A SUBSURFACE DRIP IRRIGATION SYSTEM FOR WEIGHING LYSIMETRY

S. R. Evett, G. W. Marek, P. D. Colaizzi, B. B. Ruthardt, K. S. Copeland

ABSTRACT. *Large, precision weighing lysimeters can have accuracies as good as 0.04 mm equivalent depth of water, adequate for hourly and even half-hourly determinations of evapotranspiration (ET) rate from crops. Such data are important for testing and improving simulation models of the complex interactions of surface water and energy balances, soil physics, plant growth, and biophysics that determine crop ET in response to rapid microclimate dynamics. When crops are irrigated with sprinkler systems or other rapid additions of water, the irrigation event is typically short enough that not much ET data are compromised by the lysimeter mass change due to irrigation. In contrast, subsurface drip irrigation (SDI) systems may take many hours to apply an irrigation, during which time the lysimeter mass change is affected by both ET rate and irrigation application rate. Given that irrigation application rate can be affected by pressure dynamics of the irrigation system, emitter clogging and water viscosity changes with temperature over several-hour periods, it can be difficult to impossible to separate the ET signal from the interference of the irrigation application. The inaccuracies in the data can be important, particularly for comparisons of sprinkler and SDI systems, since they are of the order of 8 to 10% of daily ET. We developed an SDI irrigation system to apply irrigations of up to 50 mm to large weighing lysimeters while limiting the period of lysimeter mass change due to irrigation delivery to approximately ten minutes by storing the water needed for irrigation in tanks suspended from the lysimeter weighing system. The system applied water at the same rate as the SDI system in the surrounding field, allowed irrigation over periods of any duration, but often exceeding 12 h, without directly affecting lysimeter mass change and the accuracy of ET rate determinations, and allowed irrigation overnight without compromising lysimeter daily ET measurements. Errors in lysimeter ET measurements using the previous SDI system, which was directly connected to the field irrigation system, were up to 10% of daily ET compared with negligible error using the new system. Errors using the previous, directly connected, SDI system varied over time due to variable system pressure, and possibly due to water temperature (viscosity) changes and emitter clogging. With the new system, all of the water transferred to the lysimeter weighing system was eventually applied by the SDI system regardless of temperature, pressure, or emitter clogging. Differences between planned and applied irrigation depth were less than 2% over the irrigation season.*

Keywords. *Evapotranspiration, ET, Subsurface drip irrigation, SDI, Weighing lysimeter.*

Subsurface drip irrigation (SDI) is playing an increasingly important role in U.S. crop irrigation, now surpassing 8% of the irrigated acreage in the nation (NASS, 2013). In arid and semi-arid regions, SDI is important because it reduces non-productive losses of water due to evaporation from the soil surface that are often large for surface irrigation systems, including sprinkler irrigation. Subsurface drip irrigation generally results in greater crop water productivity (CWP) compared with sprinkler, where

the greater CWP is variously due to greater crop production, less consumptive use of irrigation water (decreased evaporative loss), or a combination of both (Camp, 1998); less sensitivity to impaired irrigation water (Goldberg and Shmueli, 1970; Bernstein and Francois, 1973; Goldberg et al., 1976; Adamsen, 1989; 1992; Wu et al., 2001); and warmer soil temperatures (Wang et al., 2000; Colaizzi et al., 2010). Despite the greater capital costs per unit area of SDI compared with sprinkler, the advantages of SDI have often justified its installation (Bosch et al., 1992; O'Brien et al., 1998; Bortovsky et al., 2000; Enciso et al., 2005). Despite its growing use, the reasons for greater water productivity with SDI are still not fully understood, making side-by-side comparisons of SDI with sprinkler irrigation an important research endeavor.

