PASSIVE CAPILLARY SAMPLER FOR MEASURING SOIL WATER DRAINAGE AND FLUX IN THE VADOSE ZONE: DESIGN, PERFORMANCE, AND ENHANCEMENT

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ABSTRACT. *Various soil water samplers are used to monitor, measure, and estimate drainage water, fluxes, and solute transport in the vadose zone. Passive capillary samplers (PCAPs) have shown potential to provide better measurements and estimates of soil water drainage and fluxes than other lysimeters designs and field sampling methods. Twelve automated PCAPs with sampling surface dimensions of 31 cm width × 91 cm long and 87 cm in height were designed, constructed, and tops of the samplers were placed 90 cm below the soil surface in a Lihen sandy loam (sandy, mixed, frigid Entic Haplustoll). The PCAPs were installed to continually quantify the amount of drainage water and fluxes occurring under sugarbeet (*Beta vulgaris *L.) and malting barley (*Hordeum vulgare *L.) crops treated with 30 mm (low replacement) and 15 mm (high replacement) irrigation frequencies. Drainage water was extracted, collected, and measured periodically (weekly from May to mid-August, biweekly until late September, and monthly thereafter until mid-November). This design incorporated Bluetooth wireless technology to enable an automated datalogger to transmit drainage water and flux data simultaneously every 15 min to a remote host. Real-time seamless monitoring and measuring of drainage water and fluxes was thus possible without the need for costly time-consuming supportive operations. The mean difference (M_d) values between manually extracted and logged drainage water for high frequency (M_d = 0.80 mm) and low frequency (M_d = 0.26 mm) irrigations were small and not significantly different from zero. The Root Mean Square Error (RMSE) of 2.46 and 7.83 mm for high frequency and low frequency irrigations, respectively, were also small. Despite small variations in drainage water results, our novel PCAP design provided an accurate and convenient way to measure water drainage and flux in the vadose zone. Moreover, it offered a significantly larger coverage area (2700 cm^2) than similarly designed vadose zone fluxmeters or PCAPs. In the course of one year's field testing, we incorporated several additional enhancements such as PCAP container, tipping bucket and datalogger unit, all of which we recommend for optimal performance.*

Keywords. *Lysimeter, Tipping bucket, Fluxmeter, TDR sensor.*

The vadose zone, also termed the unsaturated zone, is an important layer of the soil profile between the surface and the saturation zone or permanent water table (Warrick, 2003). Chemical transport and loss with drainage water through the vadose zone and into the groundwater poses a critical problem for public health and environmental quality as well as cost-effective agriculture. Successful monitoring of pollutant transport and leaching through the soil requires accurate and appropriate methods to capture, sample, and measure drainage water and estimate water fluxes within the vadose zone. The most common and currently available field methods for drainage water and flux monitoring and sampling employ various types of water samplers or lysimeters (e.g., porous ceramic suction cups, zero tension pan lyisimeters, gravity drainable soil columns, passive capillary fiberglass wick samplers (PCAPs), and weighing lysimeters and tile drainage samplers). These samplers or lysimeters are widely used to monitor and sample leachate under saturated and unsaturated soil conditions.

Previous studies have indicated that among available lysimeters, the PCAP offers better estimates of actual soil water drainage and fluxes than alternative field methods (Louie et al., 2000; Gee et al., 2002). For example, it captures both matrix and macropore flow under both saturated and unsaturated soil conditions (Boll et al., 1992). The PCAP consists of a hanging water column created by a multi-strand fiberglass wick.

The fiberglass wicks used in the PCAP design are particularly desirable because they do not adsorb nitrate, organic chemicals, or colloids (Boll et al., 1992; Brandi-Dohrn, 1997). The PCAP wick strands utilize the tension arising from capillary potential to sample drainage water effectively under unsaturated soil conditions. The amount of tension applied by these wicks (Knutson and Selker, 1994) is a function of type, length, and diameter, all of which are carefully selected to match soil characteristics at the installation site (Boll et al., 1992; Masarik et al., 2004). The PCAPs have become especially attractive because they require no external vacuum devices to extract soil pore water

Submitted for review in August 2007 as manuscript number SW 7136; approved for publication by the Soil & Water Division of ASABE in April 2008.

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under unsaturated conditions (Gee and Campbell, 1990; Boll et al., 1992; Louie et al., 2000; Zhu et al., 2002; Czigany et al., 2005). The PCAPs have also been tested for their performance efficiencies in both lab and field conditions and have shown results superior to other samplers in terms of soil water drainage, nitrate leaching, and flux measurements (Holder et al., 1991; Poletika et al., 1992; Brandi-Dohrn et al., 1996; Knutson and Selker, 1996; Brahy et al., 2002; Zhu et al., 2002). The PCAPs have been used to measure soil water drainage (Boll et al., 1992) and nitrate leaching (Knutson and Selker, 1996; Zhu et al., 2003) from the soil and have demonstrated greater collection efficiency than other types of lysimeters (Zhu et al., 2002).

