

WATER REQUIREMENT OF SUBSURFACE DRIP-IRRIGATED CORN IN NORTHWEST KANSAS

F. R. Lamm, H. L. Manges, L. R. Stone, A. H. Khan, D. H. Rogers

ABSTRACT. *Irrigation development during the last 50 years has led to overdraft in many areas of the large Ogallala aquifer in the central United States. Faced with the decline in irrigated acres, irrigators and water resource personnel are examining many new techniques to conserve this valuable resource. A three-year study (1989 to 1991) was conducted on a Keith silt loam soil (Aridic Argiustoll) in northwest Kansas to determine the water requirement of corn (Zea mays L.) grown using a subsurface drip irrigation (SDI) system. A dryland control and five irrigation treatments, designed to meet from 25 to 125% of calculated evapotranspiration (ET) needs of the crop were examined. Although cumulative evapotranspiration and precipitation were near normal for the three growing seasons, irrigation requirements were higher than normal due to the timing of precipitation and high evapotranspiration periods. Analysis of the seasonal progression of soil water revealed the well-watered treatments (75 to 125% of ET treatments) maintained stable soil water levels above approximately 55 to 60% of field capacity for the 2.4-m soil profile, while the deficit-irrigated treatments (no irrigation to 50% of ET treatments) mined the soil water. Corn yields were highly linearly related to calculated crop water use, producing 0.048 Mg/ha of grain for each millimeter of water used above a threshold of 328 mm. Analysis of the calculated water balance components indicated that careful management of SDI systems can reduce net irrigation needs by nearly 25%, while still maintaining top yields of 12.5 Mg/ha. Most of these water savings can be attributable to minimizing nonbeneficial water balance components such as soil evaporation and long-term drainage. The SDI system is one technology that can make significant improvements in water use efficiency by better managing the water balance components. **Keywords.** Microirrigation, Water use efficiency, Water balance.*

The Ogallala aquifer is one of the largest sources of fresh groundwater in the world, covering parts of six states in the Great Plains. Many areas of irrigated corn production are experiencing overdraft of the aquifer partly because of irrigation. In western Kansas, irrigation accounts for nearly 95% of the total water use. Though occupying a small percentage of the land area, irrigation has a significant effect on total crop production and economic stabilization of the region.

Bucks and Davis (1986) listed a number of potential advantages for drip irrigation. They include increased beneficial use of water, enhanced plant growth and yield, reduced salinity hazard, improved application of fertilizer

and other chemicals, limited weed growth, decreased energy requirements, and improved cultural practices. The first two potential advantages are the most important in ensuring efficient use of the water resource. Phene et al. (1992) listed several characteristics of SDI systems that can contribute to maximizing water use efficiency, including negligible soil evaporation, percolation, and runoff.

Dawood and Hamod (1985) found water use efficiency for trickle-irrigated lima beans to be twice as high as that for furrow- and sprinkler-irrigated beans. Tollefson (1985) reported a 30% average increase in cotton yield with drip irrigation versus furrow irrigation. Sammis (1980) reported higher water use efficiencies for trickle and subsurface irrigation as compared to sprinkler and furrow irrigation for potatoes. These studies emphasize the ability to increase yield or water use efficiency for vegetable and fiber crops. However, the locations of population clusters and processing systems limit the ability of most central Great Plains farmers to be involved in the large-scale production of such crops. Drip irrigation needs to be evaluated for the principal irrigated crop in the region—corn. Corn is a vital, locally grown feed grain for the large cattle feeding industry in the region.

Clark (1979) compared the relative efficiencies of trickle, sprinkler, and furrow irrigation for corn production in Texas. He found water use efficiencies of 0.0140, 0.0119, and 0.0115 Mg/ha-mm with the three respective systems. In a limited study in Italy, Safontas and di Paola (1985) reported yield increases of up to 35% with drip irrigation as compared to sprinkler irrigation for maize. Camp et al. (1989) evaluated drip irrigation for corn production in the southeastern Coastal Plain of the

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United States. They found subsurface drip irrigation required less irrigation water than surface drip irrigation.

