SPRINKLER EVAPORATION LOSSES and EFFICIENCY[1]

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Sprinkler systems, primarily center-pivots, are widely used in the Great Plains of the United States. On the Texas High Plains alone in 1984, about 40% of the 1.8 million hectares (4.4 million acres) of irrigated land was irrigated by sprinklers (Musick et al., 1988). Methods of irrigation application using sprinklers vary considerably from high-angle high-pressure impact sprinklers, to low-angle medium- to low-pressure impact sprinklers, medium- to low-pressure spray nozzles, medium- to low-pressure rotary nozzles, ground-level LEPA (low-energy precision application) bubblers, to multi-mode LEPA devices. Each method produces different distributions of droplet sizes. Also, the application rate of the various methods can vary considerably from less than 6 mm/hr (0.2 in/hr) to rates over 100 mm/hr (4.0 in/hr). All of these variables directly affect the droplet and canopy evaporation of sprinkled water. Christiansen (1942) noted that one of the frequently asked questions about sprinkler irrigation is "*How much water is lost by evaporation when water is sprayed into the air?*" He added,"*Generally it has been assumed that the loss directly from the spray may be appreciable, especially on warm, dry days, and when the wind is blowing. In addition to the loss from the spray there are direct evaporation losses from wet surfaces during and following every application of water.*" After almost 50 years, we should agree that the same question is often asked and, in general terms, the Christiansen's response remains appropriate.

In spite of the above disclaimer, we will present information regarding evaporative losses associated with sprinkler irrigation. The objectives of this paper are to summarize information obtained using precise, weighing lysimeters to measure both the catch and evaporation of sprinkler applied water at Bushland, TX. Information on evaporative losses will be presented for medium-pressure, low-angle impact sprinklers on top of a lateral-moving sprinkler system about 4.3 m (14 ft) above the ground, medium-pressure, medium-groove, flat plate spray nozzles at an elevation of 1.5 m (5 ft.) above the ground, and low-pressure, LEPA bubblers located

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about 0.3 m (1 ft.) above the ground. This paper is a summary of work reported in Schneider and Howell (1987 and 1990). In addition, data collected by the third author on the effect of sprinkler method on crop transpiration and microclimate as part of the requirements for a Ph.D. will be presented.

REVIEW OF LITERATURE

Several components of water loss associated with sprinkler applications based on conservation of mass (Kraus, 1966) are described by the following equation

$$Q_s = Q_{ae} + Q_{ad} + Q_{fi} + Q_{gi} \qquad ...[1]$$

where Q_s is the discharge of the sprinkler, Q_{ae} is the droplet evaporation into the atmosphere, Q_{fi} is the intercepted water held on the foliage, Q_{ad} is the water drift outside of the application area, and Q_{gi} is the water reaching (or intercepted) the ground surface. Equation [1] can be expressed on a rate, mass, or volume basis. Q_{fi} represents the sum of the water evaporated from the wet foliage during the irrigation application (Q_{fe}) and the amount of water remaining on the foliage (Q_{fs}) when the application is completed as

$$Q_{fi} = Q_{fe} + Q_{fs} \qquad ...[2]$$

The water reaching the ground can be partitioned into infiltrated water (Q_{si}), evaporated water from the ground (Q_{ge}), runoff water (Q_{gr}), and water stored on the ground (Q_{gs}) as

$$Q_{gi} = Q_{si} + Q_{ge} + Q_{gs} + Q_{gr} \qquad ...[3]$$

Hansen (1960) defined ***irrigation application efficiency*** (E_a) as the ratio of the water stored in the root zone (Q_{si} in this case) to the water delivered to the field (Q_s in this case). The sprinkler irrigation application efficiency (E_a) is then defined by the fraction

$$E_a = Q_{si}/Q_s \qquad ...[4]$$

Since it remains difficult to measure each of the potential component water losses, various assumptions are often used (like Q_{gr} and Q_{gs} are zero; Q_{ge} is zero; or Q_{ad} is zero; etc.) to characterize Q_{si}. Q_{si} is often assumed equal to the volume of water caught at the ground level in a catch container.

Spray Evaporation

In most spray evaporation studies, catch cans are used to determine the losses from the sprinkler to the ground. With this method, any drift losses (Q_{ad}) would be included with the droplet evaporation estimate (Q_{ae}). Christiansen (1942) stated that he believed that much of his measured spray loss was attributed to evaporation from the catch container. Kohl (1972) evaluated evaporation losses from several collector types. He found that a plastic separatory funnel prefilled with oil effectively minimized the evaporation losses from the collector. Marek et al. (1985) found that 3.8 L (1 qt) oil cans caught 5% more water than a glass separatory funnel. Livingston (1983) indicated potential problems with catch cans in windy situations, and Steiner et al. (1983a) found problems in measuring sprinkler applications under a center-pivot sprinkler due to different wind orientation with the sprinkler line. Fischer and Wallender (1988) indicated that 127-mm diameter catch cans performed more consistently than 40-mm diameter catch cans. Kincaid et al. (1986) painted catch cans white to minimize radiation adsorption and pre-wet the cans to avoid errors associated with water losses on the walls of the catch container.

Christiansen (1942) reported mean spray losses $(Q_{ae})/Q_s$ of 3.9% for pre-sunrise conditions (near minimum air temperature and high humidity) in California. He reported spray losses from 10 to 42% during afternoon conditions with air temperatures up to 40 °C (104 °F) and relative humidity of 15%. He found little correlation with atmometer evaporation or vapor pressure deficit. Based on measurements of the water temperature and estimated thermodynamic conditions, he determined that droplet evaporation in the atmosphere (Q_{ea}) should not exceed about 2% of Q_s and that a large part of the measured evaporation losses was evaporation from the catch container itself. Frost and Schwalen (1955) reported spray losses up to 45% for extreme conditions (high radiation, high temperature, low humidity) in Arizona. Kraus (1966) using mass measurements with lysimeters found similar results in Israel for spray evaporation to those of Frost and Schwalen (1955). Mather (1950) computed spray evaporation losses by vapor profile techniques upwind and downwind (includes evaporation from the soil and vegetation) from two types of sprinkler systems of 12% in New Jersey. Till (1957) proposed that the electrical conductivity increase of the sprinkled water would directly indicate the amount of evaporation. He measured a mean evaporation loss of 1.5% from several tests in Australia. Wiser et al. (1961) concluded that the spray evaporation rate would be similar to that of a *free water surface* and independent of the application rate. Inoue and Jayasinghe (1962) estimated sprinkler spray evaporation losses to be approximately 6% based on measurements of droplet size distributions. Inoue (1963) showed spray losses increasing with wind speed; evaporation losses were 11% at wind speeds of 5 m/s (11 mph). Sternberg (1967) using weighing lysimeters to measure Q_{fs} and Q_{si} reported mean day-time evaporation losses of 20% and night-time losses of 14% at Davis, CA during summer conditions. Hermsmeier (1973) measured spray evaporation in the Imperial Valley in California by the electrical conductivity method. He reported evaporation losses of 4.7% for early morning (4:00 a.m. to 8:00 a.m.) conditions and losses up to 24% for afternoon (4:00 p.m. to 8:00 p.m.) conditions. Seginer (1970, 1971 and 1973) proposed a resistance-type model to estimate spray evaporation losses which indicated spray losses would only be a few percent of the application rate. Clark and Finley (1975) reported spray evaporation losses varying from 1% to almost 30% at Bushland, TX. For wind speeds below 4.5 m/s (10 mph), spray evaporation was correlated to vapor pressure deficit and wind speed similarly to Frost and Schwalen (1955). For wind speeds above 4.5 m/s (10 mph), the spray evaporation loss increased exponentially with wind speed. Lyle and Bordovsky (1981) evaluated application losses for LEPA irrigation with nozzles delivering water to individual furrows and using furrow dams to prevent surface runoff in Texas. They reported application losses less than 1%. Lyle and Bordovsky

