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A Simplified Weighing Lysimeter for Monolithic or Reconstructed Soils

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Abstract. *A simplified weighing lysimeter applicable to both monolithic and reconstructed soils was developed and tested in two lysimeters installed at Ismailia, Egypt and one installed at Bushland, Texas, USA. A monolithic lysimeter was used to measure reference grass evapotranspiration (ET) at Bushland because the dense subsoil and calcic horizon of the clay loam soil cannot be reconstructed. The desert sand at Ismailia allowed the use of reconstructed soils for measuring reference ET of alfalfa and ET of field crops. The main lysimeter components are the concrete foundation, deck scale, soil tank and enclosure consisting of a base, a tank and a top. The steel soil tank and enclosure are shop-fabricated, and the scale is commercially available. Field construction consists mainly of excavation, collection of the soil monolith, if needed, and installation of the concrete foundation. Field calibration of the Bushland lysimeter over a 214-mm (8.43 in.) ET range resulted in $s_{y/x}$ = 0.1 mm (0.004 in.) and r^2 = 0.9999. Similar calibration of one of the Ismailia lysimeters over an 80-mm (3.2-in.) ET range resulted in $s_{y/x}$ = 0.02 mm (0.0008 in.) and r^2 = 0.9999. In initial tests, the Kimberly-Penman equation overestimated grass reference ET, and the Penman-Monteith equation slightly underestimated grass reference ET for the Bushland environment. Hourly grass ET measured with the Bushland lysimeter agreed closely with hourly grass ET calculated by the 1963 Penman equation.*

Keywords. *Lysimeters, Evapotranspiration, Construction, Design, Monolith, Weighing.*

Weighing lysimeters are the best equipment available for accurately measuring the evapotranspiration (ET) of grass and crops (Aboukhaled et al., 1982; Howell et al., 1991). With plant growth and crop yield data, they also provide the required information for calibrating crop growth models.

The use of weighing lysimeters is limited by the high initial cost of the equipment and the trained personnel required to construct and operate the lysimeters and then to collect and interpret the data. Many weighing lysimeters have been reported in the literature (Aboukhaled et al., 1982; Harrold, 1966; Howell et al., 1991), but each lysimeter is adapted to local soils, crops, and climatic conditions. Generally, only limited design information is available, and the designer needs to consider both the requirements for the lysimeter and local construction materials and practices.

The cost of a lysimeter is determined by the size, the types of specialized equipment, and the labor and materials used in construction. The lysimeter must be large enough to provide accurate ET data and representative crop yield data for use in modeling. The soil tank must be deep enough to allow development of normal rooting and a normal soil water potential profile either with or without suction drainage. The cost of materials and equipment are influenced by how much can be purchased locally and how much must be shipped to the site. Construction costs are determined by the availability of local materials, labor and equipment as well as construction practices.

This article reports the design, installation and operation of simplified weighing lysimeters using repacked soil tanks at Ismailia, Egypt, and a monolithic soil tank at Bushland, Texas, USA.

Lysimeter Design

The lysimeters at the two sites have similar designs but have different sizes, construction details and soil placement. The Bushland lysimeter contains a monolithic soil core with a 1.50-m (4.92-ft) square surface area in a 2.44-m (8.00-ft) deep soil tank. Both the North and South Ismailia lysimeters have 1.50-m × 2.00-m (4.92-ft × 6.56-ft) surface areas with repacked soil in a 1.60-m (5.25-ft) deep soil tank. The major components of the lysimeters are the foundation, deck scale, soil tank and enclosure consisting of a base, a tank and a top as illustrated in figure 1. Since the scale is factory assembled, the soil tank and enclosure are shop-fabricated and the concrete foundation is easily constructed on site, we refer to the design as simplified. Use of the deck scale followed the work of Kirkham et al. (1984), but all other lysimeter components were designed specifically for this project.