Gee et al. (2002, 2003) developed a water fluxmeter using a fiberglass wick PCAP and a tipping bucket to continuously estimate soil drainage fluxes; unfortunately, their fluxmeter design has a relatively small surface capture area (346 cm^2) of coverage. Our enhanced PCAP-type fluxmeter design has, on the other hand, a significantly enlarged surface capture area (2700 cm^2) that enables the collection of more drainage water with greater efficiency than other types of PCAP. Useful for *in-situ* and continuous water flux estimates and measurements of drainage water, our design also employs an automated datalogger to transmit data simultaneously to a remote host by means of Bluetooth wireless communication technology. This automation enables our PCAP to continually monitor and estimate drainage water and flux as it extracts soil pore water.

The objectives of this article are to (1) describe the construction and installation of our automated PCAP design; (2) report the effectiveness of the design in estimating, monitoring, and quantifying the drainage water and flux occurring under sugarbeet and barley crops subject to two irrigation frequencies (15- and 30-mm replacements, high and low, respectively); and (3) recommend design improvements and enhancements for future models.

Materials and Methods

Soil and Site Description

This study was initiated in the fall of 2005 at the USDA-ARS Nesson Valley irrigated research farm located approximately 37 kilometers east of Williston, North Dakota (48.1640 N, 103.0986 W). This is a newly established research site that was previously in dryland hay production for over 20 years. The soil is classified as a Lihen sandy loam (sandy, mixed, frigid Entic Haplustoll), consisting of very deep, well- or somewhat excessively-drained soil. Particle size distribution analysis indicated the textural class of the surface horizon (0 to 30 cm) to be consistently within the sandy loam classification. The amount of sand, silt, and clay in the soil at 0- to 30-cm depth ranged from 640 to 674, 176 to 184, and 150 to 166 g kg^{-1}, respectively. Soil bulk density at 0- to 30-cm depth ranged from 1.51 to 1.66 Mg m^{-3}. Field-saturated hydraulic conductivity ranged from 10.4 to 31.5 mm/h at 0- to 30-cm depth. Background soil sampling prior to this project showed very low residual NO_3-N with depth, which allows better tracking of actual NO_3-N transport below the rooting zone due to specific treatments.

Design Description and Construction

The PCAP sampler is a lidded box or container buried under the soil surface. The containers used in this study were made of 9.5 mm thick natural high density construction materials (HyTEK Plastic Inc. Corvallis, Oreg.) with outside dimensions of 91 cm length × 31 cm width × 87 cm height (fig. 1).

A perforated platform was constructed and located inside the container at 15 cm above the container base. A series of evenly spaced 2.4-mm holes in the platform allowed water to collect in the bottom of the container. A 3.8-cm hole drilled in the platform center accommodated an 18-cm long glass tube located 1.3 cm above the container base. This glass tube was connected to Tygon high purity tubing up through the 3.8-cm platform center hole and held in place by a rubber stopper. Two tipping bucket gauges (RainWise Inc. Bar Harbor, Maine) were set upright in the container and fastened to the platform (fig. 1).

Each tipping bucket contained the lower free ends of a hanging water column 9.5 mm (PEP 3/8) in diameter composed of five 20-strand fiberglass rope wicks[Pepperell Braiding Co., East Pepperell, Mass. (Knutson and Selker, 1994)]. Prior to assembly, each wick had been freed of hydrophobic manufacturing chemicals by combusting at 400°C for 4 h, cleaning and rinsing with triple deionized water, and then air drying (Knutson et al., 1993). Each wick was 122 cm long; each was encased in plastic and positioned upright with 76 cm of wick extending into the tipping bucket. The plastic-encased wick system facilitated the absorption of irrigation or rainfall water at the same rate as the soil and allowed the absorbed water to drip into the bucket.

Three 3.8-cm holes drilled in the container lid accommodated the free ends of each wick system as well as the bucket wires and glass-tube-connected Tygon. The upper free ends of each wick system were manually unraveled and spread evenly through the predrilled 3.8-cm hole located in the container lid directly above the respective rain tipping bucket, creating a 2700-cm^2 soil water collection area. Spaces between strands were filled with extra wick material and fine silica flour (Soilmoisture Equipment Corporation, Santa Barbra Calif.). The thickness of silica flour layer applied on top of the samplers was approximately 1 cm. The tipping bucket wires and glass tube-connected Tygon were drawn up through the container lid at the 3.8-cm center hole, to which a 3.8-cm conduit had been attached. Each container lid was then secured in place by screws.

The external ends of the conduit and data-transmitting bucket wires were attached to and stored in an externally located box housing a datalogger (CR200, Campbell Scientific Inc., Logan, Utah) enhanced with Bluetooth technology. The datalogger continuously monitored the number of tips to estimate water flux.