Weighing lysimeters are useful tools for studying the effects of irrigation systems, crop selection, tillage and agronomic methods and weather on yield and water use. Large, precision weighing lysimeters can measure mass change accurately enough to have accuracies of better than 0.04 mm equivalent depth of water, adequate for hourly and even half-hourly determinations of evapotranspiration (ET) rate from crops in the absence of precipitation or irrigation (Evett

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et al., 2012b). Such data are important for testing and improving simulation models of the complex interactions of surface water and energy balances, soil physics and plant biophysics that determine crop ET in response to irrigation applications and rapid microclimate dynamics. When crops are irrigated with sprinkler systems or other rapid additions of water, the irrigation time is typically short enough that not much ET data are compromised by the lysimeter mass change due to irrigation. In contrast, subsurface drip irrigation (SDI) systems may take many hours to apply an irrigation, during which time the lysimeter mass change is affected by both ET rate and irrigation application rate. For example, a sprinkler irrigation of 25 mm applied with a linear move irrigation system at the ARS laboratory at Bushland, Texas, takes approximately 15 min to pass over a lysimeter while an equivalent depth SDI application takes >14 h. Given that irrigation application rate can be affected by pressure dynamics of the irrigation system and water viscosity changes with temperature over several-hour periods, it can be difficult to impossible to separate the ET signal from the interference of the SDI application.

More than a quarter century of crop ET work was done at Bushland using the four large weighing lysimeters installed there in the late 1980s (Evetts et al., 2016). Studies involved both dryland and irrigated production systems, but through 2012 all irrigation was done using a linear move irrigation system using various types of spray plates and heights. Studies using surface and subsurface drip irrigation begun in 1994 in relatively small plots, with ET determined by soil water balance using the neutron probe, confirmed the high production potential of corn and soybean when irrigated using SDI (e.g., Evetts et al., 1995, 2000). Later, a multi-year study comparing SDI, low energy precision application (LEPA) drag socks and mid elevation spray application (MESA) was carried out, again with ET determined by soil water balance using the neutron probe (Schneider et al., 2001; Colaizzi et al., 2004, 2006, 2010). Although confirming the relative efficiency of SDI and the potential for increased water use efficiency using SDI, particularly under deficit irrigation regimes, these prior studies highlighted important unanswered questions pertaining to the diel mechanisms of crop water use and energy and water balances in these comparative systems that are best addressed using weighing lysimeters.

To address unanswered questions relating to mechanisms of energy and water balances under SDI, a 20-zone SDI system was installed in 2012 and early 2013 on two of the four large weighing lysimeters at the USDA ARS Laboratory, Bushland, Texas, and their surrounding fields. Sprinkler irrigation using a 10-span linear move system was retained for the other two weighing lysimeters and fields. The intent was to perform side-by-side comparisons of SDI and sprinkler irrigation in terms of their energy and water balances during crop production in the semi-arid, highly advection climate of the Southern High Plains where pan evaporation can exceed 2,400 mm per year. Simulations performed in the 1990s using the mechanistic ENergy and Water BALance (ENWATBAL) model of Evetts and Lascano (1993) indicated that SDI could save as much as 81 mm of water compared with surface application methods such as sprinkler or gravity flow

(Evetts et al., 1995). Simulations showed that savings were due to reduced evaporation of water from the soil surface under SDI. The planned side-by-side system comparisons were intended to both test the simulation model and to elucidate the processes leading to improved crop water productivity reported in previous research. In 2013, the lysimeter SDI system was plumbed to the field irrigation supply so that irrigations were applied simultaneously to both the fields and lysimeters. The SDI system was designed to take approximately the same amount of time to apply a given depth of water as it took the linear move irrigation system to cover the adjacent equally sized fields, in this case approximately 14 h to apply 25 mm of water.

Although the drip irrigation rate appeared to be uniform over time, a considerable amount of lysimeter ET data were somewhat compromised due to the long periods of irrigation and several nighttime irrigations over midnight. Also, the emitter flow rate was subject to variations in manufacturing, water temperature (viscosity), and irrigation system pressure dynamics on a sub-daily time frame, and long-term wear and the possibility of clogging. Phene et al. (1989) described an automated lysimeter irrigation system that employed water tanks suspended from the lysimeter scale, but not weighed separately. In order to avoid confusion between lysimeter mass change due to ET and that due to tank filling, the tanks were filled at night between 12:05 and 12:25 A.M. when ET rate was minimal. The irrigation pump was similarly suspended, and operated in order to keep soil water within a range of matric potentials. Water delivery to the irrigation system was not pressure regulated; and the water storage tanks were not weighed independently of the lysimeter weighing system, which is why they were filled soon after midnight when mass changes due to ET were minimized. Other details of the design were sparse. Vaughan et al. (2007) and Vaughan and Ayars (2009) used the system of Phene et al. (1989) in their studies of lysimeter data noise reduction in which fescue grass was irrigated by SDI, but gave no further details of the system.