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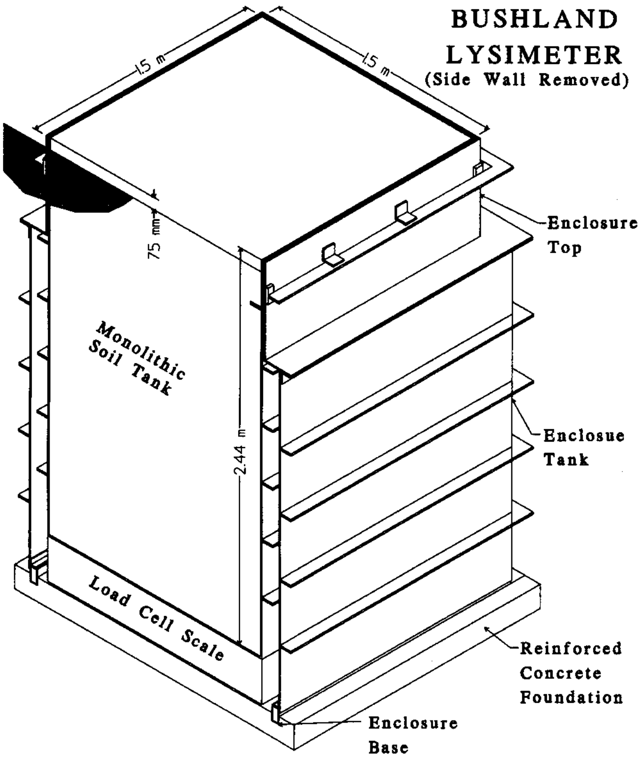

Figure 1–Isometric view of the Bushland, monolithic weighing lysimeter (1 m = 3.28 ft).

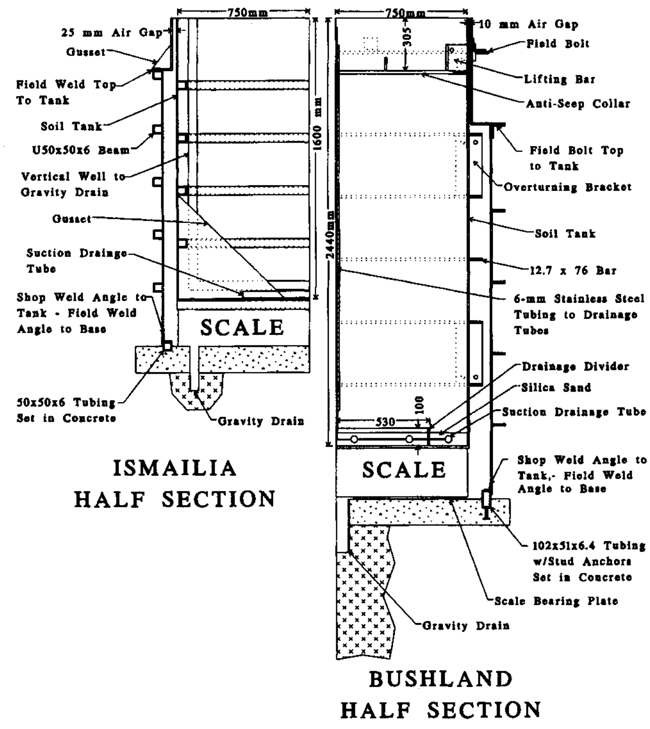

Figure 2–Half cross-sections of the Bushland and Ismailia weighing lysimeters (1 mm = 0.04 in.).

Except for the concrete foundations, all construction was of ASTM A36 steel for the Bushland lysimeter and DIN 1025 steel for the Ismailia lysimeters.