Passive Capillary Samplers (PCAPs) Installation

Twelve automated PCAP fluxmeters were placed 90 cm below the soil surface to quantify the amount of drainage water below the rootzone of a sugarbeet-potato-barley cropping system under two irrigation frequencies (30- and 15-mm replacements). Sugarbeet was grown under both conventional and strip tillage systems. Locations of 12 installed PCAPs in the field, including field size dimensions and cropping pattern is illustrated in figure 2. The extensively modified, on-site, GPS-linked, precision linear

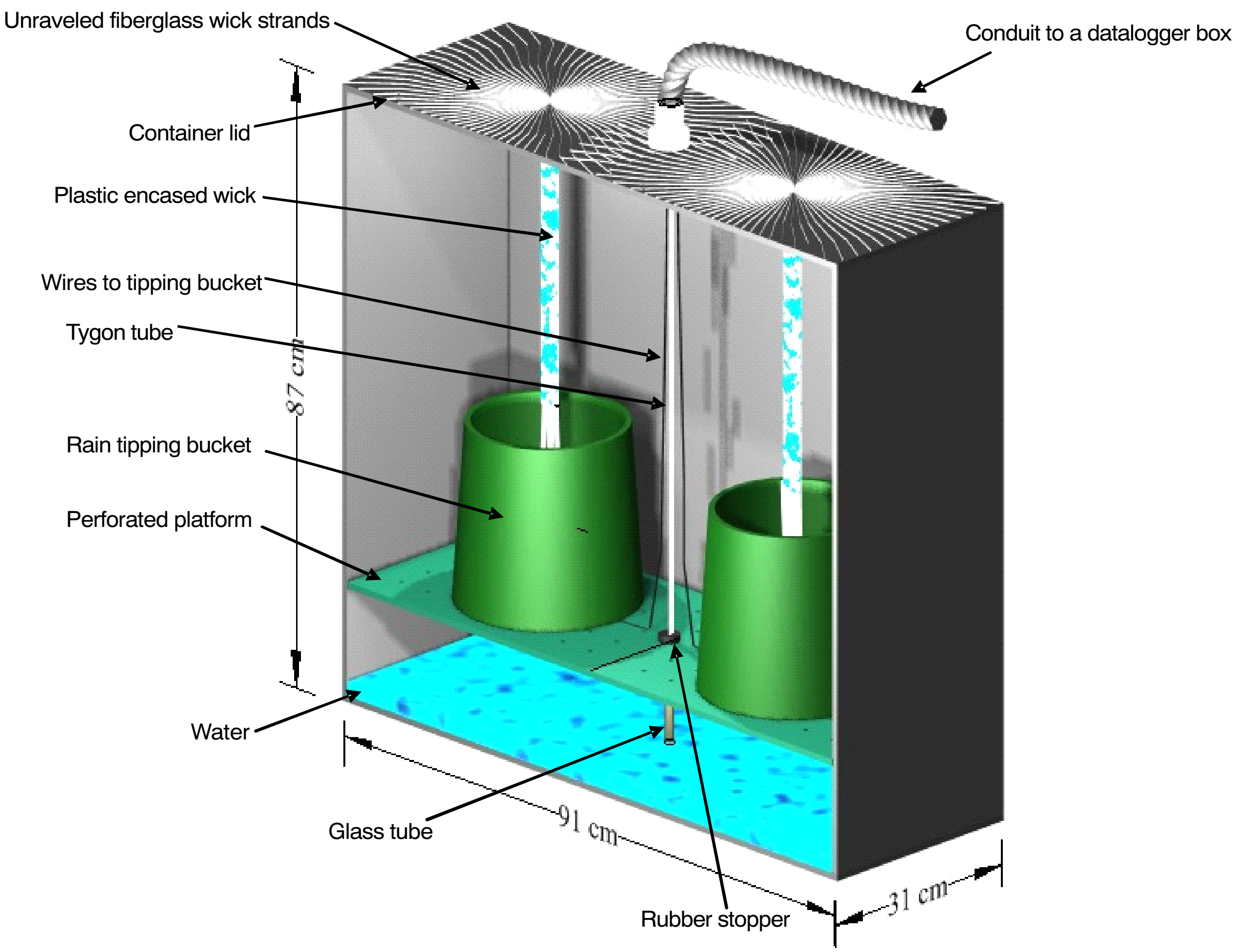

Figure 1. Schematic diagram of the passive capillary sampler (PCAP) with a front panel removed.

move irrigation system was used to allow precise water and nutrient applications.

Soil pits were excavated using a backhoe. Soil from each horizon was placed in separate piles for each pit. Each of the 12 PCAPs was placed in excavated pits 90 cm below the soil surface in a sandy loam soil during 19-21 October 2005 at the Nesson irrigated site. The bottoms of the pits were leveled and two 3.8 cm × 8.9 cm and 36 cm long pieces of wood were set in each pit to support the PCAP container. Each PCAP was leveled on the supports, after which a layer of silica powder was poured around the unraveled wick strands threaded through the container lid.

