Improvements to Measuring Water Flux in the Vadose Zone

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Improvements to Measuring Water Flux in the Vadose Zone

Kevin C. Masarik,* John M. Norman, Kristofor R. Brye, and John M. Baker

Abstract

Evaluating the impact of land use practices on ground water quality has been difficult because few techniques are capable of monitoring the quality and quantity of soil water flow below the root zone without disturbing the soil profile and affecting natural flow processes. A recently introduced method, known as equilibrium tension lysimetry, was a major improvement but it was not a true equilibrium since it still required manual intervention to maintain proper lysimeter suction. We addressed this issue by developing an automated equilibrium tension lysimeter (AETL) system that continuously matches lysimeter tension to soil-water matric potential of the surrounding soil. The soil-water matric potential of the bulk soil is measured with a heat-dissipation sensor, and a small DC pump is used to apply suction to a lysimeter. The improved automated approach reported here was tested in the field for a 12-mo period. Powered by a small 12-V rechargeable battery, the AETLs were able to continuously match lysimeter suction to soil-water matric potential for 2-wk periods with minimal human attention, along with the added benefit of collecting continuous soil-water matric potential data. We also demonstrated, in the laboratory, methods for continuous measurement of water depth in the AETL, a capability that quantifies drainage on a 10-min interval, making it a true water-flux meter. Equilibrium tension lysimeters have already been demonstrated to be a reliable method of measuring drainage flux, and the further improvements have created a more effective device for studying water drainage and chemical leaching through the soil matrix.

As the need for quality water and nutrient management continues to grow, a better understanding of water drainage and chemical leaching through the vadose zone also is needed. Leaching can move large amounts of nutrients and other pollutants from the soil surface and root zone to the ground water (Jemison and Fox, 1994). Therefore, monitoring and measuring techniques that can determine drainage flux from undisturbed soil profiles is critical for the determination of nutrient budgets and the evaluation of land-use practices on water quality.

Various technologies exist for measuring the drainage flux through the soil matrix by intercepting water and manually or automatically sampling the accumulated volume of water. Two types of sampling equipment commonly used for this purpose are zero-tension and fixed-tension lysimeters. Both have potential problems that can cause large errors in drainage flux measurements (Radulovich and Sollins, 1987; Jemison and Fox, 1992). Zero-tension lysimeters require that soil above the collection pan be saturated before water will drain into them. During unsaturated conditions water flow will bypass a zero-tension lysimeter and underestimate actual drainage amounts (Jemison and Fox, 1992). With fixed tension a constant tension is applied to the lysimeter to remove water from the soil matrix. Fixed-tension lysimeters are often used to obtain the chemical concentration of soil solution, but no useful relationship was found between the water collected and the amount of water drainage (van der Ploeg and Beese, 1977; Angle et al., 1991).

Technology exists to sample water flux in unsaturated soil. Passive capillary samplers (PCAPS) have been used to measure water drainage (Boll et al., 1992; Knutson and Selker, 1996) and chemical leaching from the soil, and have been shown to have greater collection efficiency than zero-tension pan lysimeters (Zhu et al., 2002). Passive capillary samplers rely on the capillary potential of a fiberglass wick to apply tension and sample water drainage in unsaturated soil. The tension applied by the PCAPS is a function of the wick material, as well as the wick length and diameter, which must be carefully selected to match soil characteristics at installation sites (Boll et al., 1992). Although many studies show the effects of capillary wicks on the chemistry of the solution collected to be negligible (Holder et al., 1991; Boll et al., 1992; Knutson and Selker, 1996), issues have been raised regarding the resistance of the wick material to weathering and the suitability of PCAPS for geochemical studies of dilute soil solutions (Goyne et al., 2000). Recently, Gee et al. (2002) developed a vadose zone water fluxmeter using a PCAPS and a tipping bucket to continuously measure collected water volumes. Unfortunately, this device has a relatively small surface-sampling area (346 cm^2) and installation requires the backfilling of soil above the collection device, which is a serious flaw in many studies that require drainage from undisturbed soil profiles.

Equilibrium tension lysimeters (ETLs) were developed by Brye et al. (1999) to address the problems

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Abbreviations: AETL, automated equilibrium tension lysimeter; ETL, equilibrium tension lysimeter; HDS, heat-dissipation sensor.

associated with zero-tension lysimeters and fixed-tension lysimeters and can be installed below an intact soil profile. By adjusting lysimeter suction to match soil-water matric potential, ETLs maintain equilibrium between lysimeters and the bulk soil. In their design, heat-dissipation sensors (HDS) were used to measure the soil-water matric potential adjacent to the lysimeter. A human operator visited each ETL periodically, typically two or more times per week, and manually adjusted ETL suction to match that of the surrounding soil. Essentially this represents a frequently adjusted, fixed-tension lysimeter. Equilibrium tension lysimeters have maintained their integrity for over 8 yr at the original installation sites, demonstrating the suitability of ETLs for long-term studies. They have been used successfully to measure drainage fluxes (Brye et al., 2000) as well as nitrogen and carbon (Brye et al., 2001) and soluble phosphorus leaching (Brye et al., 2002) through the soil of prairie and corn (*Zea mays* L.) agroecosystems. Despite the improved performance over previous vadose zone samplers, ETLs are still prone to error due to fluctuations in soil-water matric potential that occur in between adjustments.