The net irrigation requirement for corn in Thomas County of northwest Kansas is 391 mm with 80% chance precipitation (Soil Conservation Service, 1977). However, annual needs vary with climatic conditions. Many of the area irrigators will apply 380 to 460 mm with center pivot sprinklers and 460 to 610 mm with furrow irrigation. Because of its high efficiency, SDI may be able to reduce the amount of applied water to the net requirement.

A three-year study was initiated in 1989 to evaluate subsurface drip-irrigated corn on the silt loam soils in northwest Kansas. Objectives of the study were to determine the water requirement of subsurface drip-irrigated corn through a yield-water use relationship and to compare the irrigation requirements to the typical net irrigation requirements for the area.

PROCEDURES

FIELD STUDY PROCEDURES

The project was conducted at the Kansas State University (KSU) Northwest Research-Extension Center at Colby, Kansas, on a deep, well-drained, loessial Keith silt loam (Aridic Argiustoll). This medium-textured soil, typical of many western Kansas soils, is described in more detail by Bidwell et al. (1980). The 2.4-m soil profile will hold approximately 585 mm of plant available soil water at field capacity as determined from an unpublished drainage study conducted adjacent to this study site in 1990 and 1991. This corresponds to a volumetric soil water content of approximately 0.37 and a profile bulk density of approximately 1.3 gm/cm³.

The climate can be described as semi-arid, with an average annual precipitation of 474 mm and approximate, annual, lake evaporation of 1400 mm. Daily climatic data used in the study were obtained from a weather station located approximately 400 m east of the study site.

The study utilized a SDI system constructed in the spring of 1989 (Lamm et al., 1990). The system has dual-chamber drip tape (emitter spacing – 30 cm) installed at a depth of approximately 40 to 45 cm with a 1.5 m spacing between dripline laterals. The corn was planted so each dripline lateral was centered between two corn rows. Generally, irrigation is not needed to establish summer row crops because of the high probability of precipitation exceeding evapotranspiration (ET) in May and early June.

The 1.2-ha study area was approximately 140 m wide and 90 m long with land slope of approximately 0.5%. Six irrigation levels with three replications in a randomized complete block design were used in the study. Each subplot was 6 m wide × 90 m long, running north to south. This corresponded to eight 76-cm rows with driplines spaced every 1.5 m between corn rows. There was approximately 15 m of bulk area on the east and west edges of the study. The irrigation treatments were as follows: 125% of calculated actual evapotranspiration (AET); 100% of calculated AET (standard treatment); 75% of calculated AET; 50% of calculated AET; 25% of calculated AET; and no irrigation.

The reference evapotranspiration (ET_r) was calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heerman (1974).

The specifics of the ET_r calculations used in this study are fully described by Lamm et al. (1987). Basal crop coefficients (K_{cb}) were generated with equations developed by Kincaid and Heerman (1974) based on work by Jensen (1969) and Jensen et al. (1970, 1971). The basal crop coefficients were calculated for the area by assuming 70 days from emergence to full canopy for corn with physiological maturity at 130 days. This method of calculating AET as the product of K_{cb} and ET_r has been acceptable in past studies at Colby (Lamm and Rogers, 1983, 1985). In constructing the irrigation schedules, no attempt was made to modify AET with respect to soil evaporation losses or soil water availability as outlined by Kincaid and Heerman (1974). Although these parameters do affect AET, they will be considered only in the discussion of water use modeling.

Irrigation was scheduled using a water budget to calculate the root zone depletion with precipitation and irrigation water amounts as deposits and calculated daily corn water use (AET) as a withdrawal. Modification of the individual treatment irrigation schedules to simulate the various regimes was accomplished by multiplying the calculated AET value by 1.25, 1.00, 0.75, 0.50, or 0.25, respectively. If the root-zone depletion became negative, it was reset to zero. Each treatment was irrigated to replace 100% of its own calculated root-zone depletion, when the depletion was within the range of 20 to 35 mm. The root zone depletion was assumed to be zero at crop emergence which is a relatively realistic assumption. However, the entire 2.4-m soil profile would rarely be at field capacity. Irrigation was metered separately onto each plot with commercial, municipal-grade, flow accumulators with an accuracy of ± 1.5%.