Soil was then replaced into each pit, reproducing the soil horizons as closely as possible, until the soil had covered the top of the PCAP. The remaining soil was added with shovel and backhoe, and then mechanically compacted using plate-type power soil compacter to approximate the bulk density of the undisturbed soil. Average soil bulk densities measured at three depths were 1.539 and 1.566 Mg m^{-3} (n = 36) for disturbed and undisturbed soils, respectively. It appeared that the mechanisms of freeze-thaw actions altered soil structure and brought soil bulk density near its original condition.

Two TDR sensors (CS625, Campbell Scientific Inc., Logan, Utah) were positioned at 15- and 76-cm depths above each PCAP to continuously monitor soil moisture gradients. The wires for the TDR sensors were threaded through conduit that connected to the box containing the datalogger (fig. 3). Soil moisture content data from the TDR will be used in future studies to calculate hydraulic gradients and estimate drainage water fluxes using Darcy's equation. Therefore, the TDR moisture data are not reported in this article.

Wireless Data Collection and Monitoring Design

Our automated PCAP system combined the lysimeter and datalogger unit with wireless data collection and monitoring technology. Each wire-and-conduit-connected datalogger was attached to a Bluetooth radio transmitter (SD202, Initium Co., Sungnam, Korea) capable of wirelessly broadcasting data to a remote host or onsite/offsite computer system. Dataloggers and radio transmitters were each self-powered by a 12-VDC solar-rechargeable battery (fig. 3).

The box housing the datalogger also housed the transmitter and was equipped with an exterior Bluetooth radio receiver (MSP-102a, Initium Co., Sungnam, Korea) mounted on a metal pole 1.6 m above the soil surface. The Bluetooth receiver was connected (Bluetooth RS-232 serial adaptors (SD205, Initium Co., Sungnam, Korea) to the host computer which was bridged to a Web server for Internet-based,

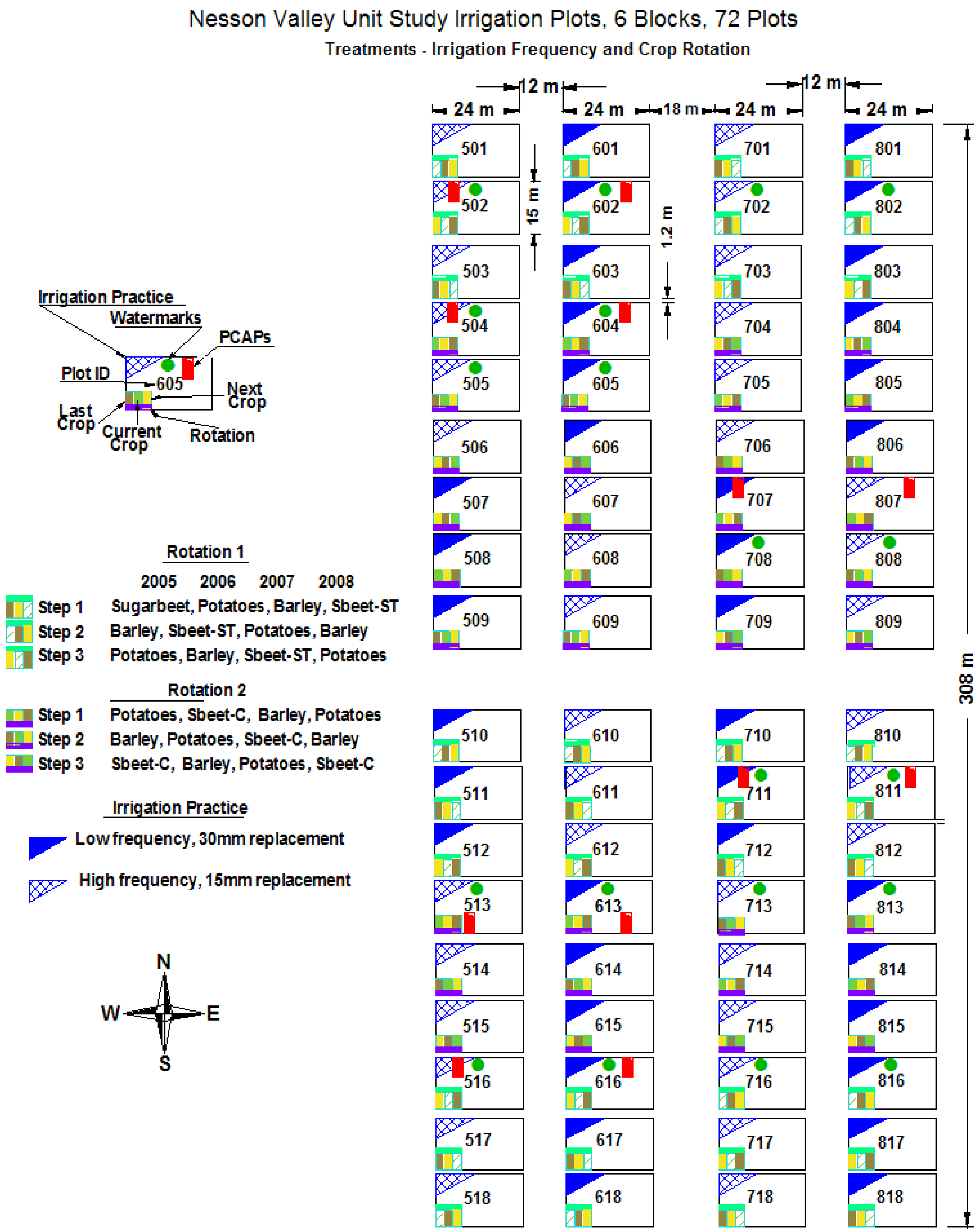

Figure 2. Locations of 12 installed PCAPs in the field, including field size dimensions and cropping pattern.