For these reasons, a design for a lysimeter SDI system that would be independent of the field SDI system was pursued with the objectives of: (1) Irrigating at the same rate, over the same period of time and to the same final application depth as the field SDI system, which required pressure regulation and the ability to begin irrigations at any time of day; (2) Separating the delivery of water to the storage tanks suspended from the lysimeter weighing system from the irrigation application itself so that water could be delivered over a short period of time, thus compromising the least amount of lysimeter ET data as possible; (3) Weighing the water delivered to the storage tanks independently of the lysimeter weighing system so that no ambiguity exists between lysimeter mass increase and the amount of water stored in the tanks and so that the tanks can be loaded with water at any time of day; and (4) Operating reliably over multiple irrigation seasons. This paper describes the engineering design, installation and analysis of operation of an SDI system for weighing lysimeters that separates the delivery of water to the lysimeter SDI system from the irrigation application itself by storing all the needed water in large tanks suspended from the lysimeter soil container by a load cell.

MATERIALS AND METHODS

The independent lysimeter SDI system was installed on two large weighing lysimeters (Marek et al., 1988) at the USDA ARS Conservation & Production Research Laboratory, Bushland, Texas (35° 11' N, 102° 06' W, 1170 m elevation above MSL) beginning in 2014, with operation of the independent system beginning on 27 August 2014. The lysimeters were calibrated using masses traceable to NIST to an accuracy of 0.04 mm depth of water equivalent, or better (Evelt et al., 2012b). The drip lines installed in the lysimeter in 2012-13 were retained in the new design, but plumbed to a pumping system and water storage attached to the lysimeter soil container such that those subsystems became part of the lysimeter mass. The SDI lines in the lysimeters were installed at the same depth (0.30 to 0.36 m) and spacing (1.52 m) and using the same 25-mm diameter drip line (model Typhoon 990, 13 mil wall thickness, Netafim, Inc., Fresno, Calif.) as in the surrounding fields. Emitters were spaced 0.30 m apart and had 0.68 L h⁻¹ (0.18 gal h⁻¹) discharge at the 69-kPa regulated line pressure. Pressure regulation for each zone in the field was applied at the zone headworks in each field. Water applied to each zone was measured by a 52-mm (2-in.) inline meter (model 36WMR2T10, Netafim, Inc., Fresno, Calif.) with >1040 mm (20 in.) (ten diameters) of straight pipe upstream of the meter and >520 mm (10 in.) (five diameters) of straight pipe downstream. Drip lines were 210-m long, the E-W width of the fields. At this length, the emission uniformity was specified as 98.6% by the manufacturer.

TANK DESIGN AND WEIGHING SYSTEM

The water storage system was sized to store enough water for a maximum irrigation depth of 50 mm over the nominal 9.15 m² effective surface area of the lysimeters, which computes to 458 L of water. Since the irrigation water could contain corrosive chemicals due to fertigation and SDI system treatments to prevent clogging, the tanks were made of plastic. Available plastic water storage tanks were of the wrong dimensions to fit into the available space between the lysimeter soil tank and the outer enclosure wall (0.635 m), or would have been too large in diameter to fit through the lysimeter entry hatch (Marek et al., 1988). Considering these restrictions, the water storage system was built from nominal 304 mm (12 in.) diameter rigid polyvinyl chloride (PVC) water pipe [302 mm (11.9 in.) inside diameter, 100 psi rating]. Three pipes, each 2.11 m long, were capped on both ends using solvent-weld cement and bundled together to make the water storage reservoir. The bundle was placed on a 12 mm × 0.67 m by 0.63 m steel plate suspended from a nominal 4448 N (1,000 lb) load cell (model SSM-HQ-1000, Interface, Inc., Scottsdale, Ariz.) attached to the lysimeter soil tank on the north side near the NW corner of the soil tank. The suspension system consisted of a nominal 32-mm (1.25-in.) galvanized steel pipe suspended from the load cell using a 19-mm (0.75-in.) rod end bearing and clevis, and connected to the centroid of the steel plate supporting the bundled water tanks. An inverted L bracket for suspending the load cell from the soil tank was fashioned of 12-mm (0.5-in.) steel plate and 76-mm (3-in.) I-beams and bolted to

the two horizontal I-beams that reinforced the soil tank just below the lysimeter enclosure roof. The center point for load cell attachment was just far enough away from the I-beams to allow 25 mm of clearance between the water tanks and horizontal I-beams. The load cell was attached using swivel bolts (rod end bearings) at both ends to prevent off axis torque loading.