The Bushland lysimeter was designed to measure grass reference ET, and the Ismailia lysimeters were designed to measure either alfalfa reference ET or ET of field crops. At Bushland, the soil is Pullman clay loam classified as a fine, mixed, thermic *Torrertic Paleustoll* with a dense subsoil from about 0.15 to 0.4 m (0.50 to 1.3 ft) and a calcic horizon from 1.5 to 2.0 m (4.9 to 6.6 ft). Disturbing either the subsoil or calcic horizon causes long-term changes in the hydraulic properties of the soil (Eck and Taylor, 1969; Allen et al., 1995). At Ismailia, the soil is an unclassified, deep, fine desert sand without layering or structure, and a repacked lysimeter was satisfactory. The monolith collection site at Bushland was about 30 m (100 ft) from the lysimeter location so soil compaction and excavation while collecting the monolith did not affect soil conditions near the lysimeter. At the lysimeter site, construction traffic was restricted to a single road, and the smallest-practical, vertical-walled pit was excavated for the enclosure. At Ismailia, backfilling the excavations for the enclosures would not be expected to change properties of the loose, unlayered sand around the lysimeters. Both soils are well drained, and high water tables were not a consideration in the design.

Soil Tanks

The soil tanks are of welded steel construction with the wall reinforcement varying for the monolithic and repacked soil tanks (fig. 2). The exterior reinforcing of the monolithic soil tank allowed the monolith to be collected as a large soil core. The single interior bar allowed for the narrow 10-mm (0.39-in.) air gap along the upper 0.61 m (2.0 ft) of the lysimeter. The inner reinforcing bar also functions as an anti-seep collar to minimize side wall percolation. For the repacked soil tanks, the reinforcing consisted of four U-beams around the interior of the tanks and gussets extending 0.61 m (2.0 ft) along the center of each wall and tank bottom. A 1060-mm (41.7-in.) square drainage divider on the bottom of the monolithic soil tank partitions drainage from the inner and outer halves of the soil monolith (Marek et al., 1988). This drainage divider also stiffens the 13-mm (0.50-in.) thick tank bottom. For the Ismailia lysimeters, the 10-mm (0.39-in.) tank bottoms are reinforced internally with gussets and externally with the same-size U-beams used to reinforce the tank walls.

The soil tanks all had 38-mm (1.5-in.) diameter by 760 mm (30-in.) long sintered, stainless-steel suction drainage tubes, and the Ismailia lysimeters also had gravity drains (fig. 2). The suction drainage tubes were made of 0.5-μm (0.00002-in.) particles and had a bubbling pressure of 12 kPa (1.7 lbf/in.^{2}). All tubes were individually piped to the tops of the lysimeters with 6.0-mm (0.25-in.) stainless-steel tubing. The Ismailia lysimeters had three tubes perpendicular to the 2.00-m (6.56-ft) walls, and the Bushland lysimeter had four tubes in both the inner and outer halves of the monolith (fig. 2). Gravity drains for the Ismailia lysimeters were fiberglass-wrapped, 50-mm (2.0-in.), slotted PVC pipe that could be pumped through a 50-mm (2.0-in.) vertical well.

The monolithic soil tank had additional features for lifting and overturning the monolith and for placing the soil tank on the deck scale. We installed the suction drainage system by overturning the monolith rather than by attaching it to a shallow tank with the drainage system and tank bottom already installed (Gee et al., 1991). To accomplish this, two pairs of overturning brackets on the tank (fig. 2) were designed to temporarily attach two W200×31 (W8×21) wide flange I beams. When the monolith was lifted from either end of these beams, the center of gravity was vertically above the lower corner. By resting the lower corner of the tank on the ground, the tank could be rolled with the crane to lie on either its end or its side. A lifting bar in each corner of the monolithic tank (fig. 2) allowed the tank to be lifted in a true vertical position. With this feature, the deck scale was uniformly loaded as the soil tank was placed on it.

Enclosure

The enclosures were also of welded steel construction and consisted of a base, a tank, and a top. The tanks were fabricated of steel plates with the Ismailia tanks being reinforced with U-beams and the Bushland tank being reinforced with solid bars. The enclosure tops were fabricated separately to allow the air gap between the soil tank and enclosure top to be adjusted in the field. The enclosure bases were designed to be placed in the concrete foundation and then for the enclosure tanks to be welded to the bases after the concrete cured. This provided a simple watertight transition from the concrete foundation to the steel tanks.