A refinement suggested by Brye et al. (1999) was to automate the vacuum controls to maintain a near-constant equilibrium with the soil. Recently, Lentz and Kincaid (2003) designed an automated system for ceramic-cup samplers to maintain equilibrium with the bulk soil. Ceramic-cup samplers were placed in the bottom of a stainless steel beaker filled with 15 to 20 cm of tamped soil and soil slurry before being pushed up into a soil-cavity ceiling to sample below an undisturbed soil column. Although laboratory experiments obtained an extraction–soil tension ratio to optimize the sampler for field soils, no attempt was made, in the field, to verify that equilibrium was maintained between the undisturbed soil and the ceramic cup in the bottom of the stainless steel beaker. Thus, even though the lysimeter tracked soil potential changes over time, there was no way to determine whether the soil potential at the top of the stainless steel beaker was near equilibrium with the bulk soil. Not only could the system chronically over- or underestimate the soil drainage, but large lags could occur between the time a drainage pulse reaches the top of the lysimeter and the lysimeter suction cup responds, leading to transient divergence of flow around the lysimeter. The system used a single vacuum source to maintain suction for 36 samplers, requiring a large network of tubing to connect individual sites to the vacuum source and a large power supply to operate.

The objective of our work was to develop and field-test a low-power, automated equilibrium tension lysimeter (AETL) to improve the response time of ETLs to soil-water matric potential fluctuations in the bulk soil and expand their use to more remote research locations. In addition, we also realized that an ETL, if it is properly controlled in true equilibrium mode, could be used as a water-flux meter if the water level inside of the lysimeter were continuously monitored. To keep up with the growing need for new technology to improve measurement and monitoring of drainage flux, we developed and tested, in the laboratory, a method for automated measurement of water level in an AETL. The level measurement device was not installed in the existing lysimeters because of the need to dig up the field site and remove lysimeters for sensor insertion, which would have disrupted the ongoing experiment.

Materials and Methods

Equilibrium Tension Lysimeters

Each AETL control system was designed to control two of the lysimeters originally constructed by Brye et al. (1999), which have collected reliable water drainage samples for eight consecutive years. The lysimeters were constructed of 1.6-mm-thick stainless steel and were 25.4 cm wide by 76.2 cm long by 15.2 cm tall. A 1-mm-thick porous stainless steel plate (0.2 μm) was welded to the top, and sidewalls that extend 2.5 cm above the porous plate were welded to the outside of the lysimeter walls. Two tubes were also welded to the pan lysimeter; one applied suction just below the bottom of the porous plate, and a second tube served as the drain for sample collection. A detailed construction diagram and installation procedure is described in Brye et al. (1999). An advantage of this design is that the porous plate on the top of the AETL makes direct contact with the undisturbed soil and is kept there by a strong spring pressure so that the AETL tension reliably represents the relevant soil-water matric potential influencing convergent or divergent flow above the lysimeter.

The system was tested on four lysimeters in two replicate plots for chisel plow and no-tillage treatments in an agroecosystem at the UW Agricultural Experiment Station in Arlington, WI. All plots were planted continuous corn rotation and were fertilized at optimum application rates.

Automated Control System

Each system was designed to control equilibrium for two pan lysimeters and a schematic of the electrical and pneumatic components is shown in Fig. 1. The AETLs were controlled by a datalogger (Model CR10X, Campbell Scientific, Logan, UT) and powered for 2-wk periods by a 12-V, 7.2 amp-hour rechargeable battery. Heat-dissipation sensors (HDS; 229-L, Campbell Scientific) connected to an excitation module (CE8; Campbell Scientific) were used to measure soil-water matric potential fluctuations in the bulk soil adjacent to each lysimeter at a depth of 1.4 m and in the soil directly above each lysimeter. The suction applied to the bottom of the porous plate was measured with a differential pressure transducer (PX170-014GV; Omega Engineering, Stamford, CT). Suction in the lysimeter was increased with a battery-operated vacuum pump (TD-2N; Brailsford and Company, Rye, NY) or decreased by bleeding lysimeter vacuum to the atmosphere, until matching was achieved between the HDS in the soil and the lysimeter. Four, 3-way, normally open, standard-mount solenoid valves fitted with 3.2-mm (1/8-in.) barb fittings (ETO-3-12 and 11752-3; Clippard Instrument Laboratory, Cincinnati, OH) were connected to the vacuum pump and pressure transducer with 3.2-mm (1/8-in.)-i.d. clear flexible PVC tubing (14-169-7A; Fisher Scientific, Pittsburgh, PA). A 12-V relay driver (A6REL-12; Campbell Scientific) in connection with the CR10X logger controlled the operation of the vacuum pump and 3-way valves. All equipment was enclosed in a 41- × 46-cm (16- × 18-in.) fiberglass enclosure (ENC 16/18; Campbell Scientific). Copper tubing (6.4-mm-o.d.) connected the vacuum line of each lysimeter to the enclosure and clear flexible PVC tubing connected the copper tubing to a 3-way