real-time online data display and monitoring. The Bluetooth transmitters were a power class1 output of 63 mW (18 dBm) with a maximum data transfer rate of 380 Kbps. The range of these units can be extended up to 1200 m with high gain antennas. Our configuration used 8.5-dBi gain patch antennas in conjunction with 2.0-dBi dipole antennas to cover our required range of 800 m. The data storage and retrieval were configured in the base computer by a software application (LoggerNet, Campbell Scientific, Inc., Logan, Utah) that uses client-server architecture.

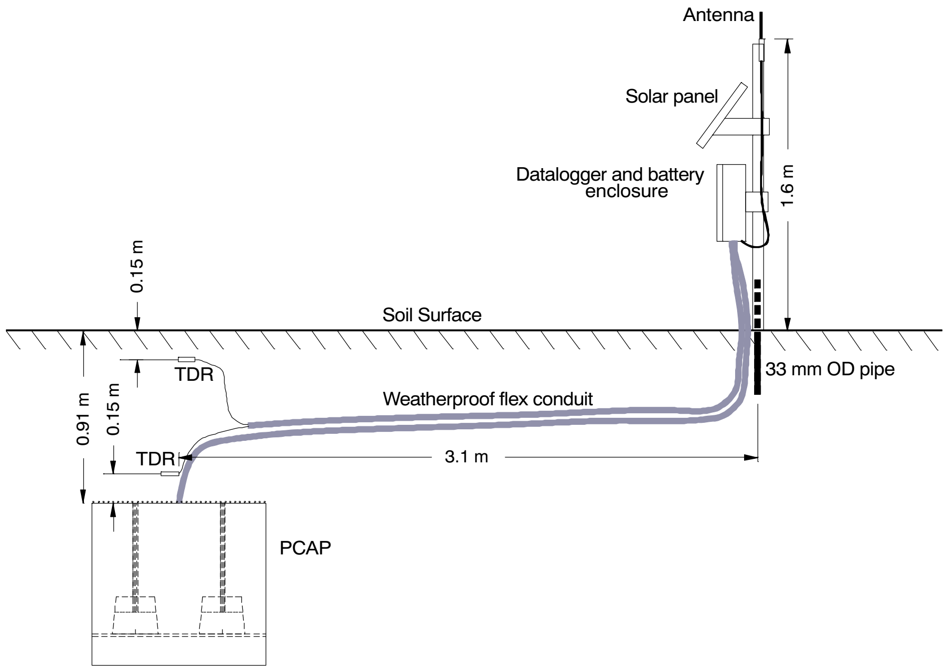

Figure 3. Detailed cross sectional view of passive capillary sampler (PCAP).

Sensory data, sampled every 15 min, were wirelessly transmitted to the remote host, located about 750 m away from the Nesson irrigated site.

PCAPs Water Sampling

Water was extracted from the PCAPs weekly from May to mid-August, biweekly until late September and monthly thereafter until mid-November. Water samples were obtained with an electric drainage extraction pump with check valve to prevent reverse flow (3.1 bar output pressure, Shurflo, Elkhart, Ind.), then measured and stored in an ice cooler. The remaining volume of water in each container was later measured in the laboratory, where a small sample was filtered using Q2 filter paper (porosity: fine, flow rate: slow; Fisher Scientific, Pittsburgh, Pa.), then stored frozen in a small container for future chemical analysis.

Drainage water moving below the rooting zone was sampled and calculated from the PCAPs in the sugarbeet (conventional tillage) and barley cropping systems under both high and low irrigation frequencies. The manually extracted (pumped) drainage water was compared with the volume of drainage water recorded by the datalogger from the tipping bucket using several statistical methods.

Statistical Analyses

Several statistical methods were used to evaluate the accuracy and performance of the PCAPs. The mean difference, M_d, and root mean square error, RMSE, were employed to determine the degree of coincidence and agreement between the extracted and logged drainage water values. The lower limit for M_d and RMSE is zero, which denotes no difference between extracted and logged values.

Linear equations were generated from the regression analysis of the cumulative drainage water extracted from the PCAP systems against the logged drainage water values. The correlation coefficients (r) and test of the null hypothesis of a slope of the regression line equal to zero were used to determine whether the line showed a statistically significant linear relationship between extracted and logged drainage water.

