I_f < 4$ days,

$$K_{ct} = (1.286 - 0.27 \ln I_f) \exp [(-0.01 - 0.042 \ln I_f) ET_{rt}]. \quad (4)$$

For $I_f \geq 4$ days,

$$K_{ct} = 2(I_f)^{-0.49} \exp[(-0.02 - 0.04 \ln I_f) ET_{rt}], \quad (5)$$

where K_{ct} is the bare surface grass reference crop coefficient, I_f is the interval between significant (>1 mm) rainfall events in the previous 14 days, and ET_{rt} is the average grass reference evapotranspiration over the previous 14 days.

2.4. Management

Site management was left entirely up to the landowners and thus was without experimental design. Table 3 gives the crop history of each site from 1994 to 1997. Irrigation water, nutrients, and chemicals were applied at the discretion of the owner. All irrigation water was sprinkler applied, with amounts measured by two nonrecording rain gauges located directly above the PCAPS at each site.

2.5. Wick and Soil Matching

Ideally, the pressure at the top of the wick should match the pressure of the soil for any soil water flux. Unmatched soil wick pressure could result in a disturbance of the native flow regime leading to nonrepresentative sampling of the groundwater recharge [*Knutson and Selker*, 1994; *Rimmer et al.*, 1995]. In selecting wicks, the procedure provided by *Knutson and Selker* [1994] was followed. The wick matching procedure for this study was governed by certain practical constraints. The maximum wick fiber length was limited to 80 cm due to the dimensions of the sampling device. This creates the critical constraint that minimum pressure applied by the wick is −80 cm H_2O. Additional constraints included that the sampling area was limited to 900 cm^2 and the selection of wicks were limited to those commercially available. Wick types were chosen based on their goodness of fit to the soil unsaturated conductivity in the pressure range of −15 to −80 cm H_2O, encompassing the conditions where most flux occurs.

2.6. Instrumentation

The PCAPS installed at the 16 original sites during the summer of 1993 were constructed from a custom molded 15-kg epoxy-coated fiberglass box (0.33 by 0.87, 0.62 m deep) supporting a stainless steel panel (1 mm thick, 0.32 by 0.86 m) with a 1.75-cm edge (Figure 1). The panel is subdivided into three 0.31- by 0.29-m sections, with one wick at the center of each section. A 31.6-mm inside diameter (ID) hole was punched in the middle of each section and fitted with an alloy 304 stainless steel pipe. A single 60-L vacuum molded high-density polyethylene (HDPE) collection vessel (0.24 by 0.78, 0.32 m deep) was fitted to the bottom interior of the fiberglass box. Silicone sealant and a rubber stopper were used to fit the pipes and HDPE sample access tubing to ensure a waterproof sampler with respect to the collection vessel. As a precaution, a drainage tube was built in to allow removal of water from the fiberglass box.

The PCAPS installed at the five additional sites during the fall of 1995 were modified to eliminate the need for a separate collection vessel and outer box (Figure 2). A custom welded 0.64-cm thick HDPE box (0.35 by 0.85, 0.67 m deep) supports an HDPE top panel (0.64 cm thick, 0.34 by 0.84 m) with a 1.75 cm edge. The top panel is subdivided into three 0.34- by 0.28-m sections, each containing one wick. A 25.4-mm ID hole was drilled in the middle of each section for the wicks.

Two types of wicks were employed; a braided 2.93-cm outside diameter (OD) medium density and 2.48-cm OD high density Amatex fiberglass wicks (10-863KR-08 and 10-864KR-08, Amatex Co., Norristown, Pennsylvania) with a maximum vertical wick length of 80 cm (Table 2). The first 20 cm of the wicks were separated into single strands and cleaned by kiln combustion according to *Knutson et al.* [1993]. The wick filaments were spread out radially on the top panel, and the end of each strand was glued down with one drop of silicone sealant.

The sampler is designed to remain in operation for an indefinite period. Using environmentally stable, nonadsorbing materials (fiberglass, HDPE, stainless steel) [*Topp and Smith*, 1992] the sampler is well suited for long-term nitrate and pesticide monitoring.