Foundation

The lysimeters all had 150-mm (6.0-in.) thick reinforced concrete pad foundations with a concrete design strength of 20 MPa (3000 lbf/in.^{2}). The Bushland foundation had one grid of 19-mm (0.75 in.) deformed reinforcing bars on a 200-mm (8.0-in.) spacing, and the Ismailia foundation had similar 13-mm (0.51-in.) bars on a 250-mm (9.8-in.) spacing. Both lysimeters had percolation drainage sumps that discharged into sand or gravel beneath the concrete pad.

Scale

A square, Weigh-tronix, Inc. deck scale with a chain link suspension and load cell in each corner was used for all lysimeters. The Bushland scale was a Model DS 606030 with a design capacity of 13.6 Mg (30,000 lbs), and the Ismailia scales were Model DS 606020 with a design capacity of 9.10 Mg (20,000 lbs). Surface dimensions of the scales were 1.52 × 1.52 m (5.00 × 5.00 ft), and the heights were 280 mm (11 in.) for the Bushland scale and 200 mm (8.0 in.) for the Ismailia scales. The scales were shipped fully assembled from the factory and needed only a suitable foundation and wiring to the data logger for installation.

The Weigh-tronix deck scales have four flexure-type load cells wired in parallel that require a DC excitation voltage of 1 to 5 V and a high resolution voltage recorder. Campbell Scientific, Inc. Model CR7 data loggers provided the excitation voltage and recorded the output signal. The load cell signal was measured every 2 to 5 s, and the average and standard deviation made over 5- to 30-min intervals was calculated and stored. A six-wire bridge configuration compensated for changes in excitation and output voltages due to temperature changes in the wiring between the data loggers and the scales. Allen and Fisher (1991) compared direct load cell-based weighing lysimeters with the load cells located either at the soil surface or beneath the soil tank. ET measurements were more accurate with the load cells placed beneath the soil tank in a more isothermal environment.

Minimizing excitation current enhanced stability and lowered noise in the scale instrumentation system. Each scale load cell had an input impedance of 350Ω so the impedance of four load cells wired in parallel was only 87.5Ω. With this low impedance, we used an excitation voltage of only 1.00 V resulting in 11.4 mA of current to a single scale. At Ismailia, we used two separate data logger instructions, each acting at different times, and separate excitation channels on the CR7 so only one scale would be excited and read at a time. An offset voltage of 1.5 V in the data logger instruction reading the load cells kept the recorded voltage near zero and made the five digit number recorded by the data logger as precise as possible. With the procedure described here, the resolution of the lysimeters was 0.04 mm (0.002 in.) of ET.

Installation Procedure

The lysimeter installation followed generally accepted procedures such as those presented by Aboukhaled et al. (1982), Howell et al. (1991), and Schneider and Howell (1991). Our installation procedure focuses on the new or unique features of the simplified lysimeters.

Bushland Lysimeter

The monolith was collected with the hydraulic pulldown procedure presented by Schneider et al. (1988) with several innovations to prevent bending of the tank walls and speed undercutting of the monolith (Schneider et al., 1993, 1996). With the hydraulic pulldown procedure, anchors are installed outside the four corners of the monolith tank, and the tank is pulled into the soil with hydraulic jacks connected to the anchors (fig. 3). As the tank is jacked down, soil is excavated around the outside of the tank to allow room for the external reinforcing. To prevent warping of the tank walls, the bottom edges of the tank were temporarily reinforced with 152×152×9.5-mm (6×6×3/8-in.) steel angles, and 50-mm (2.0-in.) diameter pipe columns transferred the force from the pulldown frame to the angles which were welded to the tank. After the monolith tank was fully pulled down, it was undercut with two steel wedges approximately 600 mm (24 in.) long along

Figure 3–Collecting the Bushland monolith using the hydraulic pulldown procedure.

each wall. The wedges were fabricated from structural T-Beams and were driven into the soil with a 3-kg (6-lb) sledge hammer. A temporary top of 13-mm (0.50-in.) steel plate was fitted over the monolith tank, and the wedges and top were chained to the tank to contain the monolith within the tank. The monolith was lifted from the ground with a 22.7-Mg (50,000-lb) capacity crane (fig. 4) and overturned for installation of the drainage system and steel bottom.