Results and Discussion

PCAP Design and Performance Evaluation

Our automated and enhanced PCAP (figs. 1 and 3) featured a collection system superior in design, technology, and sophistication to other types of PCAPs for measuring soil water drainage and fluxes in the vadose zone. It recorded *in-situ* measurements of drainage water and flux every 15 min as it extracted soil pore water. It continuously monitored and estimated drainage water and flux without the need for costly time-consuming supportive systems such as vacuums and pumps. Relatively large surface area of PCAPs (2700 cm^2) enabled the collection of more drainage water with greater efficiency than other types of PCAPs (Brandi-Dohrn et al., 1996; Zhu et al., 2002, 2003). Finally, use of Bluetooth and sensing technologies with PCAPs allowed real-time monitoring of drainage water and flux field data on the internet through wireless simultaneous transmission of sensory information to a remote host via a computer-connected receiver bridged to a Web server.

PCAP Drainage Water Collection Accuracy

Cumulative logged and extracted drainage water as well as cumulative precipitation and irrigation were displayed in figures 4 and 5. During the summer months little drainage occurred because of the high evapotranspiration rates of crops.

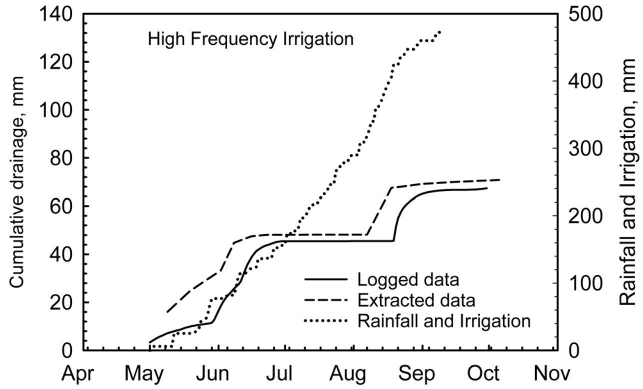

Figure 4. Cumulative drainage water (mm) under high frequency irrigation.

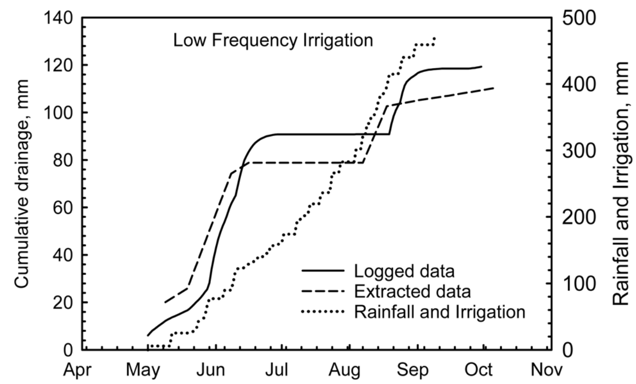

Figure 5. Cumulative drainage water (mm) under low frequency irrigation.

Descriptive statistics including mean, standard deviation, minimum, and maximum values for extracted and logged drainage water under high and low frequency irrigations are given in table 1. The mean and standard deviation values for extracted and logged data were highly related demonstrating the accuracy of the PCAPs performance.

A paired t-test also showed that the M_d values between manually extracted and logged drainage water for high frequency (M_d = 0.80 mm, t = 0.73, $p > 0.48$) and low frequency (M_d = 0.26 mm, t = 0.0.08, $p > 0.94$) irrigations were small and not significantly different from zero. The RMSEs of 2.46 and 7.83 mm for high frequency and low frequency irrigations, respectively, were also small.

The extracted and logged cumulative drainage water fluxes below the rooting zone were compared by plotting on 1:1 line (figs. 6 and 7). Regression analysis of linearity indicated that slopes were significantly different from zero ($p < 0.01$). The correlation coefficients between cumulative extracted and logged drainage water values for both high and low irrigation frequencies were high (r = 0.995 and 0.980, respectively) and significant ($p < 0.01$). Our findings indicate good agreement between the extracted and logged drainage water volumes, with R^2 equal to 0.96 ($p < 0.01$) for low frequency irrigation and 0.99 ($p < 0.01$) for high frequency irrigation (figs. 6 and 7). However, the statistical parameters, M_d and RMSE indicated that small differences existed between extracted drainage water by pump and drainage water recorded by the datalogger from the tipping buckets. The reason for these slight variations between manually extracted and logged drainage water under high frequency irrigation may be related, in part, to the reed in the reed switch bouncing on the contact point due to corrosion and therefore number of tips were not registered correctly as actual tips by the datalogger. Furthermore, this could also be attributed to inherent manufacturing differences in the tipping bucket assemblies. The tipping buckets were calibrated before installation, but the resolution for each bucket tip was approximately 0.01 mL. A small error in calibration multiplied by many thousands of tips over the season would affect the agreement between the logged and extracted data. However, the cause of variation between manually measured and logged drainage water under low frequency irrigation could have resulted from human sampling error under field conditions.