Two PCAPS were installed at each experimental site. Individual farmers designated a section of each field for PCAP placement. Ground penetrating radar (GPR) was used over the designated area to identify areas unsuitable for installation of samplers. Several passes with a Geophysical Survey Systems, Inc. SIR10A GPR with 100 and 500 MHz antennas were made at each site to identify subsurface heterogeneities which could distort infiltration laterally [*Kung et al.*, 1991]. Many of the sites had sandy lenses deposited by meandering streams not visible at the surface due to years of agricultural activity. Soil samples along the GPR transects were used to correlate depth of penetration with soil strata. Areas excluded for PCAP placement lacked homogeneous profiles or contained sloping soil interfaces that may divert water away from the samplers.

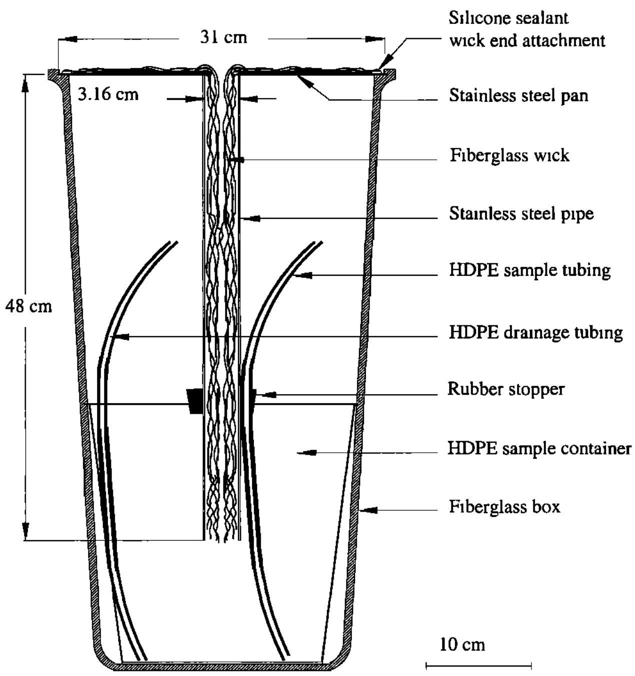

Figure 1. Cross-sectional view of PCAPS installed at the 16 original sites.

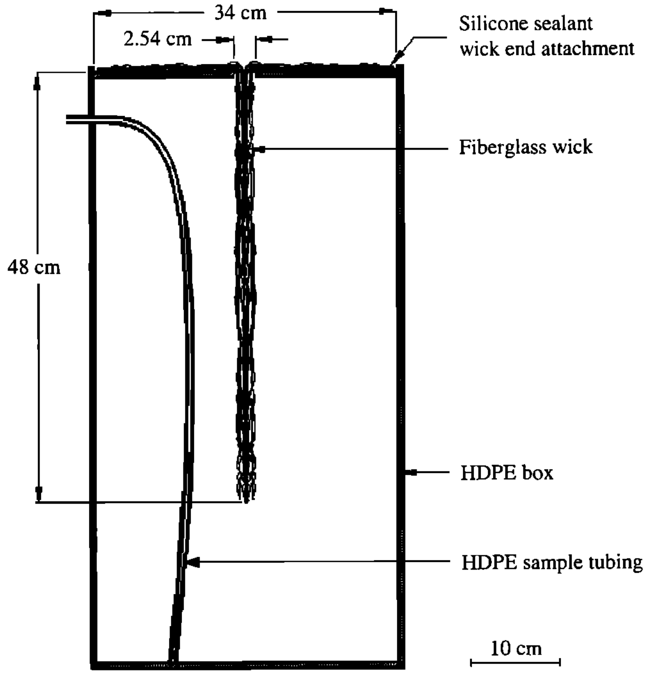

Figure 2. Cross-sectional view of PCAPS installed at the five additional sites.

The PCAPS were installed from a trench 2.4 m long, 1.2 m wide, and 2.4 m deep dug with a backhoe. A tunnel was dug in the side of the trench for the installation of each PCAPS such that the roof of the tunnel was between 0.65 and 1.0 m below the surface (Table 2). The top panel of the PCAPS was filled with slightly compacted native soil with an additional layer above the panel to fill any small gaps. The samplers were elevated with wooden wedges to bring them into firm contact with the tunnel roof. A bentonite seal was used to hydraulically isolate the samplers from the trench. Tubing to collect samples from each PCAPS was run ~10 m to an irrigation box outside the cultivated area of the field. The trenches were back-filled and compacted to avoid any settling or swelling. Installation at the 16 original sites was completed on September 1, 1993, and at the five additional sites on September 22, 1995.

