Calibration and Scale Performance of Bushland Weighing Lysimeters

T. A. Howell, A. D. Schneider, D. A. Dusek, T. H. Marek, J. L. Steiner

Abstract. *Weighing lysimetry is the primary method to directly measure evapotranspiration, and the scale performance of weighing lysimeters is often affected by wind loading. This study was conducted to calibrate the weighing lysimeters at Bushland, Texas, and to determine the effects of wind on the measurement accuracy of the lysimeter scales. Applied mass amounts equivalent to 150% of the lysimeter range were applied, and lysimeter scale calibrations were determined. Wind influences were measured by covering the lysimeters with a rubber sheet to minimize evaporation during an extended period. The lysimeters were sensitive to mass changes as small as 0.05 mm (450 g), highly linear with less than 1% total error over the 250-mm range (2.25 Mg), insensitive to load distribution on the lysimeter surface, and sensitive to surface pressures created by wind loading. The effects of wind can be minimized with data smoothing but not eliminated. The USDA-ARS weighing lysimeters at Bushland, Texas, have evapotranspiration measurement accuracy necessary to determine evapotranspiration rates as small as 0.05 to 0.1 mm/h over time periods of 30-min or greater.*
Keywords. *Evapotranspiration, Load cells, Lysimeters, Scales, Wind.*

Weighing lysimetry is commonly used to measure evapotranspiration (ET) from agronomic crops, rangelands, forests, and orchard crops (Allen et al., 1991). Since water extraction by plants and water evaporation from the soil represent about 5 to 20% of the mass of the lysimeter (depending on the lysimeter depth), many weighing lysimeters use counterbalanced scales to offset the large dead weight of the soil and lysimeter container. Reviews of lysimeter designs and discussions of lysimeters for water use studies are found in Kohnke et al. (1940), Tanner (1967), Rosenberg et al. (1968), Aboukhaled et al. (1982), Soileau and Hauck (1987), Hatfield (1990), Jensen et al. (1990), and Allen et al. (1991). Although many types of scale systems have been used in weighing lysimeters, lever-load cell scales are commonly used because counterbalancing is easy and load-cell signals can be recorded with high precision electronic data recorders.

Weighing lysimeters are generally calibrated *in situ* by covering the soil surface to minimize evaporation and adding known quantities of mass. The mass of the weighing lysimeter is affected by any load placed on the lysimeter. One of the largest loading errors is the surface pressure force exerted by wind. Harrold and Dreibelbis (1958) reported the scales under the USDA-ARS Coshocton, Ohio, monolith lysimeters were affected by winds during gusty conditions as evidenced by scale needle movements. Pruitt and Angus (1960) reported that surface pressure variation caused by wind created uncertainty greater than 0.03 mm in the scale outputs from the University of California lysimeter at Davis. They indicated that precise values of ET could be determined accurately by a line of best-fit based on 4-min lysimeter mass values over an hour time interval. Van Bavel and Meyers (1962) demonstrated the effects of surface pressure changes caused by wind on lysimeter scale performance at the USDA-ARS lysimeters at Phoenix, Arizona. They reported wind load variations up to ±1 mm on the 1.0 m^2 area lysimeters with a scale accuracy of 0.01 mm but indicated that with several data recording procedures, reliable lysimeter records could be obtained with an accuracy of ±0.05 mm with wind speeds up to 8 m/s. Ritchie and Burnett (1968) found that an electronic filter was necessary to minimize wind effects on the load cell output from the USDA-ARS weighing lysimeter at Temple, Texas, when the sampling frequency was 0.05 Hz. Armijo et al. (1972) reported wind affected the scale outputs from the University of Wyoming weighing lysimeter at the Pawnee National Grassland, in northeastern Colorado, even when the lysimeter was covered with an inverted metal stock tank. Dugas et al. (1985) reported that wind increased the range of the load cell output values from the Texas A&M University lysimeter at Temple, but that the effects of the wind loading could be removed by averaging over 10-min periods with a 0.2-Hz sampling frequency.

This article describes the calibration procedures, calibration results, and the effects of wind on the scale performance of the USDA-ARS weighing lysimeters at Bushland, Texas. The climate at this site is very windy

Article has been reviewed and approved for publication by the Soil and Water Div. of ASAE. Presented as ASAE Paper No. 87-2505.