Overall, statistical results confirm that our PCAP design offers a reliable and convenient way to measure drainage water volumes and fluxes in the vadose zone. Drainage water and fluxes can be continuously monitored and measured without the need for costly and time-consuming supportive operations such as vacuum and water pumping systems.

Table 1. Descriptive statistical summary.

Statistics	High Frequency Irrigation: Manually Extracted	High Frequency Irrigation: Logged	Low Frequency Irrigation: Manually Extracted	Low Frequency Irrigation: Logged
	Drainage Water (mm)			
Mean	5.90	5.10	9.19	8.92
Standard deviation	6.78	6.33	11.24	10.92
Minimum	0	0	0	0
Maximum	19.33	19.35	33.95	34.24

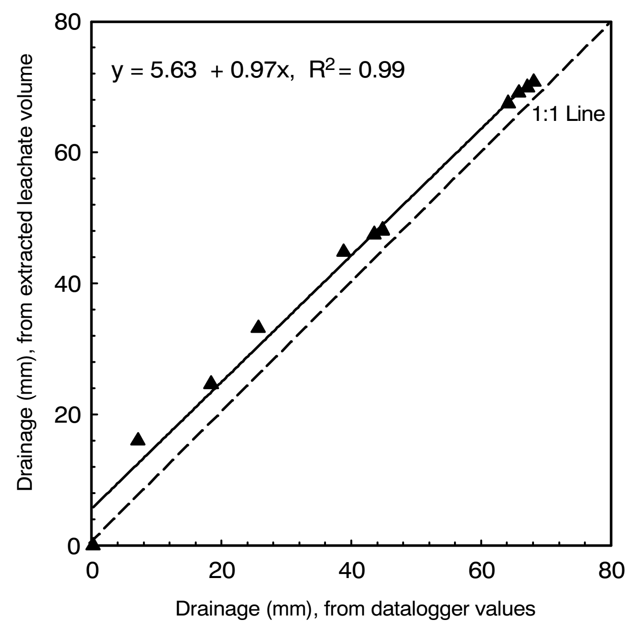

Figure 6. Cumulative drainage water (mm) calculated from extracted and logged leachate volumes under high frequency irrigation.

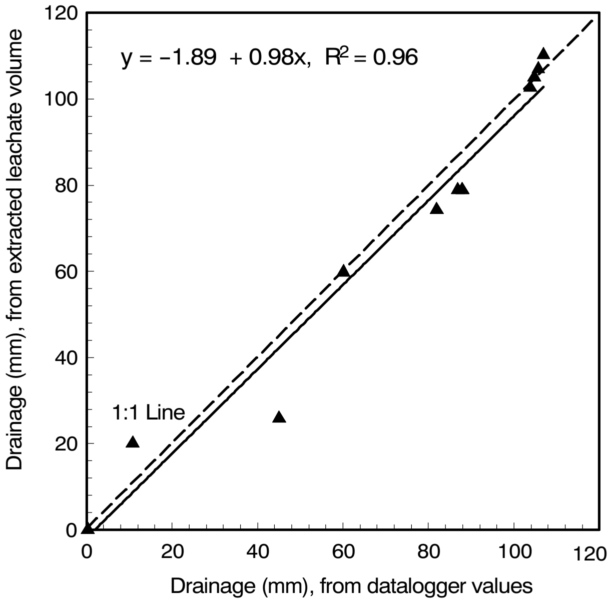

Figure 7. Cumulative drainage water (mm) calculated from extracted and logged leachate volumes under low frequency irrigation.

Design Improvements

We encountered problems with four PCAP samplers in which their data were not included in the analysis. To date we have found no perfect PCAP system for measuring drainage water and fluxes in the vadose zone. This includes our automated, state-of-the-art design, which during testing we modified as needed with the following improvements.

PCAP Container

The original design (fig. 1) of the PCAP container used 9.5-mm thick HDPE (High Density Polyethylene) material for all parts of the box (HyTEK Plastic Inc.). Less than a year after installation, several were unearthed for repairs and we discovered that the sides of two of boxes had bowed inward approximately 3 cm, cracking the glue joint securing the lid support. We suggest using 12.7-mm material for the sides or placing a support strut across the center of the box following shelf installation to resist the earth's pressure on the large surface area of the sides.

Tipping Bucket

To allow testing of the tipping buckets after the PCAPs are installed, we suggest placing a 3.2-mm polyethylene tube from the logger box through the flex conduit that attaches to the PCAP and connecting the tube end to the inside wall of the tipping bucket, using a separate tube for each tipping bucket. Operation of the mechanism can then easily be accomplished by injecting approximately 10 mL of water into the tubing with a syringe to tip the bucket. The flex conduit size should be increased from 19 to 25 mm (nominal trade size) to allow the tubing to be drawn through the conduit connectors more easily. Electrician's fish tape was used to draw the tubing and wires through the flex conduit, adding talc as necessary to decrease friction.