2.7. Sampling

Samples were collected once a month beginning in October 1993. During periods of heavy precipitation, samples were collected after every 10–15 cm of rainfall, as the maximum PCAP collection volume is 22 cm of percolation. Samples were taken, on average, every 26 days from October 1993 to November 1997. At the five additional sites, sampling began in October 1995. Sampling was discontinued at the Blueberry 2 and Orchard 1 sites in March 1996 and at the Orchard 2 site in April

1996. A vacuum pump was used to extract samples into a 4000-ml glass vacuum flask, and the total collected volume was recorded.

3. Results and Discussion

3.1. Operational Characteristics

Of the 42 PCAPS installed, 12 samplers at six sites were inoperable or did not operate efficiently, largely due to high water table conditions. Two samplers at the Peppermint 2 site were deemed inoperable due to the soil type and hydrogeology of the location. During installation, large boulder-sized rocks were encountered along with many abrupt textural changes in the soil profile. Heavy winter rains and intense irrigation kept the site constantly ponded, restricting access to the samplers. The six collection vessels from samplers at the Grass Seed 1, Peppermint 5, and Peppermint 8 sites were overflowing at least 10 out of 12 months during the first 2 years of sampling. A high or perched water table at these sites kept the sampler submerged and the collection vessels full year-around. The two collection vessels from samplers at the Organic 1 site were overflowing during half of the winter months. During the summer irrigation season, sprinkler laterals drained directly above the two samplers resulting in high-collection volumes and no estimate of the depth of water applied at the surface. Two samplers at the Peppermint 1 site collected estimated percolation very inefficiently. The inability of both samplers to estimate percolation was thought to be due to a collapse of the interior collection vessels from over-suctioning during sample retrieval. These six sites were excluded from estimates of PCAPS collection efficiency.

Two periods of unusually high precipitation occurred during January and February of 1996 and again in November and December of 1996 (for example there was ~25 cm on the 7–8 of February leading to massive regional flooding due to rain-on-snow events in the nearby Cascade mountains). This extreme precipitation resulted in high or perched water tables that flooded 43% of the PCAPS. Samplers at these sites remained below the water table for 1–3 months after the precipitation events.

3.2. Collection Efficiency of the PCAPS as Estimated with a Water Balance

To validate soil water flux measurements obtained by the PCAPS, an annual water balance was computed for each site (Table 4). Collection efficiency is here defined as the ratio of percolation measured divided by percolation estimated by the water balance. Expected total yearly percolation was calculated as total precipitation and irrigation minus total evapotranspiration. No estimate of changing soil water storage was made between sampling intervals, so it is assumed that soil water storage at the beginning and end of each year are equal. Heavy fall rains in the Pacific Northwest quickly fill available soil water storage, so a water year beginning in December and ending the following November was selected for the annual water balance. It is assumed that surface runoff and lateral subsurface flow are negligible since PCAPS were installed in fields with surface slopes of <3% and in locations without sloping soil interfaces, as well as the practical impossibility of measuring these effects in commercial agricultural fields. Noted in Table 4 are the months for which the water balance was computed at each site. Heavy rains during January, February, November, and December of 1996 resulted in the water table at several sites rising above the PCAPS level, flooding the samplers. These months were excluded from the annual water balance. At sites where no measurements of summertime irrigation were made, yearly water balance calculations begin in November and end the following May. Consistent precipitation ensures the soil profile is essentially saturated from November through May.

Figure 3 depicts the relationship between yearly water balance estimated percolation and yearly PCAPS estimated percolation. A 1:1 line is shown to illustrate the agreement between the samplers and the water balance estimated percolation. A majority of points lie above the 1:1 line, indicating that the PCAPS collected more water than predicted by the water balance for the duration of the study. For all sites, PCAPS annual collection efficiency averaged 125% with a median of 118% (C.V. = 36%). This discrepancy represents ~8% of the total annual precipitation and irrigation each site received. Regression analysis revealed a positive correlation between the PCAPS estimated recharge and the water balance recharge ($R^2 = 0.75$), indicating that the PCAPS sample amounts are indicative of environmental variability. A positive correlation coefficient ($\rho = 0.70$) between collection efficiencies of PCAPS 1 and 2 implies that the yearly collection efficiencies of the two samplers at each site tend to increase and decrease together.