Contribution from USDA-Agricultural Research Service, Southern Plains Area, Conservation and Production Research Laboratory, and Texas Agricultural Experiment Station, Bushland, Tex. The mention of trade or commercial names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service or the Texas A&M University System.

The authors are **Terry A. Howell**, ***ASAE Fellow Engineer***, Research Leader and Agricultural Engineer, **Arland D. Schneider**, ***ASAE Member Engineer***, Agricultural Engineer, and **Donald A. Dusek**, Agronomist, USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Tex.; **Thomas H. Marek**, ***ASAE Member Engineer***, Research Agricultural Engineer, Texas Agricultural Experiment Station, Texas Agricultural Research and Extension Center, Amarillo, Tex.; and **J. L. Steiner**, Laboratory Director and Soil Scientist, USDA-Agricultural Research Service, Southern Piedmont Conservation Research Laboratory, Watkinsville, Ga.

characterized by the 1991 mean annual wind speed at a 2-m height exceeding 4.3 m/s.

PROCEDURES

The USDA-ARS weighing lysimeters at Bushland, Texas (35°N Lat, 102°W Long, 1,170-m elevation MSL) described in detail by Marek et al. (1988) utilize 3 × 3 m surface dimension (9 m^2) and 2.3-m-deep soil monoliths. The lysimeters are placed on 45-Mg lever-load cell scales. The load cells are excited and measured by a Campbell Scientific, Inc. CR-7X data acquisition system with 15-bit resolution. Since the surface area of each lysimeter is 9 m^2, 9 kg of mass represents 1 mm of water depth equivalence. Calibration results will be reported in terms of water depth equivalence. The lysimeter surfaces were covered with two layers of 6-mil polyethylene plastic. Six 50- × 300-mm wooden planks held the plastic covering and supported the calibration weights.

The calibration mass standards consisted of a set of laboratory scale standards (one each 100 g ± 0.25 Mg, 500 g ± 1.2 Mg, 1 kg ± 2.5 Mg, 2 kg ± 5 Mg, 10 kg ± 50 Mg, and two 200 g ± 1 Mg and 20 kg ± 25 Mg) which meet National Bureau of Standards Class S and American Society for Testing and Materials Class 1 standards. Nine mass standards were constructed by filling 208-L (50-gal) metal drums with air-dried gravel and then sealing for a total mass of 320 kg ± 90 g. Twenty standards were constructed by filling 30 caliber military surplus ammunition cans with air-dried gravel and then sealing for a total mass of 4.5 kg ± 1 g each. These secondary container standards containing air-dried gravel were constructed by carefully determining empty container mass and filling the container in approximate 10 kg and 500 g gravel batches weighed on laboratory balances for the drums and ammo cans, respectively. The 10 kg batches were weighed to a precision of ±10 g, and the 500 g batches were weighed with a precision of ±0.01 g. The total mass of all the calibration standards was 3024 kg, which represents 336 mm of water depth equivalence. This calibration range is slightly over 150% of the safe (nonelastic) load cell range. The load cell range is approximately the maximum soil water extraction measured at this site for several different crops.

Calibration of each lysimeter was performed with the CR-7X set to excite the load cell with 5.000 V and to record the load cell analog signal at the 50-mV full-scale level with a 1.66 µV resolution at a 2-Hz sampling frequency. The CR-7X execution program used the Campbell 4-wire, full-bridge, load cell instruction. The load cell measurements were averaged for 1-min time periods by the CR-7X, and standard deviations were computed by the CR-7X for the 1-min period. The full range output signal of the load cell at 5.0 V excitation is 1.512 kg/mV {22.67 kg/[(3.0 mV/V)(5.0 V)]}. The CR-7X resolution of the load cell signal is 2^{15} or 32,768 parts or 0.00153 mV/bit (50.0 mV/32768). The resulting datalogger precision is 0.00231 kg/bit or 0.02 mm/bit in terms of water equivalence. The calibration weights and the wooden planks were stored inside a building and transported to the lysimeter site in early morning to avoid any dew or moisture change during the calibrations. The scale counter weights were adjusted before the calibrations so the load cell signal was between 0.2 and 0.5 mV/V after the plastic and wooden planks were placed on the lysimeter surface. The following procedure was used to load and unload each lysimeter:

1. Ten pairs of 4.5 kg ammo cans were placed on the lysimeter and the scale outputs determined for each pair (10 data points).
2. The laboratory scale weights were individually placed onto the lysimeter and the scale outputs determined for each weight (nine data points).
3. The laboratory scale weights were individually removed and the scale outputs recorded (nine data points).
4. Each pair of ammo cans were individually removed and the scale outputs recorded (10 data points).
5. The first drum was placed onto the lysimeter and the scale output recorded (one data point).
6. One pair of ammo cans were placed onto the lysimeter and the scale output recorded (one data point).
7. The pair of ammo cans were removed from the lysimeter and the scale output recorded (one data point).
8. A second drum was placed onto the lysimeter and the scale output recorded.
9. Steps 6 and 7 were repeated.
10. A third drum was placed onto the lysimeter and the scale output recorded.
11. Steps 1 through 4 were repeated.
12. A fourth drum was placed onto the lysimeter and the scale output recorded.
13. Steps 6 and 7 were repeated.
14. A fifth drum was placed onto the lysimeter and the scale output recorded.
15. Steps 6 and 7 were repeated.
16. A sixth drum was placed onto the lysimeter and the scale output recorded.
17. Steps 1 through 4 were repeated.
18. A seventh drum was placed onto the lysimeter and the scale output recorded.
19. Steps 6 and 7 were repeated.
20. An eighth drum was placed onto the lysimeter and the scale output recorded.
21. Steps 6 and 7 were repeated.
22. A ninth drum was placed onto the lysimeter and the scale output recorded.
23. Steps 1 through 4 were repeated.
24. Each drum was individually removed and the scale output recorded.

These procedures resulted in approximately 180 data points for each scale calibration. The exact number of data points deviated from this plan slightly if some measurements were omitted (sometimes steps 6 and 7 were omitted as drums were loaded or unloaded). The drums and 10- and 20-kg laboratory weights were placed onto the top of each lysimeter. The ammo cans and smaller laboratory weights were placed on support beams beneath each lysimeter for convenience to reduce communication to above-ground personnel. Each reading required a minimum of 2 min with the first minute used to place the particular calibration mass on the lysimeter and the second minute to record the reading. In some cases, several minutes were required for the load cell output to stabilize as indicated by the standard deviation for the 1-min time period, particularly when the drums were loaded onto or removed from the lysimeter. The 1-min time averaging period permitted the calibration of a single lysimeter within an 8-h day. Following these calibration measurements, a single drum was placed near each corner and the center of each side of each lysimeter to determine the effects of load distribution on scale performance.

Results and Discussion

The northwest weighing lysimeter was calibrated on 4 March 1987; and the southwest weighing lysimeter was calibrated on 6 March 1987. Table 1 summarizes the weather conditions during each calibration. Generally, the conditions were quite good for spring weather on the Texas High Plains, except the wind speeds were larger than desirable, approaching nearly 7.5 m/s at a 10-m elevation. The maximum 2-m elevation wind speed on these days would have been near 2.3 m/s based on the assumption of proportionality of wind speed and the logarithm of elevation. Nevertheless, the 10-m wind speeds were considerably lower than the March mean 10-m wind speed of 13.4 m/s for Bushland. Since the wind is seldom much lower than these speeds at Bushland, we deemed these conditions to be representative of the types of environments in which the lysimeters would be operating.