To provide space for the drainage system, a 75-mm (3.0-in.) thick soil layer was removed from the bottom of the monolith, and the drainage tubes were centered vertically in the excavated zone. Six-millimeter (0.25-in.) stainless-steel tubing was routed from each drainage tube to the center of one wall and then run vertically to the lysimeter surface through a square, 38-mm (1.5-in.) steel tube that had been welded to the tank wall. The 75-mm (3.0-in.) thick excavated zone was then filled with silica sand having D_{50} = 0.25 mm (0.010-in.) and C_u = 3.3. Finally, the tank bottom with the drainage divider attached was set into the sand and welded to the soil tank.

Enclosure installation consisted of excavating the pit, constructing the concrete foundation, and placing and connecting the enclosure tank to the tank base. Workers inside the excavated pit were protected from sidewall caving by steel pipes extending from the soil surface to below the bottom of the completed pit (fig. 5). Before excavation started, the 44-mm (1.7-in.) diameter × 3.0-m (10-ft) long pipes were pressed into the soil every 0.30 m (1.0 ft) around the perimeter of the square pit and U-bolted to timbers at the soil surface. We then drilled the maximum diameter borehole that could be fitted inside the square pit and hand excavated the corners of the pit (fig. 5). The operation was done sequentially by drilling about 1.0 m (3.3 ft) and then hand excavating the corners into a 1.0-m (3.3 ft) diameter pilot hole in the center of the pit. This allowed the hand excavated soil to be removed from the pit with the drilling rig. By doing most of the excavation with the drilling rig, the pit was excavated in about 3 h with five workers and the drilling rig operator.

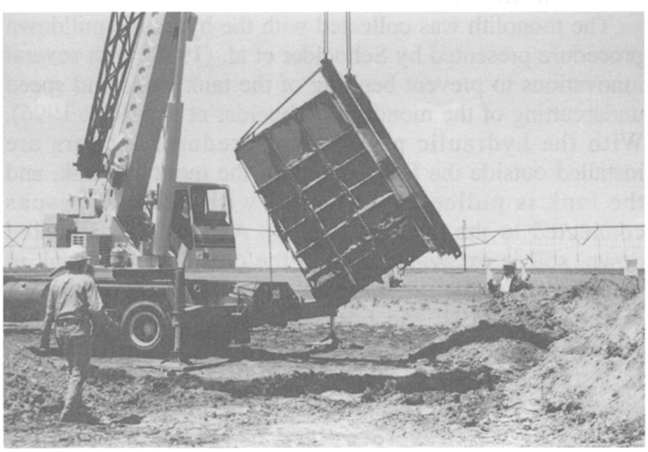

Figure 4–Lifting the Bushland soil monolith from the ground for overturning.

Figure 5–Excavating for the foundation and enclosure for the Bushland lysimeter.

The concrete foundation was placed directly on the smoothed and packed soil at the bottom of the pit. After excavating the enclosure pit, the 1.0-m (3.3 ft) diameter pilot hole from the drilling rig extended about 1.0 m (3.3 ft) below the bottom of the pit. Fine gravel was placed in this pilot hole as illustrated in figure 2 to provide percolation drainage for the enclosure. The forms, sump and reinforcing steel were set in place, and ready-mixed concrete was placed in the forms. Finally, the enclosure base and scale bearing plates were set into the wet concrete at the desired elevation.

After the concrete cured, the enclosure tank and scale were set in place with a 3.6-Mg (8000-lb) capacity fork lift. The angle at the bottom of the enclosure tank was set directly on the base installed in the concrete (fig. 2). This angle was arc-welded to the rectangular tubing with a single 8-mm (0.3-in.) fillet weld. The scale was placed on the four steel bearing plates set in the concrete and horizontally positioned with short steel rods welded to each bearing plate.