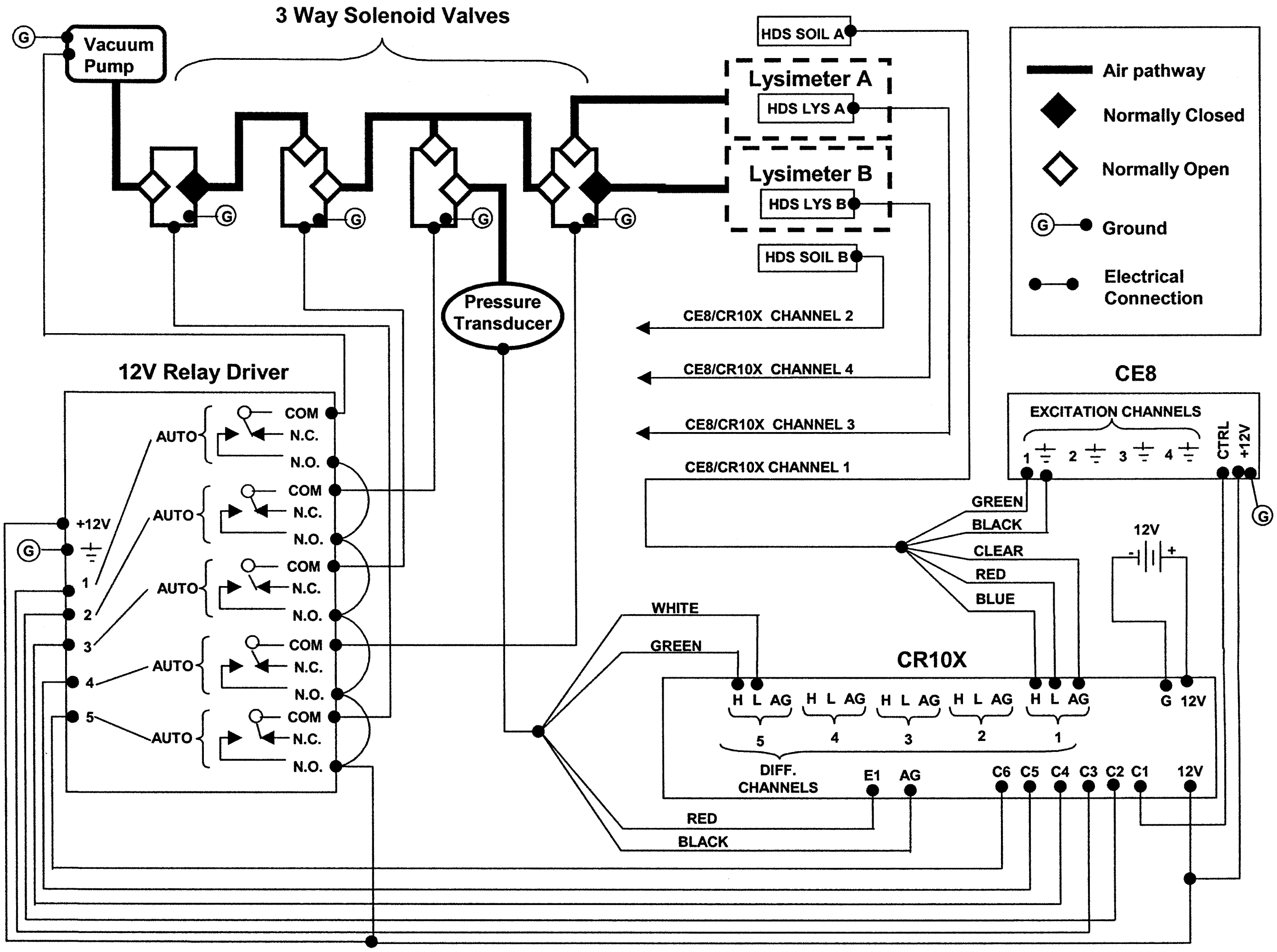

Fig. 1. Schematic diagram of an automated equilibrium tension lysimeter (AETL) system.

valve. The total cost of this control system for two AETLs, excluding the datalogger and heat-dissipation sensors, is approximately $900.