Three sources of error have been identified as potential contributors to the PCAPS measured percolation being 25% greater than the water balance estimated percolation. High water tables observed during winter months result in a soil pressure gradient much closer to zero than the unit gradient assumed in the wick matching procedure. In these situations, the wick is applying a greater tension than the surrounding soil, resulting in overcollection. In addition, the 1982 Kimberly-Penman equation has been documented to overestimate reference evapotranspiration by an average of 7% [*Jensen et al.*, 1990]. This will lower water balance estimated percolation values, resulting in increased collection efficiencies. Another factor that could contribute to the apparent PCAPS overcollection is macropore flow. During periods of high infiltration, macropores have been shown to carry significant amounts of water and solutes [*Quisenberry and Phillips*, 1976; *Odgen et al.*, 1992; *Prendergast*, 1995]. Since macropores terminating in contact with the samplers could drain until the sampler filled, the samplers could result in overreporting of macropore flow. Macropore flow might then result in increased collection efficiencies.

3.3. PCAPS Collection Efficiency as Influenced by Drainage Rate

Water balance estimates provide the best "guess" as to the amount of drainage water which may have leached below the root zone and eventually make it to the ground water. To better understand the PCAPS performance, linear regression was used to determine if a relationship exists between the percolation rate and the PCAPS collection efficiency. Monthly PCAPS collection efficiencies from November through May (months when the soil is assumed to be saturated with no change in soil water storage) for all sites are plotted against water balance estimated percolation rate in Figure 4. Water balance estimated percolation rate was calculated by dividing monthly water balance estimated percolation (precipitation minus evapotranspiration) by the number of days since the previous sampling event. Monthly collection efficiencies from

Table 4. Annual Water Balance and Collection Efficiency of Passive Capillary Samplers (PCAPS)

Site	Year	Collection Period, month/year	Precipitation + Irrigation, mm	Evapotranspiration, mm	Expected Percolation, mm	Observed Percolation, mm		Collection Efficiency, %	
						1	2	1	2
Blueberry 1	1994	Dec. 1993 to Nov. 1994	1460	1108	352	463	298	132	84
	1995	Dec. 1994 to Nov. 1995	1797	1036	761	530	580	70	76
	1996	Dec. 1995 to May 1996	1400	211	1189	1241	963	104	81
	1997	Dec. 1996 to May 1997	733	249	484	441	519	91	107
Blueberry 2	1994	Dec. 1993 to May 1994	557	288	269	445	690	165	256
	1995	Dec. 1994 to Nov. 1995	1563	1037	526	478	875	91	166
	1996	Dec. 1995 to March 1996	938	87	851		1176		138
Orchard 1	1994	Dec. 1993 to Nov. 1994	1238	934	304	764	721	251	237
	1995	Dec. 1994 to Nov. 1995	1215	593	622	704	837	113	135
	1996	Dec. 1995 to March 1996	953	87	865	844	922	98	107
Orchard 2	1994	Dec. 1993 to June 1994	624	185	439	415	531	95	121
	1995	Dec. 1994 to Nov. 1995[a]	783	642	141	219	180	155	127
	1996	Dec. 1995 to April 1996	1095	153	943	907	615	96	65
Organic 2	1994	Jan.–Nov. 1994	982	505	477	392	439	82	92
	1995	Dec. 1994 to Nov. 1995	1212	822	390	525	460	135	118
	1996	Dec. 1995 to Oct. 1996	1684	871	813	1292	677	159	83
	1997	Jan.–Nov. 1997	1130	822	308	319	330	103	107
Peppermint 3	1994	Dec. 1993 to Nov. 1994	1305	855	450	556	767	124	170
	1995	Dec. 1994 to Nov. 1995	1316	836	480	786	844	164	176
	1996	Dec. 1995 to Oct. 1996	1742	758	984	1143	937	116	95
	1997	Dec. 1996 to Nov. 1997	1576	724	852	1269	1075	149	126
Peppermint 4	1994	Dec. 1993 to Nov. 1994	1404	841	563	1328	1680	236	298
	1995	Dec. 1994 to Nov. 1995	1615	821	794	554	944	70	119
	1996	Dec. 1995 to Nov. 1996[b]	2025	766	1258	1009	1085	80	86
	1997	Jan.–Nov. 1997	1258	712	546	607	658	111	121
Peppermint 6	1996	Jan.–Nov. 1996	1937	745	1191	1839	2654	154	223
	1997	Dec. 1996 to Nov. 1997	1689	718	971	1310	1329	135	137
Peppermint 7	1996	Dec. 1995 to Nov. 1996	2237	771	1466	1367	1849	93	126
	1997	Dec. 1996 to Oct. 1997	1500	701	799	440	736	55	92
Row Crop 1	1994	Dec. 1993 to May 1994	521	261	260	303	213	116	82
	1995	Dec. 1994 to Nov. 1995	1040	854	186	339	126	182	68
	1996	Dec. 1995 to Nov. 1996	1928	930	999	743	654	74	65
	1997	Dec. 1996 to Nov. 1997	1396	430	966	258	246	27	25
Row Crop 2	1994	Dec. 1993 to June 1994	551	329	222	231	294	104	133
	1995	Feb.–May 1995	429	126	304	409	358	135	118
	1996	March–Oct. 1996	854	575	279	239	407	86	146
	1997	Feb.–Nov. 1997	946	699	247	456	572	185	232
Row Crop 3	1994	Dec. 1993 to Nov. 1994	953	442	511	592	614	116	120
	1995	Dec. 1994 to Nov. 1995	1068	707	361	483	593	134	164
	1996	Dec. 1995 to Nov. 1996	1672	744	928	1235	1468	133	158
	1997	Dec. 1996 to Nov. 1997	1488	573	916	1019	835	111	91
Row Crop 4	1994	Jan.–Nov. 1994[c]	1155	780	375	516	550	137	146
	1995	Dec. 1994 to Nov. 1995	1191	780	412	608	610	148	148
	1996	Dec. 1995 to Oct. 1996[d]	1428	618	810	1087	1397	134	172
	1997	Feb.–Nov. 1997	1154	619	535	551	562	103	105
Row Crop 5	1996	Dec. 1995 to Nov. 1996	1977	831	1146	1235	1198	108	105
	1997	Dec. 1996 to Nov. 1997	1517	726	791	701	789	89	100
Row Crop 6	1996	Dec. 1995 to Nov. 1996	1911	633	1278	780	1517	61	119
	1997	Dec. 1996 to Nov. 1997	1450	762	688	784	1089	114	158