A 22.7-Mg (50,000-lb) capacity crane was used to set the soil tank on the scale and then to place the enclosure top over the soil tank (fig. 6). To ensure a uniform air gap between the soil tank and the enclosure top, two, 10-mm (0.39-in.) thick spacers were placed in each corner as the top was lowered over the soil tank. Bolt holes in the 76×76×9.5-mm (3×3×3/8-in.) angle supporting the top were field drilled, and the top was bolted to the enclosure tank. The 44-mm (1.7-in.) pipes were then pulled out, and the

Figure 6–Lifting the finished Bushland soil monolith in preparation for setting it on the deck scale. Vertical pipes to prevent caving of pit walls are in view.

approximately 150-mm (6.0-in.) wide space outside the enclosure was backfilled. Soil was placed in layers about 0.3-m (1-ft) deep, wetted throughout the layer with a water jetting tool and hand packed with 38-mm (1.5-in.) diameter pipes. The zone below the top off the calcareous stratum was backfilled with soil from below this depth, and the zone above the calcareous stratum was backfilled with topsoil.

Ismailia Lysimeters

Installation of the Ismailia lysimeter was similar to many lysimeters with reconstructed soil tanks reported in the literature. Although reconstructed soil tanks are less difficult to fill than monolithic soil tanks, the loose sand at the site made access by trucks and cranes difficult.

Pits for the enclosures were hand excavated with 1:1 side slopes for worker safety, and soil for repacking the soil tanks was selected at the same time. This soil was stored in 0.25-m (0.82-ft) layers and protected with plastic film for later use. Figure 7 illustrates one of the fully excavated pits with the concrete foundation under construction. The field-mixed concrete foundation was constructed directly on the sandy soil at the desired elevation to support the enclosures and scales.

After the concrete foundation cured, the enclosure components, scale, and soil tank were placed to complete the lysimeter installation. The steel tanks and scales were hauled to the lysimeter site with a farm tractor and trailer because trucks were not able to drive over the deep sand. Placing the scale, enclosure tank and soil tank required a track-mounted military crane designed to operate on sandy soil.

The drainage systems were then installed, and soil was hand-placed in the soil tanks at the correct depths. Three, stainless steel suction drainage tubes were placed horizontally near the bottom of each lysimeter, and 6.0-mm (0.25-in.) stainless-steel tubing was routed from each tube to the center of one 2.00-m (6.56-ft) long wall and then to the lysimeter surface. The gravity drainage system of slotted, fabric-wrapped 50-mm (2.0-in.) PVC pipe was also installed and covered with the native soil. Soil was placed in the tanks in 0.25-m (0.82-ft) layers in reverse order of excavation. The reconstructed soil was not packed mechanically but was consolidated by wetting and gravity draining the completely filled soil tank.

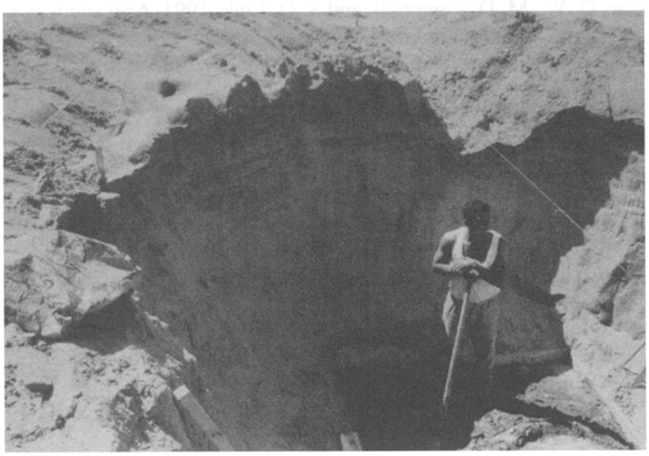

Figure 7–Installing the concrete foundation for one of the Ismailia lysimeters.