(1983) reported mean application losses of 24% in 1980 and 14% in 1981 for impact sprinklers without furrow dams and 23% in 1980 and 10% in 1982 with furrow dams (less runoff). They reported mean application losses for sprinkler and LEPA in the two years of 19% and 12%, respectively, for conventional tillage (no furrow dams) and 16% and 1%, respectively, when furrow dams were used. Steiner et al. (1983a) reported mean spray losses for a center pivot sprinkler system of 12% and 16% in two years in Kansas but rather poor correlations with vapor pressure deficit, temperature, or wind. Yazar (1984) measured sprinkler evaporation losses in Nebraska using the electrical conductivity method and reported evaporation losses between 1.5% and 16.8%. He reported exponential relationships between spray evaporation loss and both wind speed and vapor pressure deficit. Kincaid et al. (1986) showed increased spray evaporation with increased elevation of spray nozzles above the ground and increased evaporative loss with increased nozzle pressure from measurement in Idaho. Low elevation spray nozzles [elevation < 2 m (6.5 ft)] had a mean spray evaporation loss of 2%. Higher elevated nozzles [elevation > 3 m (10 ft)] had mean spray losses of 8%. Impact sprinklers at 5-m (16 ft) elevation had a mean spray loss of 12%. Kincaid (1989) developed procedures to measure individual droplet evaporation with differing diameters and presented data on droplet evaporation as influenced by droplet diameter, wind speed, and environmental conditions (air temperature and vapor pressure). Kohl et al. (1987) used potassium as a chemical tracer to measure spray evaporation losses from low-pressure sprinklers in South Dakota. They measured spray evaporation losses between 0.4 and 1.4%, and found excellent correspondence between their measured rates and evaporation rates predicted using the method of Kinzer and Gunn (1951).

Wet Foliage Evapotranspiration

Water intercepted by the crop will evaporate during the irrigation and continue evaporating following completion of the irrigation until the foliage is dry. Generally, this evaporation loss is discussed in terms of the *net evaporation loss*, which accounts for the reduction in transpiration during the same time period. Christiansen (1942) estimated that evapotranspiration rates from wetted foliage should be similar to evaporation from *free water* (open pan, etc.). Burgy and Pomeroy (1958), Frost and Schwalen (1960), McMillan and Burgy (1960), Frost (1963), McIlroy and Angus (1964), Ritjema (1965), Seginer (1967), and Heermann and Shull (1976) found similar evapotranspiration rates for wetted crops and dry crops (but with non-limiting soil water) crops. However, for taller crops, like orchards or forests, wetted foliage has been reported to have much greater evapotranspiration rates than dry foliage [Stewart (1977), Pearce et al. (1980), and Larsson (1981)]. Waggoner et al. (1969) reported short-term evaporation rates of wetted corn (LAI was 5.3) over 2.5 times that of a dry corn canopy both being measured by weighing lysimeters. Differences greater than 500% were noted when the dry canopy was slightly water stressed (stomata partially closed). They also showed that the effect lasted only a short time (less than 20 min) during typical summertime conditions in Connecticut until the canopy dried and the evapotranspiration rates became the same. McNaughton (1981) presented a theoretical equation to estimate the net interception losses (gross wet-foliage evapotranspiration less dry-foliage evapotranspiration) which showed the importance of the crop canopy resistance, particularly the ratio of canopy resistance to the aerodynamic resistance, as well as the dry-foliage evapotranspiration rate. For most conditions, his equation would predict wetted transpiration would exceed non-wetted (dry) transpiration by about 10%.

Sprinkling Effects on Microclimate

Mather (1950) indicated that downwind evapotranspiration could be reduced due to the microclimatic modification induced by sprinkling. Kraus (1966) reported reduced evapotranspiration from upwind sprinkling. Pair et al. (1969) found that sprinkled water essentially arrived at the ground (or crop) at the wet-bulb temperature. Thus, any atmospheric modification must be almost adiabatic since the atmospheric wet-bulb temperature will not change very much regardless of the irrigation water temperature. Robinson (1970) reported major microclimate differences for two alfalfa fields [each 2.8 ha (7 ac) in area], one that was sprinkler irrigated (solid-set system) and the other that was flood irrigated. Consistent reductions were noted in air temperature at 1.2-m (4 ft) for the sprinkled field. Vapor pressure was increased 1.16 kPa (0.342 in Hg) at the 0.3-m (1 ft) elevation in the sprinkled field and 0.49 kPa (0.145 in Hg) at the same elevation in the flooded field. Kohl and Wright (1974) predicted air temperature reductions of 1.0 °C (1.8 °F) and 0.7 °C (1.3 °F) and vapor pressure increases of 0.6 kPa (0.018 in Hg) and 0.4 kPa (0.012 in Hg) for wind speeds of 2 and 3 m/s (4.5 and 6.7 mph), respectively, for typical conditions in Idaho. However, measurements of air temperature and vapor pressure profiles downwind of a sprinkler lateral in an alfalfa field in Idaho showed minor effects on the microclimate downwind from the sprinkler. They reported only a small reduction in air temperature, less than 0.5 °C (0.9 °F), near the crop surface 30-m (100 ft) from the lateral. Longley et al. (1983) found much greater microclimate changes downwind from a spray lateral in Idaho with corresponding decreases in evapotranspiration from various crops grown in pots and moved to the field. Steiner et al. (1983b) measured minor changes in the microclimate of corn fields in Kansas irrigated by surface and center-pivot sprinkler methods. However, significant reductions in leaf temperatures were found for the sprinkler irrigated field compared to the surface irrigated field, which they observed could be partially due to the difference in the irrigation frequency used for the two methods.

Models of Sprinkler Efficiency

Westerman (1976a) developed a simulation model of the energy balance of a leaf which was partially wet (i.e. water droplets on the leaf) and verified the model with laboratory measurements. Their measurements showed leaf temperature decreases of 4 to 5 °C (7 to 9 °F) within 5 to 30 minutes of the leaf wetting. They determined that air temperature and humidity had as large an effect on the model results as many other parameters tested for sensitivity (Westerman et al. 1976b). Edling (1985) simulated evaporation and application distribution of low-pressure spray nozzles. He showed an exponential increase in droplet evaporation as the droplet diameter decreased below 1 mm (0.04 in.) and linear increases in evaporation with increased nozzle elevation above the ground. Silva and James (1988a) adapted the Particle-Source-Cell model of Crowe et al. (1977) and Crowe and Sharma (1981) to simulate the dynamics of sprinkler irrigation. Their model required input data from field measurements to determine the initial trajectory angles for each discrete droplet size. They found good agreement between the model and measured data (Silva and James, 1988b) for predictions of droplet and spray evaporation, except when the water temperature was high. Predictions of the microclimatic influence were not evaluated. Thompson et al. (1986) developed a sprinkler energy dynamics model and coupled it to a crop-environment model (Norman and Campbell, 1983). Their model estimated canopy evaporation for a corn crop to increase [by about 0.2 mm/hr (0.008 in/hr) over the dry crop evapotranspiration (transpiration and soil water evaporation) rate. Thompson et al. (1988) used their model to simulate application losses for a corn crop for high- and medium-pressure impact sprinklers, spray nozzles located on top of a center-pivot pipeline and on drop tubes, and drag tubes. They found for 22 °C (72 °F) water temperatures and for the environmental conditions simulated, the impact sprinklers increased the daily evapotranspiration losses by 57% compared to the same conditions without irrigation, but only 18.8% of the applied 25.4 mm (1.0 in) water was *effectively* lost. *Effective loss* was the simulated irrigated losses for soil evaporation, canopy evaporation, canopy transpiration, and droplet evaporation less the soil evaporation and canopy transpiration for the non-irrigated simulation. When the simulated water temperature was reduced to 13.5 °C (56 °F), the effective losses reduced to 18.3% due mainly to small reductions in the simulated canopy and droplet evaporation losses. The low-pressure spray nozzle systems had simulated effective losses of 16.2% and smaller canopy and droplet evaporation losses than the sprinklers. They simulated drag tube irrigation which had effective losses of only 13.5% because water was not sprayed into the air or onto the crop canopy.