Results of the calibrations for the northwest lysimeter and the southwest lysimeter are shown in figures 1 and 2, respectively. The northwest lysimeter calibration resulted in a coefficient of determination of 0.9998 between the applied calibration mass and the load cell output. The standard error of the estimate for the linear regression was 1.37 mm. The southwest lysimeter calibration resulted in a coefficient of determination of 0.9991, and the standard error of the estimate for the linear regression was 3.38 mm. These mean errors represent about 1% of the range of the lysimeters and include all the errors for the scales, load cell, and data acquisition systems as well as any errors in the applied mass, except those due to temperature fluctuations on the data acquisition system and load cell. Since both the data acquisition and load cell are located in the lysimeter access room at about 2.4 m below ground level, temperature fluctuations are relatively minor (±5° C) and should not be a significant factor. Figures 1 and 2 illustrate the linearity and hysteresis of the lysimeters. The apparent differences with the ammo cans at several points during the calibration may have been due to insufficient scale settling times, load cell creep, datalogging errors, etc. These regression lines are largely determined by the combined mass from the nine drums which contain a possible cumulative error of about 0.81 kg (0.09 mm equivalence). The regression standard errors were larger than the expected error in the secondary drum standards.

Table 1. Environmental conditions during calibration of northwest and southwest weighing lysimeters at Bushland, Tex.

Time (CST) (h)	Air Temperature (° C)	Relative Humidity (%)	Solar Radiation (W/m²)	10-m Wind Speed (m/s)	Wind Direction from North (°)
4 March 1987					
0800	1.7	86	32	4.6	239
0900	5.0	81	202	6.1	245
1000	10.0	58	408	7.1	235
1100	12.8	43	579	7.1	220
1200	15.0	40	709	6.1	209
1300	16.7	37	778	6.0	206
1400	17.2	33	791	7.4	202
1500	18.3	29	735	7.3	207
1600	18.3	27	607	7.0	202
1700	18.3	25	433	6.6	206
1800	17.8	25	225	5.9	200
6 March 1987					
0800	0.6	73	39	3.1	224
0900	6.7	48	223	3.4	228
1000	12.8	37	433	4.3	242
1100	17.2	24	604	3.1	231
1200	20.0	17	737	4.7	204
1300	21.1	15	804	6.8	197
1400	22.2	14	810	6.2	201
1500	22.8	14	750	6.5	199
1600	22.8	14	627	5.9	199
1700	22.8	14	452	5.6	185
1800	21.7	15	339	5.4	169

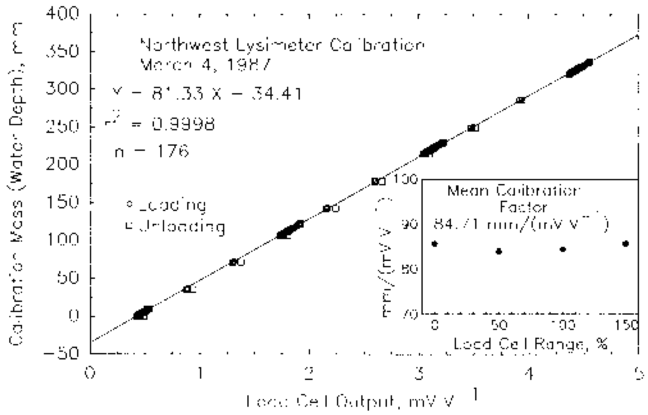

Figure 1–Northwest lysimeter calibration results.

The individual lysimeter calibration factors were based on the load cell output changes with the loadings and unloadings from the secondary standard ammo cans and laboratory weights (table 2). These weights provided a range of 144 kg (16 mm water depth equivalence) at each of the different drum loading points (approximately 25% of the load cell range from 0 to 150%). The mean error of the estimates were 0.101 and 0.045 mm for the northwest and southwest lysimeters, respectively. It was determined that the wind from the open manhole access door affected the

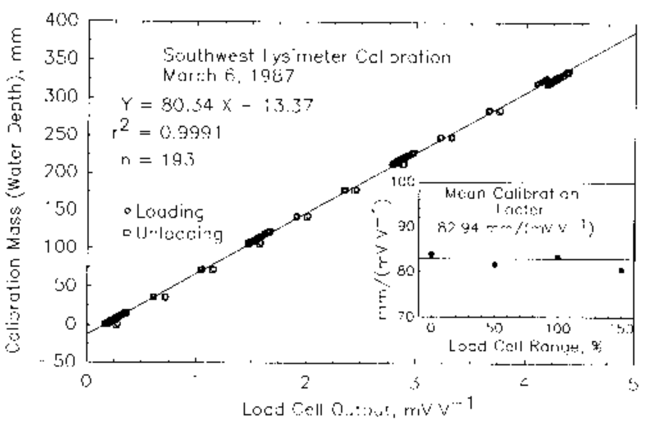

Figure 2–Southwest lysimeter calibration results.