Lysimeter Measurements

Calibration

The Bushland lysimeter was field calibrated with 60 hermetically sealed gravel containers each having a mass of 7.0 to 8.0 kg (15 to 18 lb) and weighed to an accuracy of 0.1 g (0.0002 lb) on a calibrated laboratory scale. To prevent mass changes due to evaporation, the lysimeter was covered with a thick rubber tarpaulin held in place by metal weights. The data logger was programmed to read every 1 s using the high resolution mode and an input range of ±5 mV (precision of 166 nV), and to output the average reading and standard deviation for 1-min intervals. Initially, 15+ averages were measured with the lysimeter unloaded. Then, five averages were measured after groups of ten calibration weights (70 to 80 kg increments) were placed on the lysimeter. When all weights were loaded, 15+ averages were measured with the maximum load of 480.9 kg (1060 lb) (214 mm or 8.43 in. water equivalent). The measurement procedure was repeated as weight increments were removed until 15+ averages were measured with the lysimeter unloaded.

Ninety-seven observations were used to derive the calibration equation illustrated in figure 8. The added mass (kg) was divided by lysimeter area (m^2) to express load cell output in equivalent water depth (mm). Linear regression of water depth versus load cell output resulted in a highly significant relationship with the standard error, $s_{y/x}$ = 0.1 mm (0.004 in.), and $r^2 = 0.9999$.

The Ismailia lysimeters were field calibrated using a procedure similar to that used at Bushland but with a smaller ET range because of the smaller lysimeter depth and soil water holding capacity. In the laboratory, two calibration masses were weighed to each represent 40 mm (1.6 in.) of ET. In the field, 10+ load cell outputs were measured with the lysimeter unloaded, with the masses incrementally loaded and unloaded and again with the lysimeter unloaded. The north lysimeter was representative of both Ismailia lysimeters, and linear regression of water depth versus load cell output resulted in highly significant relationship with $s_{y/x}$ = 0.02 mm (0.0008 in.) and r^2 = 0.9999 (fig. 8).

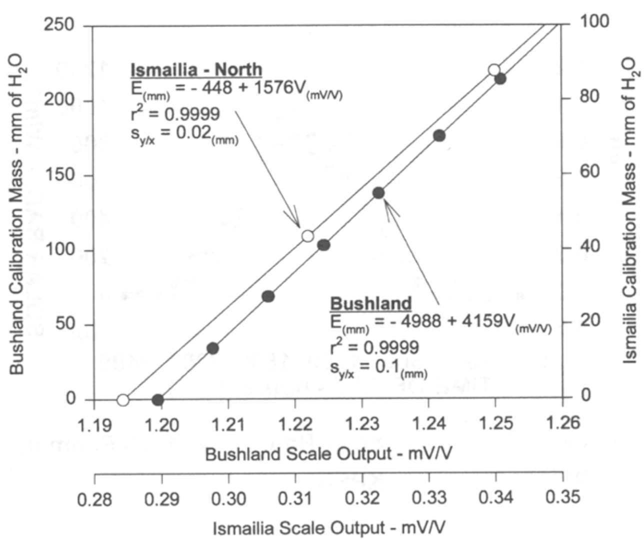

Figure 8–Calibration data for the Bushland and North Ismailia lysimeters (1 mm = 0.04 in.).