PROCEDURES

This study was conducted at the USDA-ARS research laboratory at Bushland, TX (35°-11' N. lat; 102°-06' W. long.; 1,170 m elev.). Weighing lysimeters (Marek et al., 1988) containing monoliths of Pullman clay loam soil (Schneider et al., 1988) were used. Each lysimeter was 3 m (10 ft) by 3 m in surface area and 2.3-m (8 ft) deep. Each lysimeter is centered in a 5-ha (11 ac) field. The evapotranspiration (ET) precision of the lysimeters is about 0.05 mm (0.002 in) or better (Howell et al., 1987). Associated micrometeorological measurements of air temperature, vapor pressure, and wind speed profiles and surface radiation balance are measured at each lysimeter along with routine meteorological measurements from a nearby weather station (Dusek et al., 1987). The lysimeter and field energy balance instrumentation is sampled at 1 hz and averaged for 5 min. The 5-min means are composited into 30-min means.

Transpiration was measured by the heat balance method (Baker and van Bavel, 1987) on selected plants in each lysimeter in 1989 and 1990. Between 3 and 5 individual plants were measured using Dynamax Inc.[2/] sap flux gauges (total plant transpiration). Total transpiration was estimated from the product of the mean

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[2/] Mention of a trade name or product does not constitute a recommendation of endorsement for use by the U.S. Department of Agriculture.

measured plant transpiration and the mean lysimeter plant density (plants/m^2).

The lysimeter field is irrigated with a 450-m (1,480 ft) long Lindsay electrically powered, lateral-move sprinkler system which can irrigated 2 lysimeter fields (north-south) simultaneously. The system has 10 spans, 168 mm (6-5/8 in) OD pipeline, end-cable guidance, and end-feed hose supply. Water is supplied to the system by an electrically powered centrifugal pump from a nearby surface regulating reservoir. The surface regulating reservoir is maintained by several irrigation wells located on the research farm. Essentially, both ends of the lateral-move sprinkler operate for the selected time determined by the system timer (1 min repeating cycle). Interior tower alignment is controlled by microswitches activated by taut alignment cables on each tower. At 100% timer setting (full speed), the speed of the control towers is about 2 m/min (7 ft/min). The interior towers are geared for 43% faster ground speed to maintain alignment. The system is equipped with impact sprinklers, low-pressure spray nozzles, and LEPA applicators. Senninger 6° impact sprinklers are spaced 6 m (20 ft) along the pipeline at a mean elevation of 4.3 m (14 ft). Nozzle diameters were 5.8 mm (29/128 in) in 1987 and 6.7 mm (17/64 in) thereafter, respectively. Senninger 360° spray nozzles with medium-grooved spray plates are spaced 1.5 m (5 ft) along the pipeline at a mean elevation of 1.5 m above the ground by gooseneck drop pipes from the mainline. The nozzle diameter was 2.8 mm (7/64 in) in 1987 and 3.2 mm (1/8 in) thereafter. Rainbird LEPA applicators (without nozzles) are connected to the Senninger spray heads with Senninger convertible adapters (the spray plate is removed and the adapter clips onto the nozzle) and discharge water at about 0.3 m (1 ft) above the ground. The field was furrow diked at 1.5-m (5 ft) intervals to store the LEPA applied water as well as any seasonal rainfall. The LEPA irrigations were applied to alternate furrows [1.5 m (5 ft) spacing; i.e, 2 rows between LEPA drops] as is widely practiced in the Texas High Plains. The pressure at the inlet tower was set to 220 kPa (32 psi) in 1987 and 240 kPa (34 psi) after 1987 for each irrigation. In 1987, the impact sprinkler application rate was approximately 4.0 L min^{-1} m^{-1} (0.32 gpm/ft; flow rate per unit lateral length) while the spray and LEPA application rate was approximately 5.2 L min^{-1} m^{-1} (0.42 gpm/ft). In 1988, the system was renozzled to increase the application rates to approximately 6.0 L min^{-1} m^{-1} (0.48 gpm/ft) for the impact sprinklers and 6.4 L min^{-1} m^{-1} (0.52 gpm/ft) for the spray and LEPA systems. The gross application (in mm or L/m^2) can be determined by dividing the application rate (in L min^{-1} m^{-1}) by the mean system speed (in m/min). Water to the system was metered by a Hersey propeller water meter (6 in model ML-12). Water pressure (Omega Engr. Inc., model PX302 strain gage pressure transducer), water flow rate (Hersey Prod. Inc., 6 in propeller meter model ML-12 with pulse output), water temperature (copper-constantan thermocouple), and ground speed (revolving wheel with microswitch contacts on the alignment cable) was measured at the control tower with a data logger (Campbell Scientific, Inc., CR-21X) in 1989 and thereafter.

During 1987, three large catch cans located near each lysimeter were used to measure the water application amounts. The catch cans were constructed from 108-L (55 gal) drums [520-mm (20.5 in) diameter, 340-mm (13.4 in) deep] (Schneider et al., 1990). Hook gages were used to manually record the depth of intercepted water, and a thin layer of diesel oil was used to minimize evaporation losses from the catch pans. In 1989, 200-mm (8 in) diameter tipping bucket rain gages (Sierra Misco, Inc., model 2501) [0.25 mm/tip (0.01 in/tip)] were used to measure the irrigation applications for the sprinkler methods. The LEPA application amount was estimated by measuring the time that the bubblers were over each lysimeter and calibrated flow rates for each LEPA bubbler.

Grain sorghum (DeKalb 41y) was grown in 1987 and 1988 and corn (Pioneer 3124) was grown in 1989 and 1990. The grain sorghum crops were grown on the two west weighing lysimeter fields, and the corn was grown on the two east lysimeter fields (Marek et al., 1988). Various experiments were conducted each year comparing the different sprinkler application methods. In most years, several irrigations were applied using different sprinkler methods (paired tests) on alternating lysimeter fields. In 1989 and 1990, several irrigations were applied to individual lysimeters to compare the ET during irrigation with ET from a *dry* crop.

RESULTS AND DISCUSSION

Our research on sprinkler irrigation efficiency has indicated several problems with methodology that has impacted our results: 1) ET during the sprinkling depends on the resolution accuracy of the gauges used to measure precipitation which is difficult to resolve to a 9-m^2 area for the same time; 2) misalignment of the irrigation system can result in the lateral-move system crossing the paired lysimeters at different times; 3) varying system speeds, due to misalignments, as the system moves over the lysimeters; 4) difficulty in accurately *catching* spray applications in cans or rain gauges; 5) plant interception and stem flow into or away from the lysimeter (overhanging plants); 5) difficulty in exactly estimating LEPA applications at the lysimeter walls; and 6) the spatial and temporal averaging necessary with the weighing lysimeters (5-min means and 9-m^2 areas) rather than points (either in time or space). Most measurements are mass measurements from which rates can be computed. Most of the potential water loss rates are extremely close to *noise level* in the measurements. Some of these points will be discussed in greater detail later.