Soil water amounts were monitored with a neutron probe in 30-cm increments to a depth of 2.4 m approximately once a week during each crop season. In 1989, the access tube was located in the corn row, resulting in soil water measurements approximately 38 cm from the nearest dripline. In 1990 and 1991, soil water measurements were made at three perpendicular distances from the dripline, 5, 38, and 76 cm. The irrigation schedules were not updated with respect to the measured soil water. The soil water data was used to determine how well the different schedules performed.

A ridge-till system was used in corn production with two corn rows, 76 cm apart, grown on a 1.5-m bed. The soil had been fertilized with 240 kg/ha of broadcast-applied nitrogen and 45 kg/ha of phosphorus prior to fall bedding (1988) with an Orthman Tri-Level bedder. In 1989, the corn (Garst brand 8388) was planted on 4 May at a rate 65,500 seeds/ha into bare soil with very little residue. After the 1989 corn harvest, the stalks were chopped and the soil was fertilized with 290 kg/ha of nitrogen and 55 kg/ha phosphorus broadcast-applied as a solution. No tillage was performed in 1990 prior to planting of the corn (Pioneer brand 3162) at a rate of 70,900 seeds/ha on 30 April. The interrows adjacent to the bed were corrugated at layby to a depth of approximately 20 cm in both 1989 and 1990. Furrow dams were constructed in the corrugated interrows to trap rainfall runoff and increase the efficiency of water use. Tractor traffic was confined to the corrugated rows. Following the 1990 corn harvest, the stalks were chopped and the soil

was fertilized with 260 kg/ha of nitrogen and 45 kg/ha phosphorus broadcast-applied as a solution. The beds were reshaped with a border disk which disked out the corn root clumps and heaped the residue with soil at the center of the bed. This allowed for some overwinter decay of the residue and incorporation of the fertilizer. In the spring, the beds were slightly flattened to aid in planting. Pioneer brand 3162 corn was planted at a rate of 72,600 seeds/ha on 7 May 1991. Heavy residue levels in the furrows coupled with wet soils prevented the building of furrow dams in 1991. The corn emerged on 15 May each year.

An approximately 6 m length of one corn row from each plot was hand harvested in the fall (25 September 1989, 19 September 1990, and 20 September 1991) for yield determination.

WATER USE MODEL DEVELOPMENT

An effort was made to separate the total water deposits and withdrawals in the field water supply into the various components, so that a more realistic comparison of all six treatments could be made. To make the comparisons, the components must be measured or calculated. The measured components in the study are precipitation, irrigation, and available soil water. Thus, transpiration, soil evaporation, runoff, and long-term drainage must be calculated.

Evaporation (E) and transpiration (T), though separate components, are usually calculated as the total quantity ET because of the difficulties in accurately making separate estimates. Such estimates would be highly desirable because T translates into crop yield and E does not. However, in this study, E is probably relatively constant across all treatments. The majority of the soil evaporation losses would have occurred early in the season when the plants were small and water stress levels were low. Additional evaporation losses may have occurred following precipitation events but would probably be relatively similar among treatments. The evaporation losses from irrigation would probably be negligible because irrigation was applied 40 to 45 cm below the soil surface. In summary, only the portion of soil evaporation inherently included in the AET calculation was considered in the water use model.

The availability of soil water modifies the amount of water actually used by the crop. AET was modified by K_a , the dimensionless soil water availability coefficient, to give:

$$AET_{asw} = K_a * AET \quad (1)$$

where the AET corrected for soil water availability, AET_{asw} and AET are given in millimeters per day.