[a]Data from January, February, and March 1995 excluded because PCAPS was below water table.
[b]Data from January 1996 excluded because PCAPS was below water table.
[c]Data from March 1994 excluded because PCAPS was below water table.
[d]Data from January 1996 excluded because PCAPS was below water table.

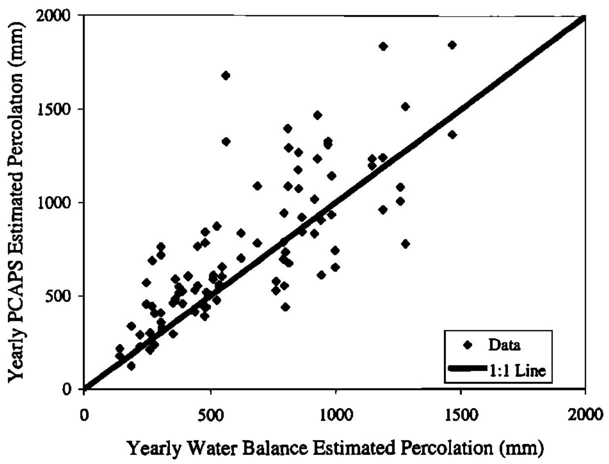

Figure 3. Annual water balance estimated percolation, PCAPS estimated percolation, and 1:1 line.

November through May averaged 116% (C.V. = 90%) with a median of 93%. A linear regression line developed by minimizing the absolute deviation from the mean indicates that collection efficiency is largely independent of drainage rate (Figure 4). Collection efficiencies exhibit the greatest variation during periods of low flux, where the water balance is most sensitive to errors in evapotranspiration estimates. During these periods of low flux, there were several months where the collection efficiency exceeded 300% (Figure 4). This is not unexpected, since overcollection of even a small amount of water can greatly increase the ratio of measured to expected percolation when the expected percolation is very small. During low flux, the observed high collection efficiencies are balanced by an equal number of near-zero collection efficiencies, when the samplers collected very little or no water. The average November through May monthly collection efficiency of 116% is less than the average yearly collection efficiency of 125%. This deviation supports the premise that an error in the evapotranspiration estimate used in the water balance is the source of the difference between the PCAPS and water balance estimates of percolation. Any overestimation of crop evapotranspiration by the 1982 Kimberly-Penman equation will lower expected percolation values, resulting in increased collection efficiencies. This will have the greatest impact on collection efficiencies during periods of high evapotranspiration and low flux.