A program written for the CR10X datalogger (Masarik, 2003) maintained equilibrium for two lysimeters independently. The suction limits were set in the program to include a 2-kPa minimum and a 35-kPa maximum tension. The 2-kPa minimum was chosen because, even at saturation, a small suction must be applied before water can be pulled through the porous plate. The maximum tension of 35 kPa is just slightly below the maximum suction achievable by the vacuum pump and slightly drier than field capacity. Lysimeter suctions greater than 35 kPa cause the pump to run excessively; therefore, if the soil-water matric potential of the bulk soil measured greater than 35 kPa, no tension was applied to save battery life and prevent the lysimeter from cavitating. With a larger pump requiring three times as much power, the lysimeter could maintain equilibrium with the soil up to a suction of 60 kPa. For the soil used in this test, field capacity was reached before exceeding the 35-kPa suction, so the low-power pump was deemed sufficient.

Every 10 min the program recorded soil-water matric potentials using the HDSs for the two lysimeters (A, B) in the bulk soil and in the soil directly above the lysimeters. The soil-water matric potential measurement of sensors in the bulk soil was used to control the suction inside the lysimeter, while the HDSs above the lysimeter were used to validate the equilibrium between the lysimeters and the soil. Because HDSs operate near the voltage resolution of the dataloggers, the signals were averaged over a 10-interval period (approximately 100 min). With the recorded soil-water matric potential, the program assigns 5 min to achieve equilibrium for each lysimeter, and continues this process every 10 min until equilibrium is achieved between the lysimeter and the bulk soil. The suction inside the lysimeter is set 2 kPa greater than the soil-water matric potential of the bulk soil to overcome the resistance of the porous plate.

The control program also contained an algorithm to prevent continuous operation of the pump if cavitation of the lysimeter occurred. The arbitrarily chosen indicator for this is a continuous duty cycle for 12 consecutive 10-min execution intervals; when this occurs, the program stops controlling the lysimeter and requires human attention for manual reset. Hourly averages of the following data were stored: soil-water matric potentials for all four HDSs, Lysimeter A and B suctions, vacuum pump time for Lysimeter A and B, and battery voltage.

Water drainage was collected throughout the year since the lysimeters were located below the frost layer in the soil. Lysimeters were sampled approximately once every 14 d for the majority of the year and once every 30 d during periods when the soil surface was frozen. During sampling the program operation was suspended while the leachate was collected from the pan lysimeter. The first liter of leachate was collected for chemical analysis, while any remaining volume was measured and discarded (Brye et al., 1999).

Heat-Dissipation Sensors

The ability of the AETL to maintain equilibrium with the soil is dependent on accurate soil-water matric potential measurements. Therefore, an accurate calibration of the HDSs is critical to maintaining equilibrium of the AETLs. Each HDS's individual response curve was determined to ensure accurate measurements when placed in the field. The air-dry value was obtained by measuring the response of the sensor when it was dry and suspended in air, while the saturated value was obtained after soaking the sensors in water overnight. It is important to note that vacuum saturation was not used in calibrating these sensors because sensors did not return to vacuum saturation values after a drying cycle. Because water drainage is minimal when soils are below field capacity and tension was not applied when the soil-water matric potential measured less than −35 kPa, the most critical part of the HDS calibration was near saturation. A pressure plate was used to force water out of sensors placed in a silty-clay-loam slurry (same soil as field installation) at pressures of 5, 10, 20, 30, 40, 50, and 100 kPa. Sensors were allowed to equilibrate at each pressure and measurements were obtained using a Campbell Scientific datalogger (Reece, 1996; J. Bilskie, personal communication, 2001). Heat-dissipation sensors were excited with electrical current for a period of 10 s and the difference in temperature of the thermocouple inside of the ceramic cylinder before and after heating was recorded. A linear calibration equation was determined by plotting the natural logarithm of the calibration tensions (kPa) against the measured temperature (°C) difference (Campbell Scientific, 1998). The logarithmic relation between tension and temperature differential held for all sensors to a tension of at least 100 kPa. However, for some sensors the linear relation did not fit the 10-MPa point for the air-dry temperature difference as suggested by Reece (1996); as a result, the calibration may lose accuracy when measuring tensions above 100 kPa and can only be considered as semiquantitative measurement at tensions greater than 100 kPa. On each calibration curve sensors at saturation appeared to have a temperature difference consistent with a 5-kPa tension, which may be the air-entry value of the ceramic. One remarkable observation related to the calibration stability of the HDSs was the agreement within a few kPa of the HDS above the lysimeter and the lysimeter suction, suggesting that the calibrations on the HDSs have been stable during 8 yr of continuous use.