K_a was calculated as:

$$K_a = 1 \text{ if ASW is } \geq [B * (MASW)] \quad (2a)$$

$$K_a = [ASW / (B * (MASW))] \text{ if ASW is } < [B * (MASW)] \quad (2b)$$

as outlined by Hanks (1974), where ASW and MASW are the available and maximum available soil water amounts in the soil profile and B is a dimensionless coefficient. A value of 0.6 was used for B for the 240-cm soil profile in this report. Hanks (1974) proposed a value of 0.5 for B. A

similar value was used by Amos et al. (1989) for corn production on silt loams in eastern Kansas. Ritchie (1973) proposed that soil water in field situations is equally available until 80% of the soil water supply is exhausted, which would correspond to a B value of 0.2. However, in this study, these lower values of B resulted in higher calculated water use than measured in the field for the drier treatments. Intuitively, one would suspect that K_a can vary with soil type, soil profile depth, potential evapotranspiration rate, crop, and other parameters. Indeed, the literature has several proposals for the functional shape and the specific constants used to calculate K_a (Howell, 1979).

Long-term drainage (PERC) from the soil profile under the various irrigation treatments was calculated using an empirical equation for the Keith silt loam:

$$PERC = -50.0 * (W/946)^{19.94} \quad (3)$$

where W is the total water content in millimeters for the 2.4-m soil profile, and PERC is the long-term drainage rate in millimeters per day. This equation was derived for this soil type from data obtained from an unpublished drainage study conducted in 1990 and 1991 immediately adjacent to this site. The procedure to characterize drainage rates from the soil using equations of this type was thoroughly discussed by Miller and Aarstad (1974).

The various water balance components were accumulated over time by daily modeling of AET_{asw} , PERC, and ASW with the additions of the measured values of irrigation (IRR), precipitation (RAIN), assuming the initial ASW measured with the neutron probe. The calculated water balance (sum of AET_{asw} and PERC) was compared to the measured water balance (sum of IRR, RAIN, and the change in soil water measurements) for the June to September periods for each of the three years. It should be noted that the measured water balance would inadvertently include any runoff that occurred. However, runoff was probably negligible in these three years because of the low slope, furrow dams, and residue management.

RESULTS AND DISCUSSION

CLIMATIC CONDITIONS

Seasonal precipitation (May to September) varied from a high of 403 mm in 1989 to near normal levels of 309 and 332 mm in 1990 and 1991, respectively (fig. 1). However, in all three years, May precipitation was significantly greater than the 99-year mean. The corn emerged on 15 May in each year, so crop water use from the available May precipitation amounts was low. In each year, one or more of the principal growth months, June, July, or August had less than normal precipitation.

The cumulative calculated evapotranspiration (AET as calculated by $K_{cb} * ET_r$) was near the 20-year mean for all three years of the study (fig. 2). However, in 1990, the progression of cumulative AET was significantly higher than normal from mid-June to mid-July, a period characterized by windy conditions and several days with temperatures exceeding 40° C.

Although May through September precipitation was higher than normal in 1989 (fig. 1) and AET was near normal (fig. 2), a relatively dry period during the critical growth period from mid-July through mid-August resulted