Figure 1 illustrates typical *net* application rates for the three sprinkler methods for the system under study. The graph is 5-min rates of lysimeter mass change. Although, the spray data was for a different day than the sprinkler and LEPA data, essentially only the area under each curve would change (not the peak) as the irrigation amount changed. The impact sprinklers applied water at a peak rate of 18 mm/hr (0.7 in/hr) compared to the much greater application rates for spray at 70 mm/hr (2.8 in/hr) and LEPA at over 120 mm/hr 4.7 (in/hr). Application times varied from 25 min for the LEPA to 45 min for the spray to 100 min for the impact sprinklers for a 25-mm (1 in) application. It should be noted that the LEPA was applying water to only two of the four furrows in the lysimeter so the *effective* application rate to those furrows receiving water would be doubled [240 mm/hr (9.4 in/hr)]. This emphasizes the necessity for surface storage capacity for LEPA to avoid runoff. The low-pressure spray may also require some type of surface management to control runoff. Comparing the sprinkler to the spray method, the much greater time for the application should result in greater canopy evaporation losses for the sprinkled crop. Assuming that both methods result in similar canopy water interception at the end of the irrigation, the canopy evaporation of both

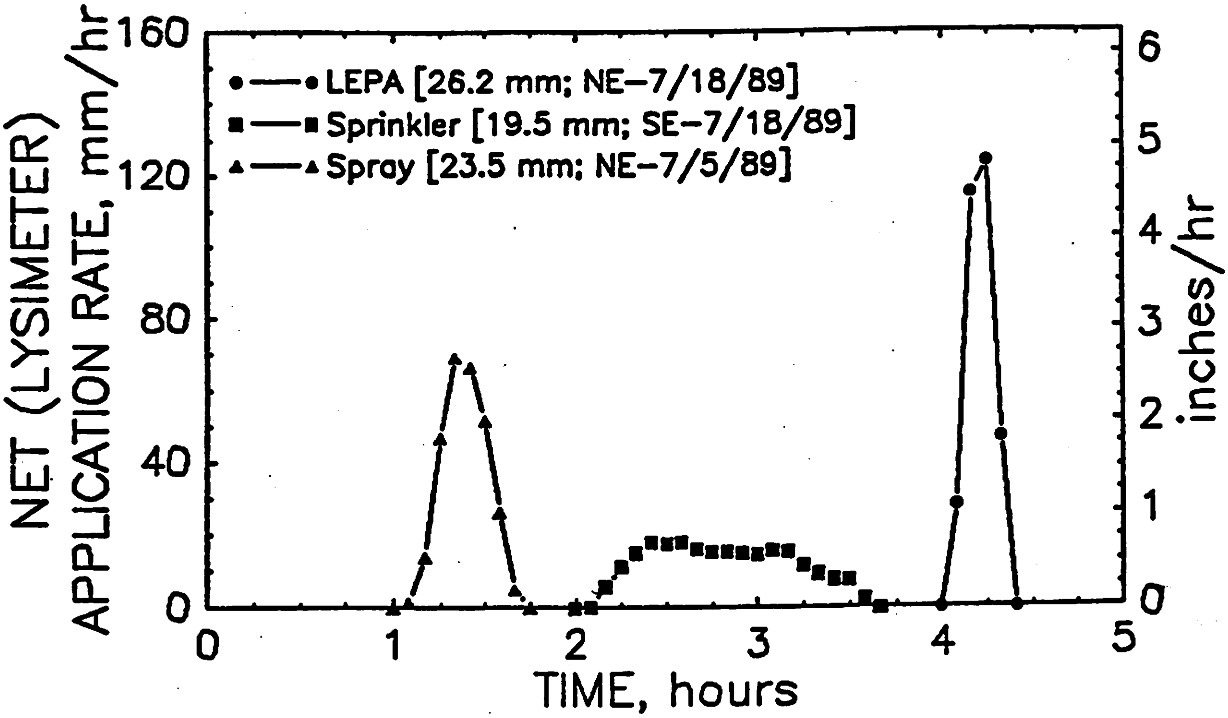

Figure 1. **Comparison of *net* application rates measured using weighing lysimeters for impact sprinklers, spray nozzles, and LEPA methods.**

methods following the irrigation until the canopy is dry should be similar. Since the sprinkler and spray methods wet the entire soil surface, they should be expected to have greater soil water evaporation than LEPA, which only wets about 40 to 60% of the soil surface area. However, since water may remain ponded in the furrows with LEPA for a long time (up to several hours or longer), the differences in soil water evaporation may not be very great. For the spray and sprinkler methods, the soil water evaporation losses should be similar (the spray should be slightly less by the amount of wet soil evaporation that occurs under the sprinkler until the soil surface under the spray method becomes wetted, which would be about 20 to 30 min for this case).

Several irrigations were applied to only one of the paired lysimeters with other remaining dry. Figure 2 shows an example for August 3-5, 1989 when the LAI was 4.5 for the corn. For this irrigation the SE lysimeter was not irrigated while the NE lysimeter was irrigated on Aug. 4 with the system moving from east to west. Several data points for both the NE and SE lysimeter were omitted on Aug. 3 due to personnel interferences in moving stem flow gauges; however, the data after 1400 is relatively free from interferences. This graph shows the 30-min ET rates illustrating the following points: 1) similar ET rates for the two lysimeter on Aug. 3 and 4 before the irrigation was applied (mid-night to beginning of irrigation, the NE lysimeter had used 5.8 mm and the SE lysimeter had used 5.9 mm); 2) slightly greater ET rates for the irrigated lysimeter compared to the dry lysimeter on the afternoon of Aug. 4 following the irrigation; 3) by 1430 (CST) on Aug. 4 (about an

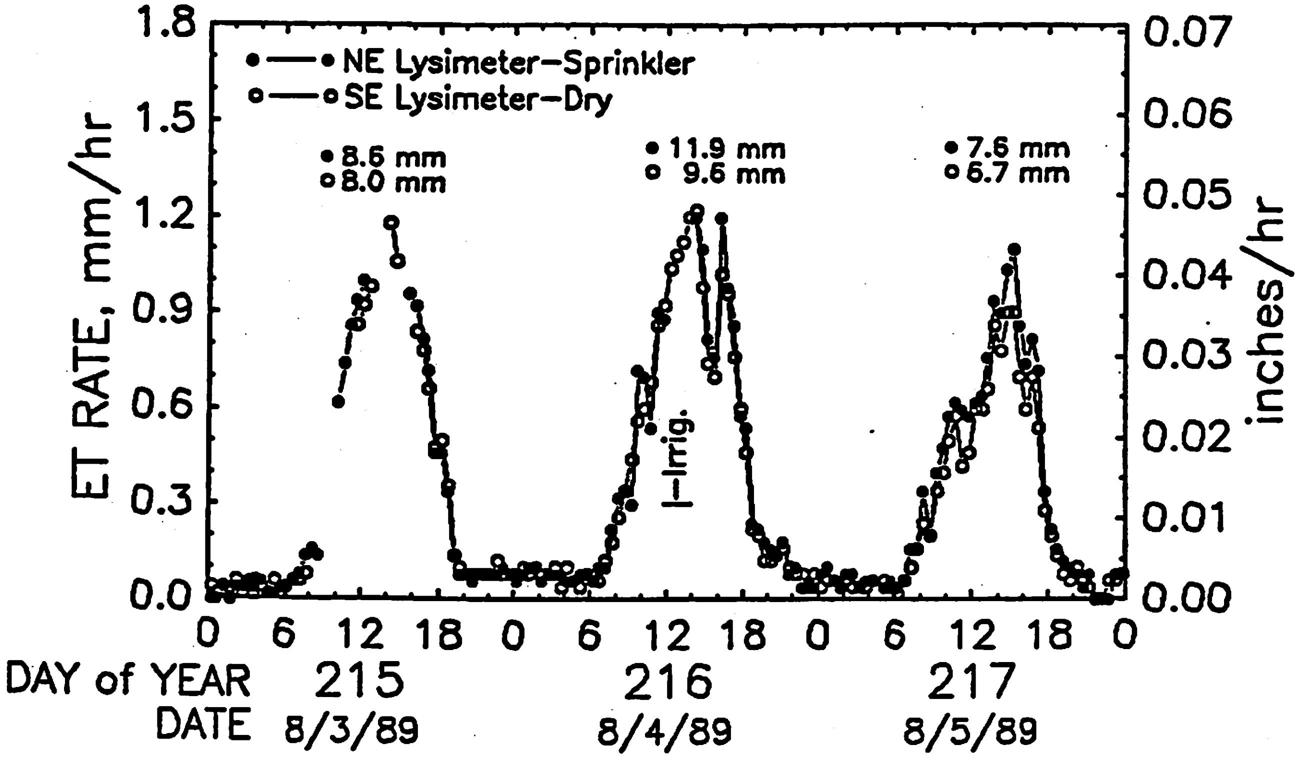

Figure 2. ET rates (30-min data) showing a comparison for a non-irrigated lysimeter (SE) and a sprinkler irrigated lysimeter (NE) on Aug. 2-5, 1989.

hour following completion of the irrigation), the two ET rates were essentially the same (from 1430 until the irrigation on the field was completed, the NE lysimeter used 4.4 mm while the dry SE lysimeter used 4.2 mm); 4) the ET rates for the irrigated lysimeter remained slightly above the dry lysimeter during the evening and night when soil water evaporation should dominate the water use; and 5) the ET rates were essentially the same the following morning (Aug. 5) until mid-day (presumably the stomatal conductance on the dry lysimeter may have decreased slightly due to the environmental conditions or slight water stress). The total ET for Aug. 5 was 7.6 mm for the irrigated lysimeter (NE) and 6.7 mm for the dry lysimeter (SE) about the same ratio as on Aug. 3.