The ~470 kg mass of the tanks when fully loaded with water presented an asymmetrical loading to the lysimeter weighing system. This was not expected to cause inaccuracy in the lysimeter weighing system because Howell et al. (1995) tested similar asymmetrical loading during their lysimeter calibration exercise on the same lysimeters without deleterious effect. Water was delivered to the tanks over a 5 to 15 min period, depending on the depth of irrigation, and the mass of delivered water was measured by both the load cell suspending the tanks and by the lysimeter weighing system, providing a double check on irrigation depth delivered. The three tanks were plumbed together at both top and bottom ends using nominal 19 mm (0.75 inch) PVC tubing, and equipped with a vacuum/air relief valve [19 mm (0.75 in.) Guardian Air/Vacuum Relief Air Vent, NETAFIM USA, Fresno, CA] at the top end. Thus, water delivered to one tank filled them all, and water pumped from the tanks emptied them all. Delivery of water to the tanks was by a dedicated nominal 25 mm (1 inch) line from the field SDI headworks. This line was not pressure regulated, so water flow was at the approximately 172 kPa (25 psi) pressure at which water was delivered to the headworks. Delivery of water was controlled by two solenoid valves (Model 8210G095, ASCO, Florham Park, N.J.) connected in series for redundancy. The 120 VAC solenoid valves were powered through a solid state relay (Model D2410, Crydom, Inc., San Diego, Calif.) controlled by a 5-VDC signal from the datalogger. All plumbing used either rigid or flexible polyvinyl chloride tubing rated for 689 kPa (100 psi) or greater. Connections were made by drilling and tapping through the double thickness of pipe wall and end cap for nominal 19 mm (0.75 in.) Schedule 80 NPT to hose barb fittings and flexible PVC tubing.

PUMPING AND PRESSURE CONTROL SYSTEM

Tanks were plumbed from the bottom end to a 0.75-kW (1/4-hp), magnetically coupled pump (Part no. SK-72012-20, Cole-Parmer, Inc., Vernon Hills, Ill.) (fig. 1). The pump was positioned slightly lower than the bottom of the tanks to ensure priming. Pump characteristics were dictated by the flow rate of the 20 emitters in the two drip lines in the lysimeter at the 69-kPa (10-psi) design pressure (0.57 L min⁻¹ × 20 = 11.4 L min⁻¹; 0.18 gph × 20 = 3.6 gph), and the vertical distance between the pump (3 m, 10 ft) and the drip lines. Thus, a pump capable of delivering at least 11.4 L min⁻¹ (3.6 gph) at 99 kPa (14.3 psi) was needed. Furthermore, the system design included a pressure tank and pressure switch so that the pump would not continuously run. The chosen pump was rated at 34 L min⁻¹ (9 gpm) at 128 kPa (18.6 psi). The magnetic drive pump was chosen because the pumped water was exposed only to polypropylene plastic parts, eliminating the possibility of corrosion induced by water quality or dissolved fertilizers, and because of its quiet, nearly vibration-free operation. Downstream of the pump, a 26-L

(7-gal) pressure tank temporarily stored water. A pressure switch was plumbed in between the pump and pressure tank, and was set to control the pump so as to maintain pressure in the tank between 138 and 414 kPa (20 and 60 psi) during irrigation. A check valve between the pump and pressure tank prevented backflow into the pump and storage tanks. Power to the pressure switch, and thus to the pump, was controlled using a solid state relay (Model D2410, Crydom, Inc., San Diego, Calif.) controlled by a 5-VDC signal from the datalogger. Downstream of the tank, pressure was regulated to 99 kPa (14.3 psi) using a 7 to 172 kPa (1 to 25 psi) adjustable pressure regulator (Model 1/2 LF263A 1-25, Watts, North Andover, Mass.) equipped with a pressure relief valve (Model A-4000-144, Johnson Controls, Milwaukee, Wis.), and pressure gage for setting the regulator, in order to supply water to the drip lines above at 69 kPa (10 psi), equivalent to regulated pressure of the field SDI system.