Water Level Detection

A wide range of options were available for measuring liquid level. We chose to test a sensor that probably would already be in use at locations where AETLs might be deployed. A new and inexpensive soil moisture gauge was chosen that measures in the frequency domain (ECH_2O probe; Decagon Devices, Pullman, WA). It requires little power and can be read directly using a CR10X datalogger. It was installed in an open-top lysimeter, diagonally from the upper front of the lysimeter internal cavity, just below the level at which the porous surface would be attached, to the lower rear of the cavity across the width of the lysimeter. Diagonal rather than vertical orientation was used to maximize the depth resolution of the measurement. For testing purposes the top was left off of the lysimeter. Water was added incrementally, and the water depth was measured with a measuring tape while the datalogger collected data from the ECH_2O probe.

Results and Discussion

Automated Equilibrium Tension Lysimeters

To test the AETL system under field conditions, two control systems were connected to four existing ETLs. Appropriate installation of ETLs, described in detail by Brye et al. (1999), is nontrivial and is critical to their subsequent performance. The ETLs were connected to the AETL pneumatic and control circuits and the system was operated from 8 Aug. 2001 to 31 Dec. 2002. The datalogger used to operate the AETL also recorded soil-water matric potentials, lysimeter suctions, and leachate volumes. A weather station was also installed nearby to record hourly climatic data.

Hourly averages of the soil-water matric potentials and the lysimeter suction for a 9-d period are shown in Fig. 2. The graph shows the response of soil-water matric potential above the lysimeter to the lysimeter suction, which was applied to match that of the bulk soil. The soil-water matric potential above the lysimeter decreased as the soil-water matric potential of the bulk soil decreased, verifying the operation of the lysimeter control system. The soil-water matric potential above the lysimeter measured slightly less than the soil-water matric potential in the bulk soil due to the 2 kPa of excess suction applied to the lysimeter.

The daily cycling of soil-water matric potential, which is closely followed by the lysimeter control system, is believed to arise from temperature sensitivity of the datalogger, which is within manufacturer specifications. Logger noise levels limit the resolution of HDSs, with 0.4-μV changes causing 10% uncertainty in recorded-tension estimates. Loggers with better voltage resolution would reduce this uncertainty, but averaging also helped to reduce its impact.

The soil-water matric potential of the bulk soil and daily precipitation amounts, along with cumulative drainage collected from the lysimeters and cumulative precipitation, are shown in Fig. 3. The soil-water matric potential measurements show the response of the bulk

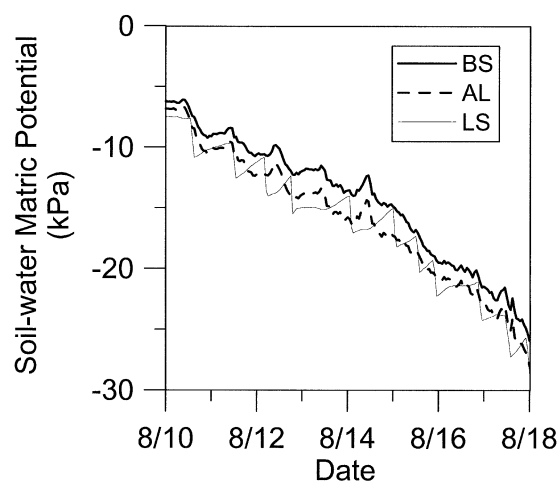

Fig. 2. Hourly response of the automated equilibrium tension lysimeter (AETL) system to changes in soil-water matric potential of the bulk soil (BS), above the lysimeter (AL), and of the lysimeter suction (LS).