Table 2. Calibration results for Bushland weighing lysimeters based on the laboratory weights (loading and unloading)

Load Cell Range (%)	Linear Regression: Intercept a (mm)	Slope b [mm/(mV V^{-1})]	Coeff. of Determ. (r^2)	Std. Error Estimate $S_{y/x}$ (mm)	Calib. Factor $\Delta Y/\Delta X$ [mm/(mV V^{-1})]
Northwest Lysimeter					
0	−42.09	85.61	0.9992	0.087	85.75
50	−46.94	84.02	0.9975	0.154	85.00
100	−16.67	72.40	0.9139	0.070	84.49
150	−20.04	74.70	0.8365	0.094	85.70
Mean	−31.44	79.18	0.9368	0.101	85.24
All	−34.12	81.36	0.9999	1.056	84.71
Southwest Lysimeter					
0	−11.12	74.73	0.9756	0.037	83.90
50	−16.20	83.20	0.9597	0.048	81.62
100	−19.15	83.39	0.9351	0.061	83.32
150	−15.37	80.03	0.9824	0.032	80.52
Mean	−15.46	82.84	0.9632	0.045	82.34
All	−11.12	79.62	0.9998	2.265	82.94

standard deviation of the load cell values for the northwest lysimeter calibration. The manhole access door to the southwest lysimeter was closed during calibration and this greatly improved the accuracy of the calibration results by reducing wind and pressure effects at the doorway. Both lysimeters produced calibration factors very close to the expected nominal value of 83.98 mm/(mV/V) which is based on the load cell size of 22.7 kg, the scale mechanical advantage 100:1, and the nominal factory load cell output of 3 mV/V at full load. These calibration values have remained rather stable (data not reported) with subsequent calibrations and load cell replacements. A recent calibration conducted in February 1995 (data not shown here) produced calibration factors that deviated between 0.5 to 0.7% from the factory load cell values (using the scale mechanical advantage and the load cell range). The 1995 calibrations were conducted with both four- and six-wire load cell bridge measurement configurations and indicated only minor insignificant differences since the lead wire length from the load cell to the datalogger is less than 5 m and in a rather constant thermal environment. Allen and Fisher (1991) reported reduced data recording precision for a load cell lysimeter using a six-wire bridge configuration compared to a direct four-wire configuration.

Load distribution on the lysimeter surface did not affect the calibrations. The maximum measured error from the distributional loadings was 2.22% of the applied 35.4-mm load. This load distribution testing is extreme in that it represents a water column of 696 mm on a single square meter, which never would be expected to occur naturally. The distributional loadings did not show any significant trends with respect to scale sensitivity.

The scales were tested to verify stability of the load cell output. The soil surface was covered with a closed pore rubber mat, held in place with steel bars to minimize evaporation, and the scale outputs were recorded at 1-Hz frequency and averaged over 1-min time periods. Figure 3 illustrates a typical single day (3 December 1987) of test results in which the mean mass of the covered lysimeter was 155.878 mm, standard deviation of the 1-min lysimeter mass was 0.038 mm, and the standard error was 0.001 mm. These results are similar to those reported by Van Bavel

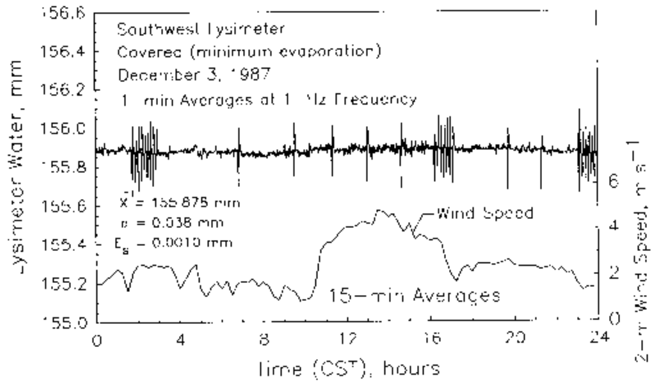

Figure 3–Southwest lysimeter mass during 3 December 1987, while covered to prevent soil evaporation ($\overline{X}$ – mean, σ – standard deviation, and E_s – standard error).

and Meyers (1962) for the USDA-ARS weighing lysimeters at Phoenix, Arizona. Figure 3 indicates good lysimeter stability, even though slight deviations are evident in the mass of the lysimeter over this day. The larger periodic spikes in load cell measurements were subsequently traced to electrical grounding interferences with the dataloggers that have been eliminated by earth grounding the data acquisition systems.