System control logic was programmed into a high precision datalogger (model CR6, Campbell Scientific, Inc., Logan, Utah) that was used to monitor, every 6 s, the load cell for the lysimeter weighing system, the load cell for the SDI water storage, the load cells for the lysimeter drainage sys-

tem tanks, as well as sensors for many environmental variables (Evelt et al., 2012a, b). The storage tank weighing system was calibrated with this system using masses traceable to NIST. The 6-s readings were accumulated to 5-min mean and standard deviation values.

Neutron probe readings were conducted at eight locations in each field on a weekly basis to guide irrigation management. Irrigations were managed to replenish soil water in the top 1.5 m of soil to field capacity levels as determined using the field-calibrated neutron probe (Evelt et al., 2008). The crop water requirement could be applied in one, two or more irrigations in a week depending on total depth required, evaporative demand and the possibility of intervening precipitation events. Earlier SDI work at Bushland indicated that the water holding capacity of the Pullman soil was such that there were no significant differences in corn yield between irrigation intervals that ranged from daily to three days (Howell et al., 1995). However, Evelt et al. (1996), using the same system at Bushland, found that a daily irrigation decision interval avoided stress and yield reduction of corn that occurred with a three-day decision interval during a dry and hot growing season.

Once depth of an irrigation was decided, the field SDI system was started and, after a 20-min delay for the field SDI system to stabilize, a variable in the datalogger was changed manually to indicate the depth of application desired on the lysimeter. The datalogger program then opened the solenoid valves for water entering the water storage tanks, and closed the valves when the load cell data indicated that the required amount of water had been stored. The initial and final mass of the storage tanks were recorded in the datalogger output. After the solenoid valves for supply water were closed, the system waited for a 10-minute period to allow the weighing system to stabilize and to output a five-minute mean value and standard deviation for irrigation depth verification purposes. Then, the solid state relay controlling power to the pressure switch (and pump) was closed by the datalogger, starting the pump. The datalogger monitored the storage tank mass and turned off the pump once the requisite mass of water had been delivered to the lysimeter SDI system. The water storage set point in the datalogger program was set to never empty the storage tank fully, which served two purposes. First, this avoided air entry into the pump chamber. Second, it provided sufficient water head at the end of irrigation for the pump to operate without cavitation. The system was completely controlled remotely through telemetry so as to avoid disturbance of the crop on and surrounding the lysimeter (Evelt et al., 2012a).

Figure 1. (A) View from the west side of the weighing lysimeter foundation, outer enclosure (retainer tank), soil monolith container, scale system, and relative positions of irrigation water storage tanks and cage for pumping system shown in B. LC is the storage tank load cell. (B) Schematic of lysimeter SDI pumping system. Shown are the cage supporting the pump, check valve, pressure switch, pressure tank, pressure gage and second check valve. The adjustable pressure regulator and second pressure gage are supported by the bottom flange of the W-beam from which the cage is suspended.

RESULTS AND DISCUSSION

The storage tank weighing system resolution was dictated by the full scale load cell output (3 mV/V), the full-scale load cell capacity (4448 N, 1000 lb), the load cell sensitivity (0.003 mV/lb, 0.000674 mV/N), and the resolution of the datalogger (0.33 μ V), which computes to 0.0055 mm equivalent depth of water, more than adequate for our purposes. The calibrated accuracy was equivalent to 0.07 mm depth of

water ($r^2 \geq 0.9999$). Considering that irrigations were typically on the order of 25-mm depth, this accuracy metric amounts to $<0.3\%$, which compares favorably to the accuracy of the water meters used on each zone of the field SDI system. For 15 irrigations in 2014, the mean standard deviation of readings from the 20 zone water meters was equivalent to 0.85-mm depth of applied water. Actual water applied using the lysimeter SDI systems was determined from the load cell readings and compared with the intended application depth entered into the datalogger, showing that irrigation depths were achieved to within $>98\%$ of target depth. The time of lysimeter irrigation applications was comparable with the time of field irrigations.