Figure 3 shows a comparison of LEPA and sprinkler methods on July 18, 1989 when the LAI was about 4.8. The top graph in Fig. 3 shows the ET rates (15-min data) before and after sprinkling illustrating relatively close agreement between the two lysimeters. The middle graph (Fig. 3) shows the mass change (5-min data) for the two lysimeters. The LEPA lysimeter net catch was 26.2 mm while the sprinkler lysimeter net catch was 19.5 mm. Since the LEPA system has a larger application rate, the net ratio of the catches for the LEPA/Sprinkler was 1.23 indicating that the LEPA lysimeter caught 23% more of the water applied. The bottom graph (Fig. 3) shows the lysimeter net catch rate compared to the rain gauge catch for the sprinkler method and volume calculated catch for the LEPA. The lysimeter net catch agreed with the estimated LEPA application. The sprinkler data illustrate several points – 1) the difficulty in determining the irrigation application rate with similar precision to

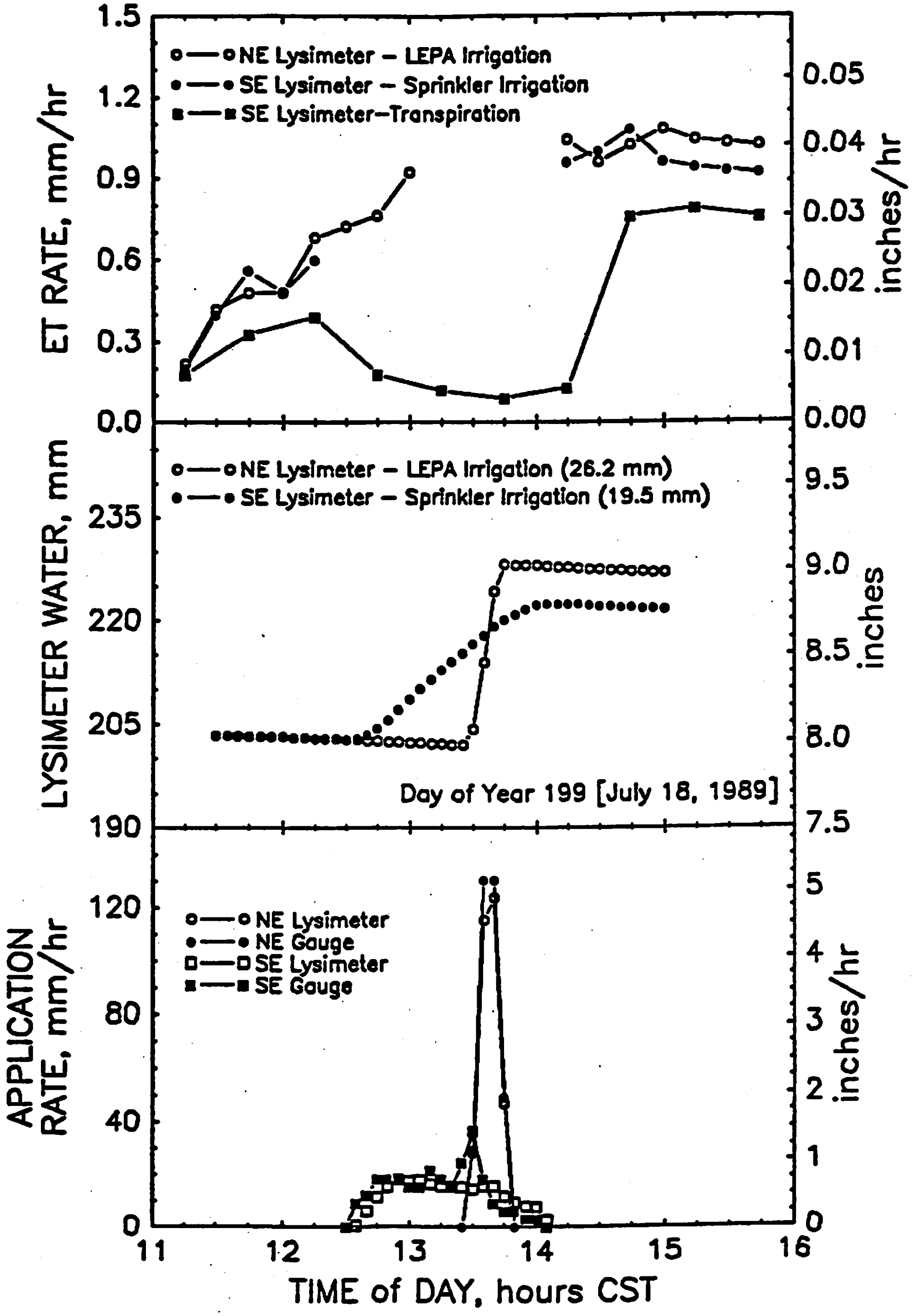

Figure 3. Comparison of sprinkler and LEPA data for July 18, 1989: top graph shows ET and transpiration rates; middle graph shows lysimeter mass (water) changes during irrigation; and bottom graph shows application rates.

the lysimeter precision [0.1 mm (0.004 in) or better] using standard rain gauges, and 2) the problem in equating a point measurement (rain gauge) to an areal measurement (lysimeter). Essentially, the rain gauge and net lysimeter catch indicated application rates about 20 mm/hr (0.8 in/hr). This rain gauge was located east of the lysimeter by about 1.5 m (5 ft) so the rain gauge began catching irrigation water before the lysimeter and stopped catching water before the lysimeter irrigation was completed (unfortunately, the rain gauge directly north of the lysimeter in-line with the irrigation system, which would more nearly reflect the application timing with the lysimeter, did not work properly for this irrigation). The measured transpiration for the sprinkler lysimeter is shown on the top graph. The transpiration data for the LEPA lysimeter was lost due to power supply problems on that date. The transpiration of the sprinkler irrigated corn was about 70% of the total ET during the morning until the foliage was wetted by the irrigation. Immediately upon wetting, the transpiration dropped to less than 10% of total ET during the sprinkling and remained low following completion of the irrigation until the foliage dried. Upon drying, the transpiration rate returned to about 70% of total ET.

Figure 4 shows the ET rates (30-min data) for July 17-19, 1989. Again, several data points were omitted for July 17 due to lysimeter drainage operations and personnel working on instruments (on both July 17 and the morning of July 18). Basically, similar trends were observed as discussed above for Fig. 2. Of particular note, the ET rates were almost identical for the two lysimeters following the irrigations and through the night and the next day (July 19). The increase of 23% in the net catch for the LEPA application compared to the sprinkler application (adjusted by the different gross application rate differences) is due mainly to reduced spray evaporation [possibly, as much as 1 to 2 mm (0.04 to 0.08 in)] and absence of *net* wet canopy evaporation [possibly, as much as 0.5 to 1 mm/hr (0.02 to 0.04 in/hr) depending on prevailing environmental conditions].