Wind greatly affects the scale performance, as many others have reported for similar lysimeters. Figure 4 shows the effect of wind (2 m above 0.3-m-tall standing sorghum stubble with a dry soil surface) on the standard deviation of 1-Hz frequency lysimeter load cell output values averaged over 15-min time periods for a 10-day period (16 to 25 November 1987). The 15-min standard deviation is rather consistent at about 0.42 mm for winds less than 5 m/s, but increases with wind speeds above 5 to 6 m/s. Dugas et al. (1985) reported that load cell signal range for 0.2-Hz measurement frequency and 10-min averaging increased with increasing wind speeds above 5 m/s, but that the mean load cell signal over these 10-min periods was stable. This is similar to our results as illustrated in figure 4.

The derivatives of the scale output, which are the ET rate (if no other mass changes occur like rainfall, irrigation, drainage, etc.), were determined for 5-min time periods

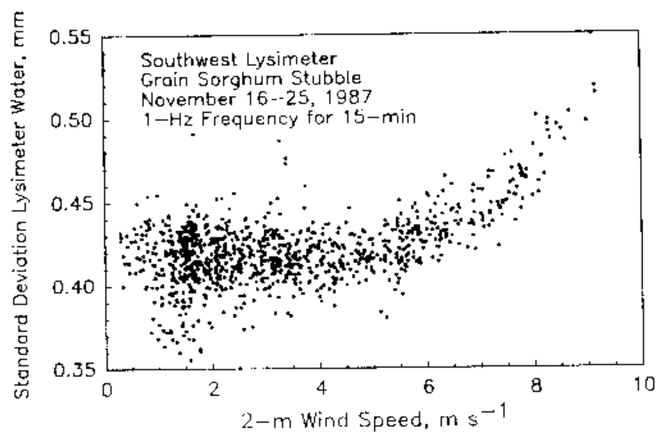

Figure 4–Southwest lysimeter mass 5-min standard deviation with 1-Hz sampling frequency as affected by wind at 2-m elevation above a uniform-height grain sorghum stubble (approximately 0.3 m tall) for 10 days (16 to 25 November 1987).

(fig. 5) for 1 October 1987. Grain sorghum was growing on the southwest lysimeter on this day. The lysimeter mass change indicates that the total ET for this day was 3.55 mm. The total mass curve is relatively smooth illustrating the monotonic decrease in lysimeter mass during this day. The insert to figure 5 shows the 5-min average load cell output for the same day from 1100 to 1200. The ET rate was computed as the differences in the five-minute average scale outputs during the day and expressed as mm/h. Figure 6 illustrates the evapotranspiration rate of grain sorghum on 1 October 1987 smoothed with 15-, 30-, and 60-min equally weighted running averages. The evapotranspiration rate appears "noisy" for the 15-min running averaging period (three 5-min averages) while the 30- and 60-min running averaging periods (six and twelve 5-min averages, respectively) appeared considerably more stable. During this day, the 15-min mean wind speeds at 2-m above the grain sorghum crop ranged from 1 to 6 m/s. Bausch and Bernard (1992) reported good agreement between evapotranspiration measurements using the Bowen ratio energy balance and the lysimeters with corn for 30-min latent fluxes, which exceeded 550 W/m^2 on 6 and 7 June 1990, confirming the representativeness of the lysimeter mass measurements.