Water storage tanks typically were filled in less than 10 min, causing practically a step increase in lysimeter mass and water storage tank mass. Comparison of lysimeter and storage tank mass increases showed agreement to within $<1\%$ on average. Over the duration of irrigation, mean water delivery rate to the lysimeter drip lines was equivalent to a 0.66 L h^{-1} emitter flow rate, close to the emitter flow rate specified for the field, 0.68 L h^{-1} at the design operating pressure of 69 kPa. Because storage tanks were not filled during precipitation events, and since irrigation from storage tanks had no effect on total mass on the lysimeter weighing system, the new system prevented confounding effects of precipitation on determining applied irrigation depth. Even if tanks were filled during a precipitation event, the fact that tanks were weighed using separate load cells would prevent confusion between precipitation and water storage that can occur with the lysimeter weighing system. Because of the short period of tank filling and the fact that tanks were weighed using a separate load cell, there was no need to restrict the period of tank filling to the period of minimal ET rate that occurs near midnight. In this way the system presented herein has a distinct advantage over that described by Phene et al. (1989, 1991).

Comparison of the standard deviation of lysimeter mass measurements was made between lysimeters irrigated using the sprinkler system (except for the actual time of sprinkler irrigation) and the SDI-irrigated lysimeters using data from the SDI application period. For nine irrigation events, the SD of lysimeter mass measurements was the same regardless of irrigation application method, indicating that the lysimeter SDI irrigation system did not adversely affect noise.

Until 27 August 2014, constant emitter flow rate was assumed to calculate the increase in lysimeter mass that would be caused by irrigation. The calculated mass increase due to irrigation is generally larger than the mass increase sensed by the lysimeter weighing system because ET during irrigation works to decrease the lysimeter mass increase that would be expected with the irrigation addition. With no other factors affecting lysimeter mass during the irrigation event (e.g., precipitation, drainage, and maintenance), the difference between irrigation-caused mass increase and sensed mass increase, converted to equivalent depth of water, is termed the adjusted storage (mm). Crop ET is then derived from decreases in the adjusted storage. However, as shown in the following discussion, the constant emitter flow rate assumption was not supported by mass change data. The discrepancy between assumed and actual emitter flow degraded

the accuracy in the adjusted mass change, and hence the accuracy of ET.

Examining the lysimeter 5-min mass change for irrigations occurring during the two hours around midnight when ET was negligible revealed that the mass change was equivalent to emitter flow rates ranging from as large as $0.0295 \text{ mm min}^{-1}$ early in the season to as small as $0.0236 \text{ mm min}^{-1}$ late in the 2014 season (fig. 2). The larger value is equivalent to the flow rate expected at 104-kPa (15-psi) system pressure while the smaller value is equivalent to the flow rate expected at 62 kPa (9 psi). Flow rate did decline over the season. Whether flow rate changes were due to declines in system pressure or to partial emitter clogging is not entirely clear, although the decline near the end of the season was likely due to partial clogging. Clearly, lysimeter irrigation cannot be accurately calculated from an assumed emitter flow rate, which is one reason the new irrigation system was needed. Figure 3 illustrates the error that can occur when system pressure is reduced, in this case due to a lightning strike. While irrigation continued, as indicated by the increasing value of raw lysimeter storage data (red line), the rate of mass increase due to irrigation was reduced, thus there was a discrepancy between assumed and actual mass increase resulting from irrigation. This discrepancy appeared as an unexpected sharp decrease in the adjusted mass storage (black line) just before day of year 138. This error in the adjusted storage data led to a 0.4 mm error in calculated ET.

Figure 4 illustrates how a small change in assumed application rate, from 0.0270 to $0.0275 \text{ mm min}^{-1}$, corrected a 0.3 mm (10%) error in daily ET. The change in flow rate is what would be expected from a change in pressure from 84 to 87.6 kPa (12.2 to 12.7 psi). In contrast to figure 4, figure 5 illustrates how a smaller flow rate was needed to correct lysimeter storage later in the season (DOY 232). At approximately DOY 232.3, the rate of decrease in adjusted storage mass changed immediately after the irrigation event ceased, even though ET rate would not be expected to change. Decreasing the assumed flow rate from 0.0275 to $0.0259 \text{ mm min}^{-1}$ removed this obvious error in the corrected storage and reduced overestimation of daily ET by 8%. Figure 6 illustrates how a similar change in flow rate also resulted in an

Figure 2. SDI application rates calculated from lysimeter mass changes for 0.2 d near midnight when ET rate was negligible for irrigations in 2014 before the new lysimeter SDI system was installed. Data are for the Northeast (NE) and Southeast (SE) lysimeters.