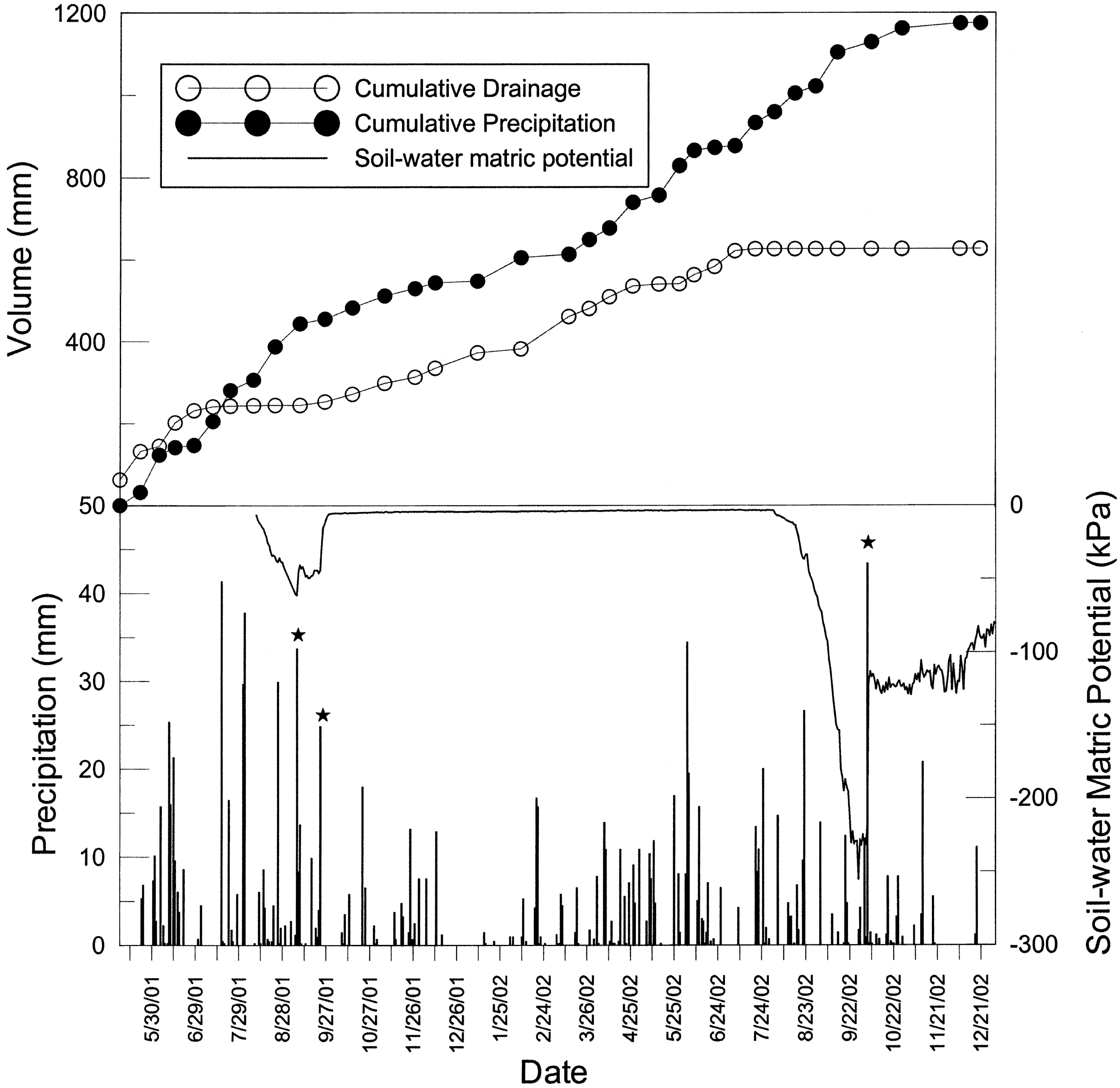

Fig. 3. Natural variation of the bulk soil suction (kPa) along with daily precipitation (mm) and leachate volumes collected (mm) at each sample date. The stars represent precipitation events that resulted in sudden increases of soil-water matric potential.

soil to the conditions experienced within the corn agroecosystem. During the summer little drainage occurred because of the high evapotranspiration rates of the corn crop, which usually exceed the amount of precipitation during the growing season. It is generally during this time when the soil-water matric potential decreased below −35 kPa and the program stops the operation of the vacuum pump; however, data collection continued as normal. The program automatically reactivated the pump operation anytime the soil-water matric potential increased above −35 kPa. As the corn matured and evapotranspiration rates increased, the amount of water within the soil matrix decreased. The corresponding decrease in soil-water matric potential is evident during both growing seasons, in particular during 2002 from 15 August to 10 October when it reached a low of −230 kPa. The total precipitation from May to October was 503 mm in 2001 compared with only 356 mm in 2002, which may explain the nearly 200-kPa-lower minimum soil water matric potentials for the 2002 growing season. Since precipitation in 2002 was less than in 2001, the water demand of the crop was met by removing more of the water stored within the soil.

Shortly after the major precipitation event on 10 Oct. 2002, the soil-water matric potential increased by 100 kPa, verifying the movement of water downward through

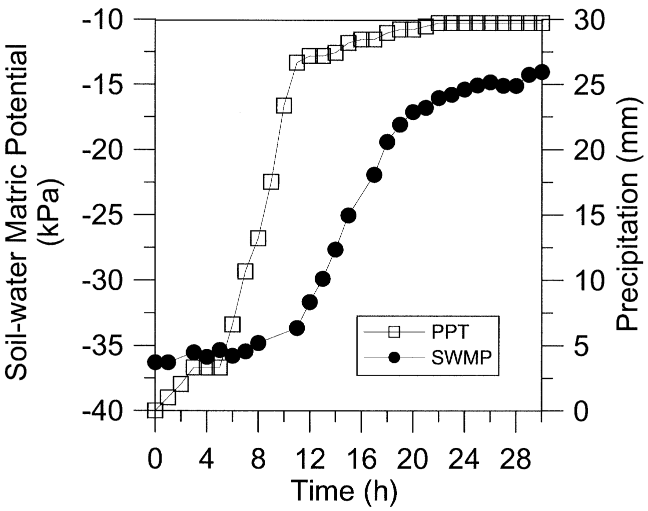

Fig. 4. Hourly measurement of soil-water matric potential and cumulative precipitation (PPT) following the rainfall event on 24 Sept. 2001.