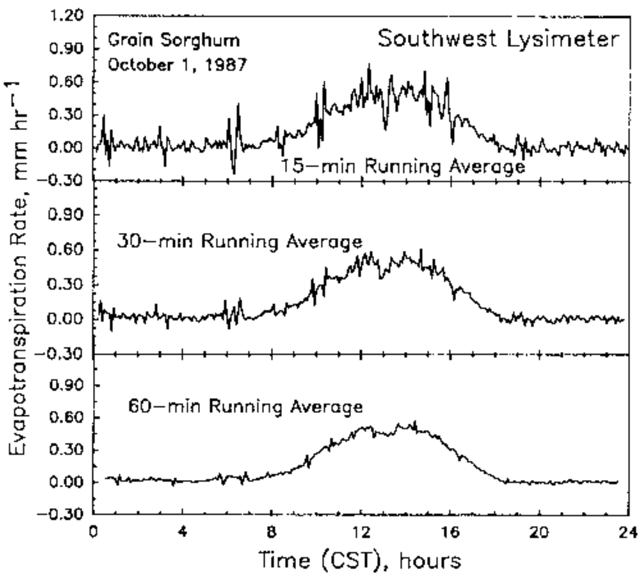

Figure 6–Grain sorghum ET rate during 1 October 1987, for 5-min differences in lysimeter mass with 15-, 30-, and 60-min equally weighted running averages.

Summary and Conclusions

The USDA-ARS weighing lysimeters at Bushland, Texas, were found to be sensitive to mass changes as small as 0.05 mm over the entire expected soil water depletion range of 250 mm. The lysimeter outputs are highly linear with a 1% total error over the range of the scales. Load distribution on the lysimeters did not affect the scale accuracy. The lysimeter output values are relatively stable if averaged for time periods of at least 30 min. Wind speeds greater than 5 to 6 m/s increased the standard deviation of the scale outputs. These lysimeters can accurately measure short-time ET rates with an accuracy of ±0.05 mm/h, daily ET, or irrigation and rainfall with a accuracy of ±0.1 mm or better, and seasonal soil water depletion with an accuracy of ±2 mm or better.

In practice, we recommend at least 15-min measurement averaging periods, sampling frequencies greater than 0.5 Hz (≈ 400 to 500 data points in a composite average), and either four- or six-wire bridge configurations (six wire if thermal changes or lead length resistance are appreciable factors) for similar lysimeters. For these lysimeters a four-wire bridge configuration was used before 1995, but our 1995 calibration experiments indicated a small advantage for the six-wire bridge configuration. At Bushland, the lysimeter mass is measured at 0.5-Hz frequency and averaged for 15 min. The 15-min means are composited into 30-min means for determining ET rates. Occasionally, 5-min mass means (usually with a 1-Hz frequency) are used to follow short time changes (like irrigations) where the mass changes are larger.

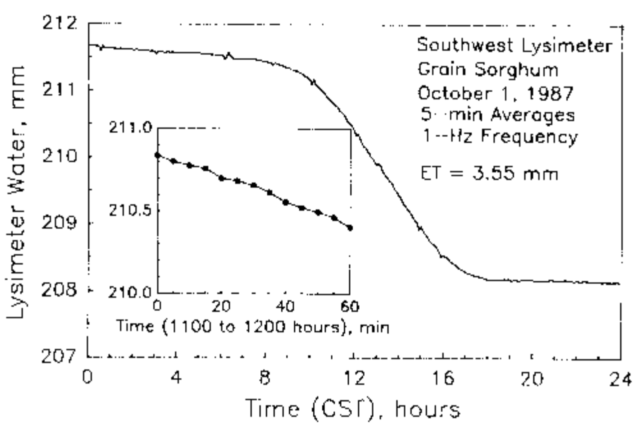

Figure 5–The 5-min average southwest lysimeter mass during 1 October 1987, with grain sorghum growing. The insert graph is a detailed view of the 5-min average lysimeter mass from 1100 to 1200.

Acknowledgments. The authors acknowledge the assistance in calibrating these lysimeters and processing the data from Karen Copeland, Biological Technician, and Joe Serda, Agricultural Research Technician, and Judy Tolk, Plant Physiologist, USDA-ARS, Conservation and Production Research Laboratory, Bushland, Texas. We also acknowledge the advice received from Dr. R. J. Reginato, Area Director, USDA-ARS, Pacific Area, Albany, California (former Soil Scientist with U.S. Water Conservation Laboratory, Phoenix, Arizona), and Dr. W. A. Dugas, Professor, Texas Agricultural Experiment Station, Blackland Research Center, Temple, Texas, regarding calibration procedures and lysimeter operation. Dr. S. R. Evett, Soil Scientist, USDA-ARS, Conservation and Production Research Laboratory, Bushland, Texas, coordinated 1995 recalibration of the lysimeters.