We also modified the method used to maintain the position of the tipping bucket gauges (fig. 1). The tipping buckets had originally been secured to the perforated platform inside the container with machine screws and nuts but no lockable washers or anti-vibration compound. The vibration incurred during transport from the assembly lab to the research site (125 km) apparently detached the nuts from the machine screws. One of the PCAPs was later subjected to a water level high enough to float the tipping bucket off the platform. When the water was evacuated the gauge did not return to a level position. Wicks will likely fall out of a floating tipping bucket. To address this problem, we drilled pilot holes in the platform and inserted self-tapping screws through the base of the tipping buckets into the pilot holes in the platform. This modification allows the platform to be installed before the tipping bucket is attached because access is not required to the platform base to install the nuts. The self-tapping screws will not vibrate out; and because the platform can be installed prior to the tipping buckets, the support strut component will not interfere with installation.

The tipping bucket in one of the PCAPs failed a year after installation. The connection between the wire and the reed switch had corroded so badly that one of the wires was physically disconnected from the reed switch terminal. This problem has not been encountered in any of the other tipping buckets by the same manufacturer when they were used for above ground applications. The use of a conformal acrylic casting resin to seal the reed switch connections prior to installation should prevent this problem.

Datalogger Unit

Each logger box and antenna arrangement is mounted on a pipe that slips over a shorter piece of pipe driven into the ground (fig. 3). This arrangement was designed to enable the logger, the solar panel, and the antenna assembly to be lifted up and off the shorter pipe as a unit and temporarily placed on the ground to prevent interference with field operations such as planting, spraying, and harvesting. We suggest allowing an extra 0.6 m of slack in the flex conduit above the soil surface to enable the longer pipe to be lifted clear of the shorter pipe. Partial dislodging of the shorter pipe initially occurred when we lifted the longer pipe up and off the shorter pipe; dislodging took up all remaining slack in the flex conduit and prevented the logger assembly from being completely laid down. We welded a 20-cm piece of angle iron to each shorter pipe prior to reinsertion in the soil to address this problem. The 20-cm addition provided a foothold to secure the shorter pipe and prevent partial dislodging while the larger pipe was being removed.

The solar panel tended to rotate out of position in strong winds; to eliminate this tendency we welded a 5-cm piece of angle iron onto the larger pipe. This addition nested over the 20-cm addition on the smaller pipe as an inverted "V" (Λ) in cross section.

The logger box components had to be fastened more securely to withstand frequent position changes. The original design utilized only the foam material that came with the enclosures, cut out to accommodate the logger and battery. Although streamlined in appearance, this design allowed the battery to fall out if the enclosure door did not remain shut during manual data downloading. To secure the battery, we bolted a piece of 5-cm length × 5-cm height × 5-cm width × 0.6-cm thickness polypropylene angle material to the foam housing.

TDR Moisture Sensor

The shallowly-placed (15-cm depth) TDR sensors in plots requiring deep tillage later had to be located and placed deeper, prior to tillage operations, then unearthed and repositioned at the proper depth. They are easier to locate if they are always oriented in the same direction.

Lastly, the Tygon tubing and conductor wires should not be taped to each other during installation. If one of the TDRs is faulty, it is much simpler to cut the conductor next to the faulty TDR, tape the old wire to the new one, and pull the new wire in from the logger end. If tubing and wires are taped together, disconnect both at the logger end and attach a cord to the wires. After attaching the cord, pull out the wires from the end of the conduit near the TDRs, sever the tape holding the conductors together, and attach and pull the new conductors through with the cord.

Conclusions

In this article we demonstrated and evaluated the utility, performance, and accuracy of a newly designed, automated PCAP fluxmeter for *in-situ* continuous measuring drainage water and fluxes in the vadose zone. Our design has a significantly enlarged surface capture area (2700 cm^2) that enables the collection of more drainage water with greater efficiency, less variability and better accuracy than other types of PCAPs compared with other fluxmeters. It employs an automated datalogger to transmit data simultaneously to a remote host by means of Bluetooth wireless technology. This design allowed real-time monitoring and estimating of drainage water and fluxes as it extracted soil pore water. Automation allowed our PCAP sampler to operate without the need for costly and time-consuming supportive systems such as vacuums and pumps. We found good statistical agreement between the extracted and logged drainage water fluxes, with a R^2 value equal to 0.96 for low frequency irrigation and 0.99 for high frequency irrigation. Regardless of small variations between manually extracted and logged drainage water, our results confirmed that our design provides a reliable, accurate, and convenient means to measure water drainage and fluxes in the vadose zone. The total cost associated with construction and installation of each PCAP was approximately $1881.

Acknowledgments

The authors wish to acknowledge Amy McGregor, Dale Spracklin, Bryan Gebhard, John Reiger, Tylor Tjelde, and Rene France for their assistance with construction and installation of the PCAPs as well as with water sampling and lab analysis. We also thank Dr. Yuanhong Zhu from Pennsylvania State University, Dr. Zhengxia Dou, and Mr. John Toth from University of Pennsylvania for their valuable comments and suggestions. The helpful suggestions of the Associate Editor, Dr. Prasanna Gowda, and three anonymous reviewers are greatly appreciated.

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