the soil matrix. Sudden increases in soil water content also occurred within the same day of major precipitation events on 7 and 24 Sept. 2001. Figure 4 shows that an increase of soil-water matric potential at a depth of 1.4 m was recorded within hours of the peak of the precipitation event and steadily increased over the next 20 h. These sudden increases in water content observed after major precipitation events indicate macropore flow for which previous manual adjustment of ETLs could not properly account.

Following the rainfall of 24 Sept. 2001 the soil-water matric potential increased and remained nearly constant at −5 kPa until the following summer. This increase in soil-water content, which was also observed in 2002, is indicative of the decrease in evapotranspiration due to crop senescence and seasonal climatic changes. Following the end of the growing season, precipitation begins to replace the water within the soil matrix that was removed by the corn plants. Because of the below normal precipitation and large amount of water removed during the 2002 growing season, the soil still had not reached field capacity as of 31 Dec. 2002. Periods with soil-water matric potential below field capacity (−30 kPa) resulted in little to no leachate being collected. As a result no drainage occurred from July 2002 to December 2002 since the soil above the lysimeter was drier than field capacity.

A comparison was performed using data collected from the original ETLs designed by Brye et al. (1999) and the automated design. Results in Table 1 compare the variability of sampling methods using data collected during years with similar precipitation patterns. Similar precipitation patterns result in similar patterns of collected drainage volumes and drainage variability from the mean for the two periods should also be similar if the manual adjustment and automated control systems are equivalent. Two periods were chosen in which precipitation events of varying degrees of magnitude occurred with similar frequency. Precipitation events during the growing season were not considered when choosing periods, because very little drainage occurs during this period due to evapotranspiration. Results indicated that the variability from the mean of the new system to maintain equilibrium and measure leachate volumes was comparable with that of the original ETL system.

Water Level Detection

The results of the water level detection tests are shown in Fig. 5. The ECH_2O probe displayed reliable results and has the added advantage of simplicity in operation and a low power requirement. The probe data can be fit to any of a number of calibration functions; the one shown has a standard error of estimate of 0.35 mm (R^2 = 0.998). Inclusion of this probe in future AETLs will provide a continuous measurement of water depth, creating a water-flux meter with sub-mm scale resolution of drainage and also making it possible to determine macropore flow rates in the field.

Conclusions

The development of an automated equilibrium tension lysimeter has successfully expanded the existing capabilities of ETLs. Without the need for a large power supply, AETLs can now be used in remote research locations. More importantly, the automatic adjustment of the lysimeter tension enables a near-constant equilibrium to be maintained between the lysimeter and the soil, providing a more accurate collection of water drainage over other drainage sampling devices. The AETL also has the added advantage of measuring soil-water matric potentials to monitor when wetting and drying periods occur within the soil. The ability to monitor soil-water matric potential adds validity to drainage measurements and can be used to interpret drainage variations below the root zone. Demonstration of the ability to measure the level of water within the lysimeter repre-

Table 1. Comparison of leachate volume variation collected from replicate lysimeters in two tillage treatments using the original equilibrium tension lysimeter (ETL) system and the new automated (AETL) system during periods with similar precipitation patterns.

				Leachate volumes‡			
				Chisel plow		No tillage	
	Collection period	Total precipitation	n†	Rep 1	Rep 2	Rep 1	Rep 2
		mm		mm			
Original	1 Oct. 1996–30 Sept. 1997	744	23	13.9 (0.9)	21.5 (1.1)	13.0 (1.1)	9.8 (1.3)*
New	1 Oct. 2001–30 Sept. 2002	603	22	16.6 (1.1)	17.4 (1.1)	16.3 (0.9)	10.0 (0.8)

* Significant at the 0.05 probability level.
† Number of times the lysimeters were sampled.
‡ Values are means with coefficients of variation in parentheses.