References

Aboukhaled, A., A. Alfaro and M. Smith. 1982. Lysimeters. FAO Irrig. and Drain. Paper No. 39. Rome, Italy: FAO.

Allen, R. G. and D. K. Fisher. 1991. Direct load cell-based weighing lysimeter system. In *Lysimeters for Evapotranspiration and Environmental Measurements, Proc. of the Int. Symp. on Lysimetry*, eds. R. G. Allen, T. A. Howell, W. O. Pruitt, I. A. Walter and M. E. Jensen, 114-124. New York: Am. Soc. Civil Engr.

Allen, R. G., T. A. Howell, W. O. Pruitt, I. A. Walter and M. E. Jensen, eds. 1991. *Lysimeters for Evapotranspiration and Environmental Measurements. Proc. of the Int. Symp. on Lysimetry.* New York: Am. Soc. Civil Engr.

Armijo, J. D., G. A. Twitchell, R. D. Burman and J. R. Nunn. 1972. A large, undisturbed, weighing lysimeter for grassland studies. *Transactions of the ASAE* 15(5):827-830.

Bausch, W. C. and T. M. Bernard. 1992. Spatial averaging Bowen ratio system: Description and lysimeter comparison. *Transactions of the ASAE* 35(1):121-128.

Dugas, W. A., D. R. Upchurch and J. T. Ritchie. 1985. A weighing lysimeter for evapotranspiration and root measurement. *Agron. J.* 77:821-825.

Harrold, L. L. and F. R. Dreibelbis. 1958. Evaluation of agricultural hydrology by monolith lysimeters. USDA-ARS Tech. Bull. No. 1179. Washington, D.C.: USDA.

Hatfield, J. L. 1990. Methods of estimating evapotranspiration. In *Irrigation of Agricultural Crops*, eds. B. A. Stewart and D. R. Nielsen, 435-474. Madison, Wis.: Am. Soc. Agron.

Kohnke, H., F. R. Dreibelbis and J. M. Davidson. 1940. A survey and discussion of lysimeters and a bibliography on their construction and performance. USDA Misc. Pub. No. 372. Washington, D.C.: USDA.

Jensen, M. E., R. D. Burman and R. G. Allen, eds. 1990. *Evapotranspiration and Irrigation Water Requirements.* ASCE Manuals and Reports on Engr. Practice No. 70. New York: Am. Soc. Civil Engrs.

Marek, T. A., A. D. Schneider, T. A. Howell and L. L. Ebling. 1988. Design and construction of large weighing monolith lysimeters. *Transactions of the ASAE* 31(2):477-484.

Pruitt, W. O. and D. E. Angus. 1960. Large weighing lysimeter for measuring evapotranspiration. *Transactions of the ASAE* 3(2):13-15, 18.

Ritchie, J. T. and E. Burnett. 1968. A precision weighing lysimeter for row crop water use studies. *Agron. J.* 60:545-549.

Rosenberg, N. J., H. E. Hoyt and K. W. Brown. 1968. Evapotranspiration, A review. MP-20. Lincoln: Univ. of Nebraska and Nebraska Exp. Sta.

Soileau, J. M. and R. D. Hauck. 1987. A historical view of U.S. lysimetry research with emphasis on fertilizer percolation losses. *Int. Conf. on Infiltration Development and Application*, Honolulu, Hawaii, 6-9 January.

Tanner, C. B. 1967. Measurement of evapotranspiration. In *Irrigation of Agricultural Lands*, eds. R. M. Hagan, H. R. Haise and T. W. Edminister, 534-574. Madison, Wis.: Am. Soc. Agron.

Van Bavel, C. H. M. and L. E. Meyers. 1962. An automatic weighing lysimeter. *Agricultural Engineering* 43(10):580-583, 586-588.