Another comparison of LEPA to impact sprinkler irrigation is shown in Fig. 5 for a set of irrigations applied on July 12, 1990 (day of year 193). The corn height was 2.0 m on this day and the leaf area index was 5.0. Some clouds reduced solar radiation during the afternoon just as the sprinkler irrigation was completing (Fig. 5, top). In the morning before the irrigations, transpiration was about 70% of ET for the plants on the NE lysimeter (to be sprinkled) and 76% of ET on the SE lysimeter (to be LEPA irrigated) (Fig. 5). This difference is believed to be due to plant differences than to transpiration differences. Nevertheless, the transpiration rate on the NE lysimeter was greatly reduced by the wetted foliage as soon as the irrigation reached the lysimeter at about 1130 CST as shown in Fig. 5. The transpiration remained low until the foliage dried at about 1445 CST nearly an hour after the irrigation was completed. The transpiration rate on the SE lysimeter dipped slightly at the same time as it was being LEPA irrigated (Fig. 5, bottom), but the transpiration reduction is believed to be related to the reduction in solar radiation at the same time (see Fig. 5, top). The SE lysimeter transpiration tracked the lysimeter ET very closely during the entire day (Fig. 5, bottom).

Figure 6 shows the effect of the sprinkler method on air temperature within and just above the corn canopy on the same date as Fig. 5. Air temperatures within the canopy were reduced from about 24 °C (75 °F) before the irrigation to 21 °C (70 °F)

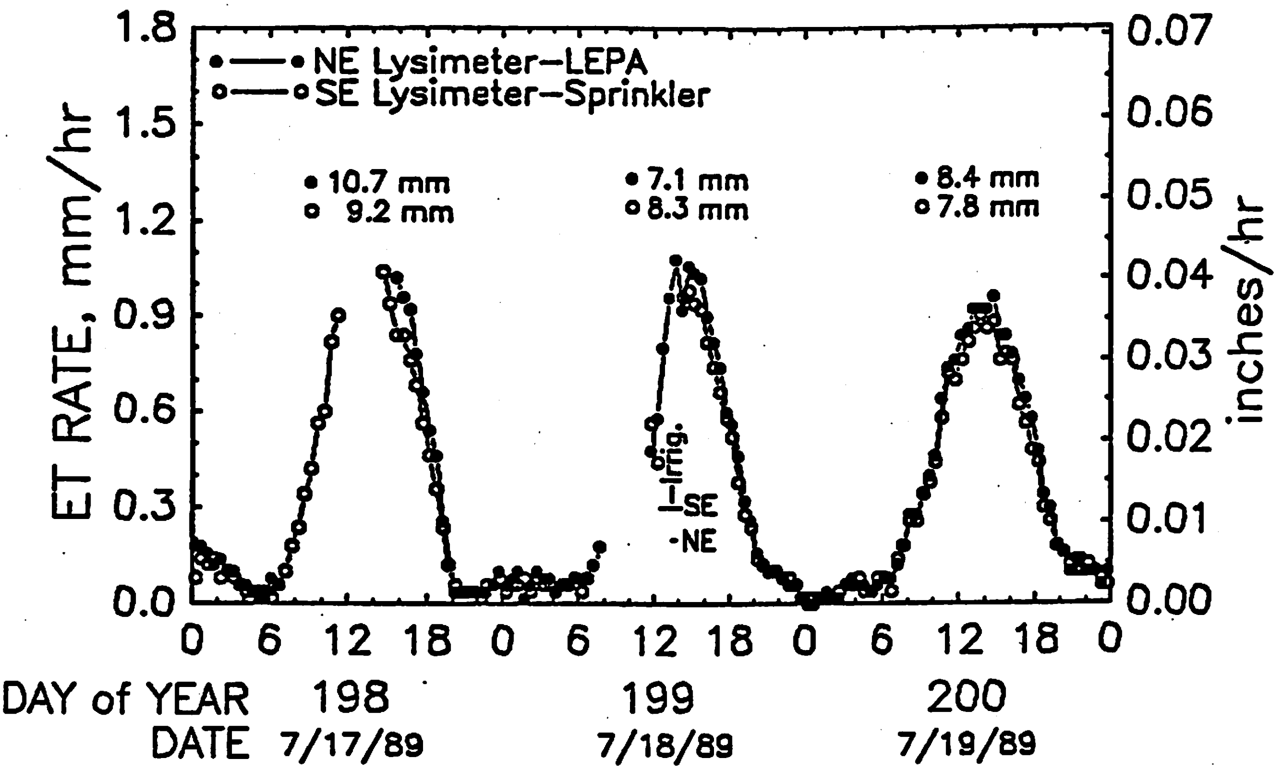

Figure 4. **ET rates (30-min data) showing a comparison for LEPA and sprinkler irrigation measured on July 17-19, 1989.**

during the irrigation. Air temperature at the top of the canopy [2.16-m (7 ft) elevation, crop height of 2.0 m (6.5 ft)] declined slightly during the sprinkler irrigation. The air temperatures within the corn canopy were not greatly affected by the LEPA irrigation. Figure 7 shows the corresponding change in vapor pressure deficit within and just above the canopy for the same time. The vapor pressure deficit within the sprinkled canopy (NE) was greatly reduced during the irrigation while the profile on the LEPA irrigated lysimeter (SE) did not change much during the irrigation. The profiles of air temperature (Fig. 6) and vapor pressure deficit (Fig. 7) were essentially the same at both lysimeter sites both before the irrigations (1000 to 1100 CST) and following the irrigations (1600 to 1800 CST).

Table 1 shows a summary of the irrigation efficiency data for irrigation applications in 1987 and 1989. Data for 1988 and 1990 are still being analyzed. Impact sprinkler irrigation efficiency has ranged from 73 to 93%, while spray nozzle irrigation efficiency ranged from 77 to over 100%. LEPA irrigation application efficiencies ranged from 93 to 100%. Application efficiencies above 100% are believed to be due to more water being intercepted by lysimeter plants than by outside plants hanging over the lysimeter. In 1990, great care was taken to space the plants within the lysimeter and outside the lysimeter exactly the same distance from the lysimeter walls; however, in previous years the plant spacing next to the lysimeter walls was more variable. The partitioning of the measured water losses into spray drift, spray evaporation, and canopy evaporation remains difficult. Our results indicate that spray droplet evaporation (Q_{se}) may be on the order of about 1 to 3% with *net* canopy evaporation (Q_{fe}) losses approaching about 0.5 to 1 mm/hr (0.04 to