Figure 3. Example of raw lysimeter water storage data from the NE lysimeter adjusted during an SDI application by assuming a constant SDI application rate of $0.0276 \text{ mm min}^{-1}$. At day of year 137.92, the pressure in the SDI system changed (possibly due to a lightning strike), causing the application rate to change and the adjusted lysimeter storage to decrease suddenly and be incorrect for the rest of the day. The arrow points to the inflection caused by this rate change. The approximate error was 0.4 mm.

8% reduction in calculated daily ET after the correction. Although the changes in assumed flow rate appear to be small, over a season the accumulated error in ET can be considerable. Figure 6 also shows how lysimeter storage correction methods detailed in Marek et al. (2014) are used to adjust for a person standing on the lysimeter to take neutron probe readings just before noon (spike in the raw data), removal of water from the drainage tanks (decrease in raw storage just after noon), and increases in mass due to precipitation late in the day.

Examples of corrections to lysimeter storage made after the new lysimeter SDI system was installed are shown in figure 7. No assumptions about the rate of SDI application were necessary to correct the lysimeter storage data. Over the short periods needed to transfer water to the SDI storage tanks on the lysimeter soil container, the mass storage was adjusted for the difference in storage just before the transfer began and just after the transfer ended. A small further adjustment was made to correct for the ET that occurred during the transfer period. The ET rate during the transfer period

Figure 4. (Top) Example of raw lysimeter water storage data (red line) from the NE lysimeter on day of year 192 in 2014. Also shown is the adjusted storage. Adjustment during an SDI application was made by assuming a constant SDI application rate of $0.027 \text{ mm min}^{-1}$. The apparent increase in lysimeter storage (mass) late in the day was the result of the value of 0.027 being too small. (Bottom) Increasing the assumed application rate to $0.0276 \text{ mm min}^{-1}$ essentially eliminated the false increase in lysimeter mass late in the day, removing a 0.36 mm (14%) error in ET.

Figure 5. (Top) Example of raw lysimeter water storage data from the NE lysimeter on day of year 232 in 2014. Also shown is the adjusted storage. Adjustment during an SDI application was made by assuming a constant SDI application rate of $0.027 \text{ mm min}^{-1}$. The apparent decrease in lysimeter storage (mass) early in the day during irrigation does not match the rate of storage decrease immediately after irrigation ceased. The arrow indicates the point of inflection. The mismatch indicates that for this irrigation, the rate of 0.027 was too large. (Bottom) Reducing the assumed application rate to $0.025 \text{ mm min}^{-1}$ eliminated the error in corrected storage. The rate of $0.025 \text{ mm min}^{-1}$ is from figure 2.

was assumed to be the average of ET rates for five 5-min periods before the transfer began and five 5-min periods after the transfer ended.

Figure 8 illustrates the changes in water tank mass (in equivalent depth of water over the 9.15-m^2 lysimeter effective area, see Evett et al., 2012b) for an overnight irrigation

Figure 6. (Top) Example of raw lysimeter water storage data from the NE lysimeter on day of year 234 in 2014. Also shown is the adjusted storage. Adjustment during an SDI application was made by assuming a constant SDI application rate of 0.0275 rather than $0.027 \text{ mm min}^{-1}$. The apparent decrease in lysimeter storage (mass) early in the day during irrigation is larger than the rate of storage decrease immediately after irrigation ceased, indicating that for this irrigation, the assumed rate of 0.0275 was too large. (Bottom) Changing the assumed application rate to $0.024 \text{ mm min}^{-1}$ essentially eliminated the error in storage, decreasing calculated daily ET by 1.39 mm . The rate of $0.024 \text{ mm min}^{-1}$ is from figure 2.