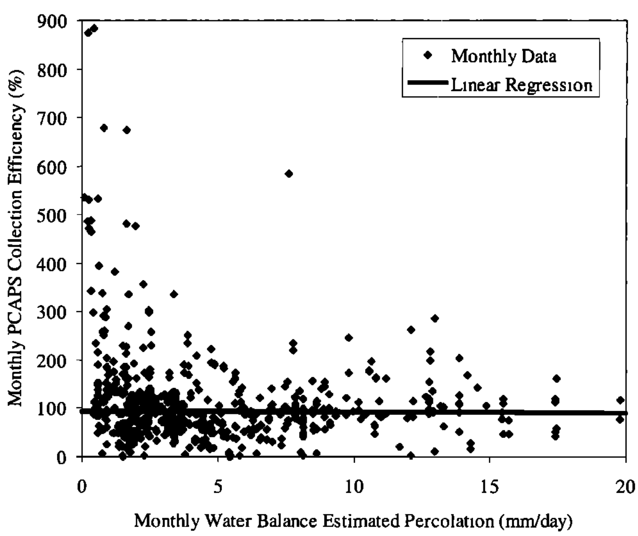

Figure 4. Monthly PCAPS collection efficiency as a function of estimated percolation rate.

3.4. Number of Samplers Required

The number of PCAPS needed to estimate the annual recharge at each site was determined from the mean collection efficiency confidence interval:

$$\bar{y} \pm t_{\alpha/2,n-1}\left(\frac{s}{\sqrt{n}}\right), \tag{6}$$

where $\bar{y}$ is the mean yearly collection efficiency, n is the number of samplers, t is the t statistic with $n - 1$ degrees of freedom and a probability of exceedance of $\alpha/2$, and s is the sample standard deviation. The sample standard deviation was estimated from the pooled standard deviation of the yearly collection efficiencies for all sites. Therefore the number of samplers estimate incorporates the variation resulting from the PCAPS, each soil type, and each management system. For analysis using the t statistic to be valid, samples must be independent and follow a normal distribution. The data appear to be well described by a normal distribution. From the normally distributed annual collection efficiencies in Table 4, the minimum number of samplers needed to estimate the mean annual recharge at each site with a 15% bound on the mean and 95% confidence level is 25. A more appropriate bound on the mean may be of the order of 30%, given that the coefficient of variation for the yearly collection efficiencies is 36%. A minimum of eight samplers are needed to estimate the mean annual recharge at each site with a 30% bound on the mean and 95% confidence level. This number corresponds closely to the results of *Brandi-Dohrn et al.* [1996a] and is thought to be due to intrinsic variability of percolation. To obtain the 95% confidence level, the eight samplers must be located as to provide independent measurements of percolation.

4. Conclusions

The PCAPS showed little evidence of technical failure over the 4 years of sampling covered in this study. Only two of the 42 installed samplers were determined to have been subject to functional failure, the mechanical failure attributed to an apparent collapse of the interior HDPE sampling box due to oversuction during sample retrieval. Ten of the 42 installed samplers were frequently below the water table, resulting in flooded collection vessels. These PCAPS were installed in locations susceptible to high or perched water tables throughout the year.

PCAPS yearly collection efficiency averaged 125% (C.V. = 36%) in comparison to a water balance estimate of recharge. The difference between the estimates of recharge was largely independent of expected percolation. Three likely sources of this discrepancy have been identified. High water tables observed during winter months result in a soil pressure gradient much closer to zero than the unit gradient assumed in the wick-matching procedure. In these situations, the wick is applying a greater tension than the surrounding soil, resulting in overcollection. Possible overestimation of reference evapotranspiration used to compute the water balance percolation will also result in increased collection efficiencies. In addition, macropore flow may have delivered more water to the samplers than would have been observed in native soil. To estimate the mean annual recharge at each site with a 30% bound on the mean and 95% confidence level, eight samplers are needed. One individual PCAPS may not give an accurate estimate of recharge, but several PCAPS can be used to give a good estimate of actual groundwater recharge.

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