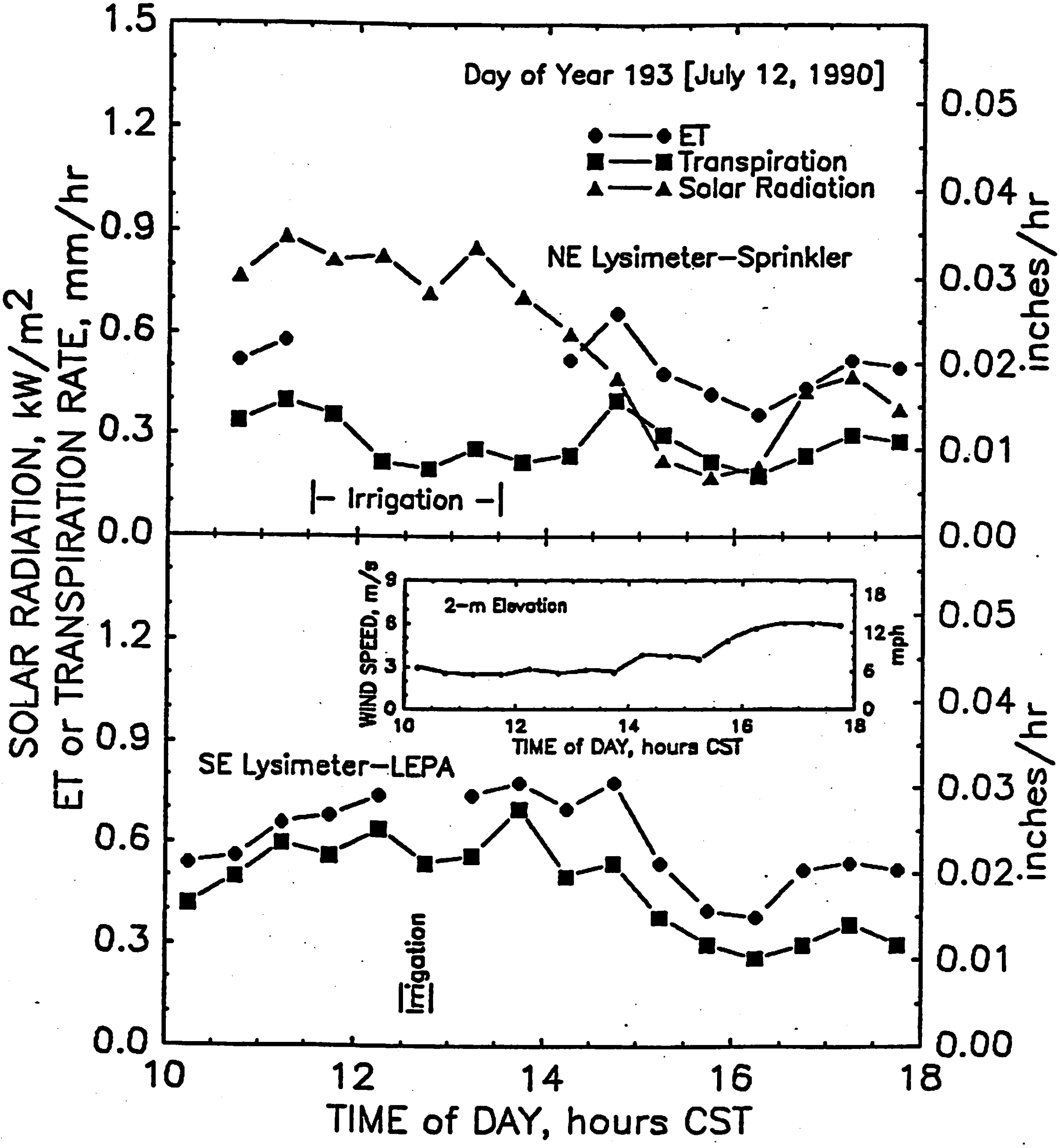

Figure 5. ET and transpiration rates measured on July 12, 1990 during a sprinkler irrigation (NE lysimeter; top) and a LEPA irrigation (SE lysimeter; bottom).

0.08 in/hr) during the irrigation as well as the evaporation of the plant intercepted water (Q_{fs}), which might be as much as 1 to 2 mm (0.04 to 0.08 in) for corn. As an example, for daytime conditions and assuming a two hour sprinkler application time and an application of 25 mm (1 in), we could estimate Q_{ae} as 0.75 mm (0.02 in) (3%

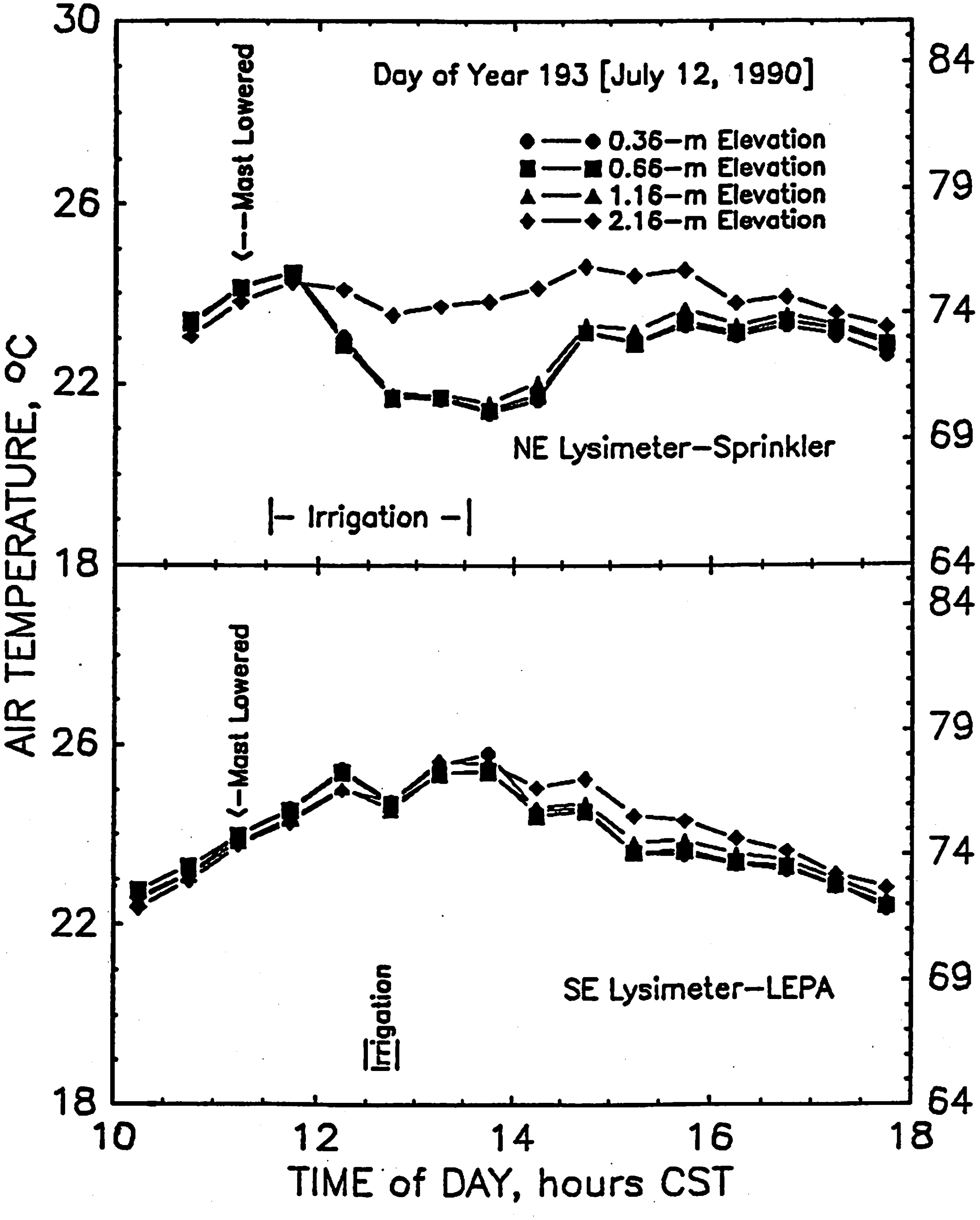

Figure 6. Air temperature profiles measured on July 12, 1990 during a sprinkler irrigation (NE lysimeter; top) and a LEPA irrigation (SE lysimeter; bottom)

of Q_s), Q_{fe} as 2 mm (0.08 in) [1 mm/hr (0.04 in/hr)], and Q_{fi} as 1 mm (0.04 in). Then E_a would be about 85% if Q_{ge} and Q_{ad} are ignored. This estimate for E_a is close to the mean of the impact sprinkler data presented in Table 1. For a spray nozzle example if we assume the same conditions and simply reduce the application