on days of year 176 and 177 of the 2015 cropping season. Addition of water to the tanks occurred over a 10-min period and resulted in an increase of tank storage of 20.14 mm as shown by the raw storage data (red line). The relative storage data show only the stair stepping pattern of water removal from the tank as the pump cycled to maintain pressure in the pressure tank feeding the drip lines. As determined by the step mass decreases of the storage tanks, the sum of water applied on DOY 176 and 177 was 20.17 mm. Slight discrepancies such as this ($<0.2\%$) occur due to the 5-min averaging interval in the datalogger program, which can result in irrigation being terminated 5 minutes early, 5 minutes late, or right on time to achieve the final tank storage value resulting from the irrigation depth entered into the control program. Note that this error is the same order of magnitude as the approximately 0.027-mm min^{-1} application rate. If an error occurs at this rate for an entire five minute interval, the overall error in application rate would not rise to more than 0.6% for the magnitude of irrigations typically applied (≥ 25 mm).

The new system did not confound lysimeter mass change due to ET with lysimeter mass change due to emitter discharge, and the new system has proved reliable over more than two cropping seasons. Even if partial emitter clogging occurs in the lysimeter SDI system, the gross amount of water scheduled to be applied will be applied by the new system since it will keep operating until the intended water application from the storage tanks is completed, making the new system potentially more reliable than a system pressurized directly by the field water supply such that application depth is only controlled by emitter flow rate and supply pressure. Comparison of planned irrigation depths and achieved

Figure 7. (Top) Example of raw lysimeter water storage data from the NE lysimeter on day of year 239 in 2014. The raw data show a sharp increase in storage (mass) due to transfer of water to the SDI storage tanks on the lysimeter. Also shown is the adjusted storage. Adjustment during the SDI application was not necessary. The only adjustment made due to irrigation was made for the short period of water transfer, which took less than ten minutes. **(Bottom)** Example of raw lysimeter water storage data from the NE lysimeter on day of year 241 in 2014. The raw data show a sharp increase in storage (mass) due to transfer of water to the SDI storage tanks on the lysimeter, and a spike due to a person taking neutron probe readings on the lysimeter. Also shown is the adjusted storage. In this case, the water transfer to the storage tanks occurred over three 5-min periods.

Figure 8. (Top) Irrigation tank changes in water held in terms of equivalent depth of water for day of year 176, 2015. The raw data show the increase in water held to be 20.14 mm. The adjusted data are the storage relative to the full (zero) condition of the tanks. These relative storage data show only the stair stepping pattern of water removal from the tank as the pump cycled to replenish water in the pressure tank feeding the drip lines. The water applied on day of year 176 was 14.97 mm. **(Bottom)** The water applied on day of year 177 was 5.20 mm.

depths of irrigation for the 2015 irrigation season showed less than a 2% (<4 mm) difference, with regression slopes not significantly different from unity and r^2 values >0.99 .

SUMMARY AND CONCLUSIONS

A system for independent subsurface drip irrigation (SDI) of weighing lysimeters was designed, installed, and tested over three cropping seasons. The system separates delivery of water mass to the lysimeter weighing system from the delivery of water through the SDI system to the soil in the lysimeter. Water is transferred from the supply line to the tanks suspended from the lysimeter weighing system in less than 10 min, compromising only a small amount of lysimeter data for any irrigation event. Once water is stored in the tanks, SDI application proceeds at the same rate as in the field, over practically the same period of time, without impacting lysimeter mass change, thus allowing lysimeter mass change to reflect only evapotranspiration and any mass increase due to precipitation that may occur. ET data from lysimeters irrigated with the new system are as accurate as data from lysimeters irrigated quickly using sprinkler or other surface application system.

Because of the separation of the storage tank weighing system from the lysimeter weighing system, we could modify our irrigation system operation to irrigate on the basis of more than the soil water status determined by the neutron probe. As we have demonstrated in previous research reports, examples of irrigation criteria are lysimeter mass loss (ET), predicted ET based on weather measurements, soil water status feedback using automated soil water sensing (e.g., Lascano et al., 1996), and plant stress feedback (Evetts et al., 1996) or a combination of soil water and plant stress indices, again automated (e.g., O'Shaughnessy et al., 2014, 2016).

Most of these could be applied on almost any decision interval from half-hourly to daily or longer. Future research plans include using some combinations of these methods.

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