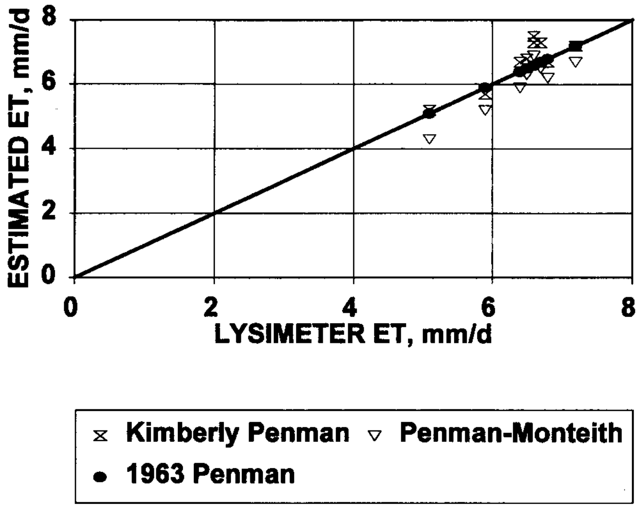

Figure 9–Daily lysimeter ET at Bushland compared with ET calculated by the Kimberly Penman, Penman-Monteith, and 1963 Penman methods for 23 June through 2 July 1995 (1 mm/d = 0.04 in./d).

EVAPOTRANSPIRATION

Figure 9 illustrates nine days of grass lysimeter ET measurements with the Bushland lysimeter compared with computed ET using the REF-ET (v. 2.14) (Allen, 1990) program for the Penman-Monteith (PM), Kimberly-Penman (KPEN), and 1963 Penman equations. The tall fescue grass (*Festuca arundinacea* Schreb., cv Green Emerald) reached full cover in late May and was mowed twice weekly to a 0.10-m (4.0-in.) height. With the default ratio of 1.25 for alfalfa to grass ET, the KPEN overestimated grass ET slightly. Conversely, the PM equation using grass leaf area and roughness algorithms by Allen et al. (1989) and 0.10-m grass height underestimated grass ET for 3 of the 9 days. Of all the equations in REF-ET, the 1963 version of the Penman equation (Penman, 1963) had the closest agreement with the lysimeter measured ET for these few days. The Hargreaves equation (not shown) underestimated daily ET slightly more than the PM method but was consistent with the ET measurements.

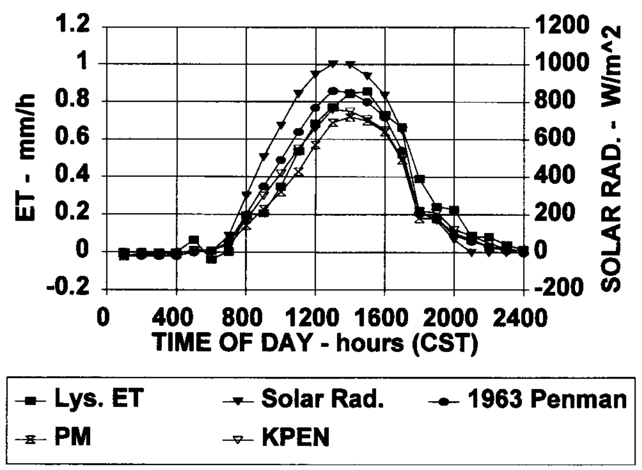

Figure 10–Hourly ET and solar radiation at Bushland compared with ET calculated by the Kimberly-Penman, Penman-Monteith, and 1963 Penman equations for 2 July 1995 (1 mm/d = 0.04 in./d).

Figure 10 illustrates hourly lysimeter grass ET rates at Bushland and rates calculated by the Penman-Monteith, (PM), Kimberly-Penman (KPEN) and 1963 Penman equations for 2 July 1995. Agreement between the measured values and values calculated by the 1963 Penman equation is good with an average underestimation of only 1.9%. The KPEN equation underestimated the peak ET rate by 12%, and the PM equation underestimated cumulative reference ET for the day by 21%.

CONCLUSION

The lysimeter design presented here was used for two lysimeter installations with greatly different soil conditions and construction environments. The prefabricated steel tank construction, simple concrete foundation, and commercially available scale were easily adapted to the two environments. Field construction consisted mainly of collecting the soil monolith if needed, excavating for the enclosure and constructing the concrete foundation. The three-part enclosure design provided a simple, water-tight transition with the concrete foundation and an easily adjusted air gap with the soil tank. The lysimeter design has worldwide applicability for low cost measurement of ET.

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