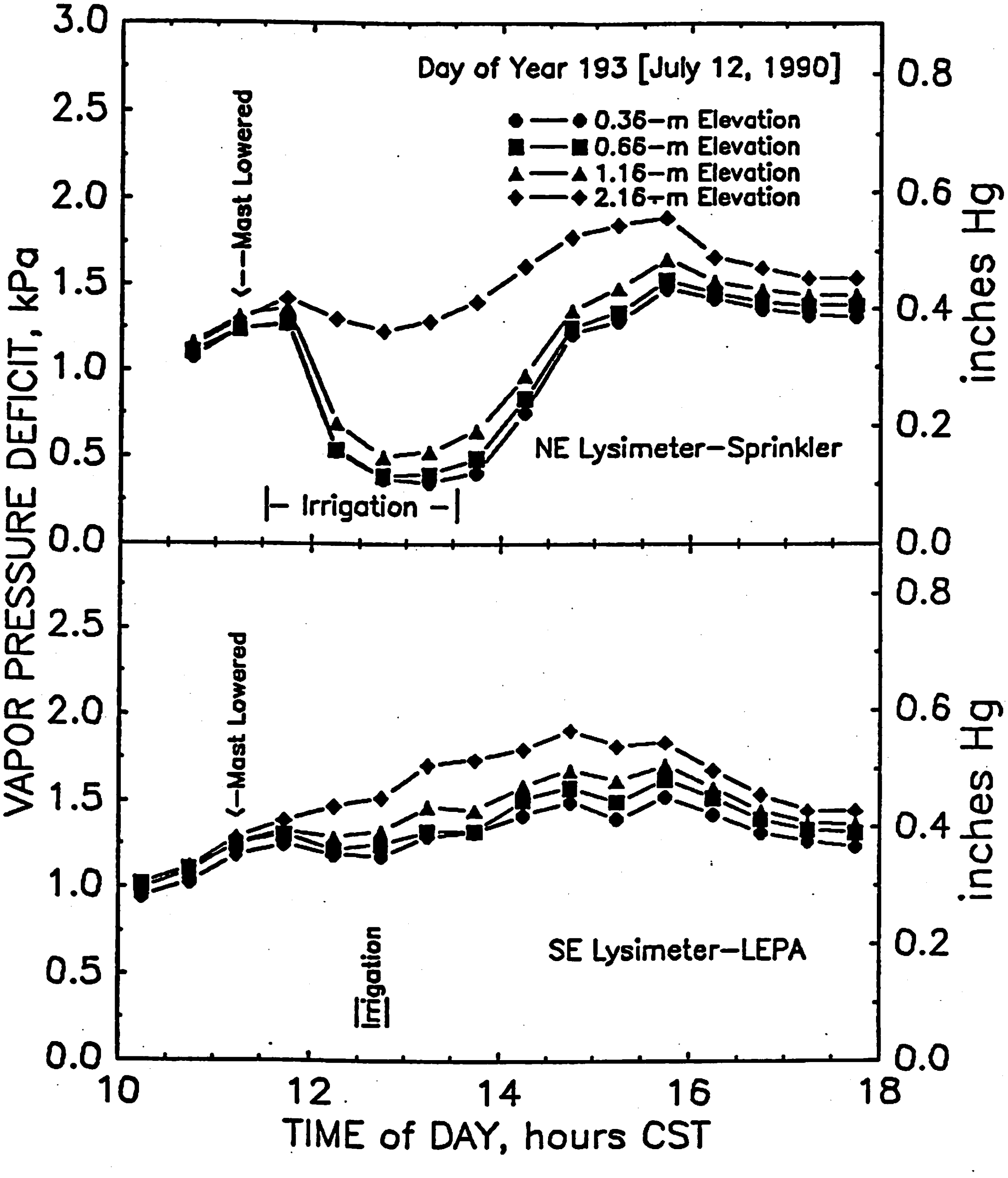

Figure 7. **Vapor pressure deficit profiles measured on July 12, 1990 during a sprinkler irrigation (NE lysimeter; top) and a LEPA irrigation (SE lysimeter; bottom).**

time to 45 min and assume less spray evaporation loss (1%), E_a will be estimated as 92%, again ignoring Q_{ge} and Q_{ae}, which is similar to the trend in the measurements. The E_a for LEPA must be greater than either sprinklers or spray applications (if Q_{gr} is controlled) since Q_{ae}, Q_{fe}, and Q_{fs} are essentially zero leaving only Q_{ge} as the

Table 1. Application depth, catch depth, and sprinkler application efficiency for impact sprinklers, spray nozzles, and LEPA at Bushland, TX determined using weighing lysimeter catch from a lateral-moving sprinkler system.

	IMPACT SPRINKLERS				SPRAY NOZZLES				LEPA			
Date	Lys.	Appl. Depth mm	Catch Depth mm	E_a %	Lys.	Appl. Depth mm	Catch Depth mm	E_a %	Lys.	Appl. Depth mm	Catch Depth mm	E_a %
1987 (Grain Sorghum)												
7/22-24	NW	37	27	73	SW	47	37	79				
7/29-31	SW	49	39	80	NW	54	52	96				
8/21-23	NW	48	41	85	SW	61	47	77				
Avg.				79				84				
1989 (Corn)												
7/5					NE	22	23	104				
					SE	22	22	100				
7/7					NE	29	30	103				
					SE	25	23	92				
7/11	SE	23	19	83	NE	27	28	104				
7/18	SE	25	20	80					NE	26	26	100
8/1	NE	15	11	73					SE	14	13	93
8/18	SE	15	14	93					NE	21	20	95
Avg.				82				101				96

NOTE: To convert mm to inches divide mm by 25.4.

major source of water loss. Under a full canopy, Q_{ge} could be as much as 0.2 to 0.4 mm/hr (0.008 to 0.016 in/hr) (10% to 30% of total ET rates). Thus, estimated LEPA application efficiencies in range of 95 to near 100% certainly would be possible as verified with the measurements *if runoff is assumed to be zero.* Most ofour measurements have been for daytime irrigations. Nighttime losses to spray droplet evaporation should decrease, but *net* foliage evaporation losses will increase since transpiration is negligible at night.

CONCLUSIONS

Sprinkler irrigation methods can be efficient even in harsh environments, such as the Texas High Plains. Measurement of sprinkler irrigation losses, particularly with moving systems, is difficult even under the best of circumstances. Irrigation application methods for moving sprinkler systems were shown to have dramatically different application rates, which directly affect the potential for surface runoff and the type and duration of canopy wetting. The application method did not affect crop ET after the irrigation to any appreciable extent. ET rates following canopy drying approach ET rates for non-irrigated canopies if the unirrigated crop is not under any significant soil water deficit.

The method of sprinkler application greatly affects the partitioning of the water losses. Sprinklers and spray nozzles each have spray droplet evaporation losses, which seem to be in magnitude of 1 to 3%. Sprinklers and spray nozzles result in canopy wetting which increases the evaporation of water from the canopy while reducing transpiration during the wetting. In addition, water intercepted by the canopy evaporates following the irrigation while transpiration will be reduced during this period but not in the same amount. LEPA applications avoid most of these evaporative losses, but because of the extremely high application rate LEPA has to be used with furrow diking or some management methods to enhance infiltration.

Sprinkler irrigation does change the microclimate during the irrigation event. With sprinklers, air temperature and vapor pressure deficit, particularly within the crop canopy, are lowered. LEPA does not greatly alter the crop microclimate.

In the environment of the Texas High Plains and for moving sprinkler systems, we found sprinkler irrigation efficiency to be about 80 to 85% for low-angle, medium-pressure impact sprinklers on top of the pipeline. For medium-pressure, medium-grooved spray nozzles at 1.5 m (5 ft) above the ground, we found irrigation efficiency to be about 85 to 95%. We found LEPA irrigation application efficiency to be about 95 to 100%. For all methods, the elimination of runoff is required to obtain these irrigation application efficiencies. Since the spray and LEPA methods have such high application rates, runoff control may be critical to successful adaptation of this technology which could reduce net water losses by 5 to 20%.

In final conclusion, we still have to agree with Christiansen's remarks made nearly 50 years earlier. But improvements in sprinkler irrigation, particularly the development of center-pivot systems; low-pressure, low-angle impact sprinklers; low-pressure spray nozzles; and LEPA, have improved sprinkler irrigation methods on the Great Plains. These improvements have 1) reduced irrigation water use, 2) stretched available groundwater resources, and 3) improved potential grower profit.

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