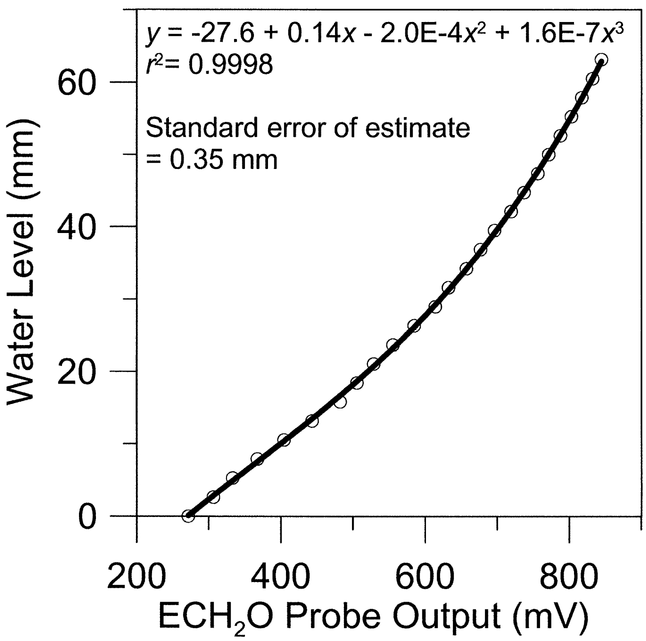

Fig. 5. Water level versus ECH_2O probe output. The ECH_2O probe was measured by a datalogger after each increment of water was added and water level was confirmed with manual measurement.

sents a further advancement in vadose zone measurement and monitoring, which makes AETLs true water-flux meters and allows temporal resolution of unsaturated drainage that was never before possible.

References

Angle, J.S., M.S. McIntosh, and R.L. Hill. 1991. Tension lysimeters for collecting soil percolate. p. 290–299. *In* Groundwater residue sampling design. Vol. 465. Am. Chem. Soc., Washington, DC.

Boll, J., T.S. Steenhuis, and J.S. Selker. 1992. Fiberglass wicks for sampling of water and solutes in the vadose zone. Soil Sci. Soc. Am. J. 56:701–707.

Brye, K.R., T.W. Andraski, W.M. Jarrell, L.G. Bundy, and J.M. Norman. 2002. Phosphorus leaching under a restored tallgrass prairie and corn agroecosystems. J. Environ. Qual. 31:769–781.

Brye, K.R., J.M. Norman, L.G. Bundy, and S.T. Gower. 1999. An equilibrium tension lysimeter for measuring drainage through soil. Soil Sci. Soc. Am. J. 63:536–543.

Brye, K.R., J.M. Norman, L.G. Bundy, and S.T. Gower. 2000. Water-budget evaluation of prairie and maize ecosystems. Soil Sci. Soc. Am. J. 64:715–724.

Brye, K.R., J.M. Norman, L.G. Bundy, and S.T. Gower. 2001. Nitrogen and carbon leaching in agroecosystems and their role in denitrification potential. J. Environ. Qual. 30:58–70.

Campbell Scientific. 1998. Soil water potential probe instruction manual. Campbell Scientific, Logan, UT.

Gee, G.W., A.L. Ward, T.G. Caldwell, and J.C. Ritter. 2002. A vadose zone water fluxmeter with divergence control. Water Resour. Res. 38 DOI 10.1029/2001WR000816.

Goyne, K.W., R.L. Day, and J. Chorover. 2000. Artifacts caused by collection of soil solution with passive capillary samplers. Soil Sci. Soc. Am. J. 64:1330–1336.

Holder, M., K.W. Brown, J.C. Thomas, D. Zabcik, and H.E. Murray. 1991. Capillary-wick unsaturated zone soil pore water sampler. Soil Sci. Soc. Am. J. 55:1195–1202.

Jemison, J.M., and R.H. Fox. 1992. Estimation of zero-tension pan lysimeter collection efficiency. Soil Sci. 154:85–94.

Jemison, J.M., and R.H. Fox. 1994. Nitrate leaching from nitrogen-fertilized and manured corn measured with zero-tension pan lysimeters. J. Environ. Qual. 23:337–343.

Knutson, J.H., and J.S. Selker. 1996. Fiberglass wick sampler effects on measurements of solute transport in the vadose zone. Soil Sci. Soc. Am. J. 60:420–424.

Lentz, R.D., and D.C. Kincaid. 2003. An automated vacuum extraction control system for soil water percolation samplers. Soil Sci. Soc. Am. J. 67:100–106.

Masarik, K.C. 2003. Automated equilibrium tension lysimeters [Online]. Available at www.soils.wisc.edu/~masarik (verified 16 Feb. 2004). Univ. of Wisconsin, Madison.

Radulovich, R., and P. Sollins. 1987. Improved performance of zero-tension lysimeters. Soil Sci. Soc. Am. J. 51:1386–1388.

Reece, C.F. 1996. Evaluation of a line heat dissipation sensor for measuring soil matric potential. Soil Sci. Soc. Am. J. 60:1022–1028.

Van der Ploeg, R.R., and F. Beese. 1977. Model calculations for the extraction of soil water by ceramic cups and plates. Soil Sci. Soc. Am. J. 41:466–470.

Zhu, Y., R.H. Fox, and J.D. Toth. 2002. Leachate collection efficiency of zero-tension pan and passive capillary fiberglass wick lysimeters. Soil Sci. Soc. Am. J. 66:37–43.