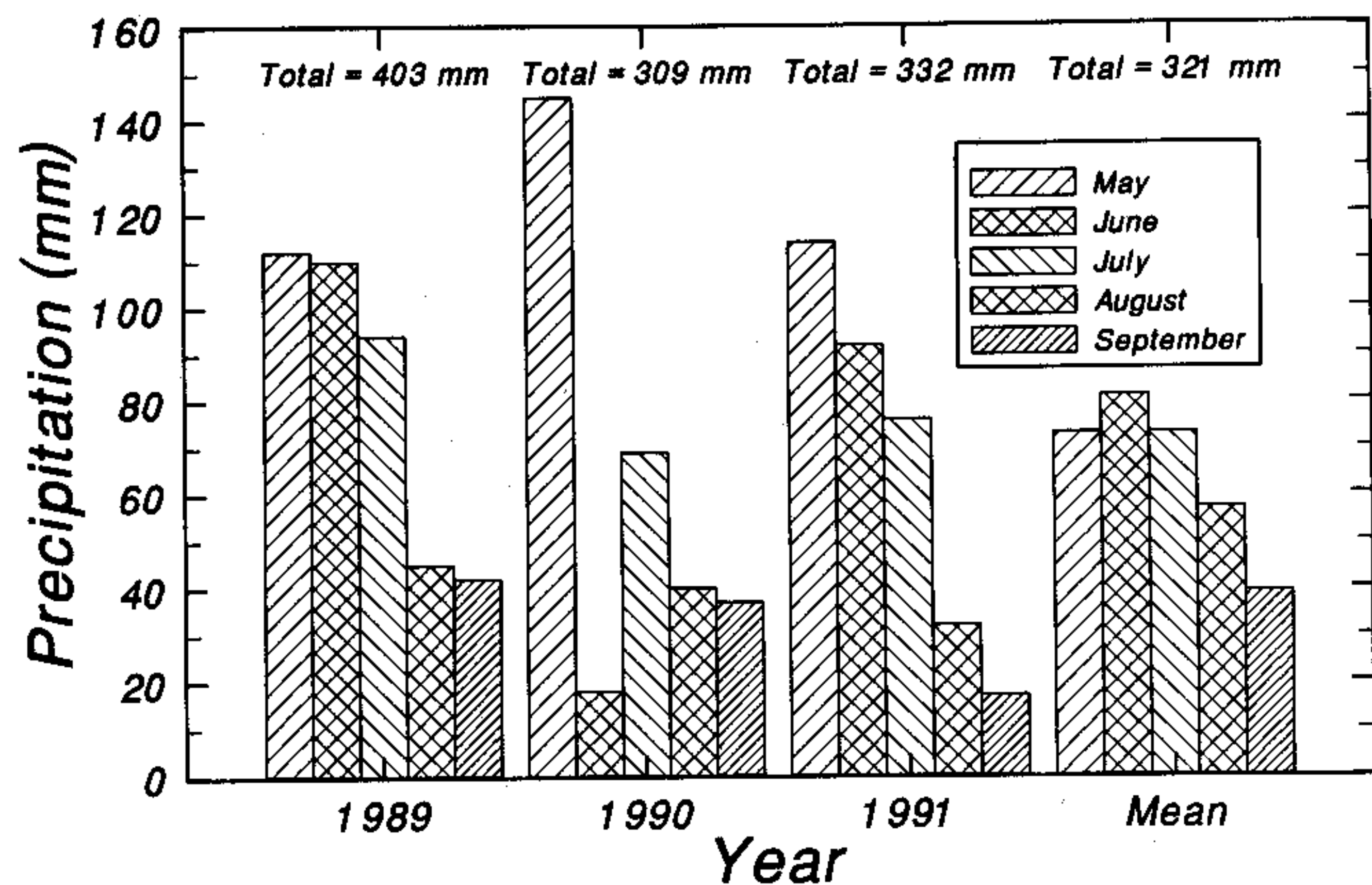


Figure 1—Growing season precipitation recorded at Colby, Kans. (1989 to 1991).

in a just slightly above-normal irrigation requirement for the standard 1.00*ET treatment (table 1). The normal net irrigation requirement is 391 mm based on an 80% chance precipitation. A severe hail storm on 30 June 1989 reduced crop yields.

Overall irrigation requirements were highest in 1990, with the standard 1.00*ET treatment exceeding the normal net requirement by 65 mm. The extremely high AET from mid-June to mid-July coupled with low precipitation resulted in irrigation needs that the majority of irrigation systems in northwest Kansas could not match during the time period. Fortunately deep soils with available water buffered the corn from excessive water stress during the period.

The crop year 1991 was characterized by slightly above-normal precipitation in June and July but appreciably below-normal precipitation in August and September. The irrigation requirement in 1991 was approximately 35 mm above normal.

The climatic conditions for the three years can be summarized overall as being near normal. However, the irrigation requirements were generally above normal because of the timing of periods of high ET and low precipitation. Of course, the timing of irrigation events with respect to when precipitation occurs can also affect the overall amount of irrigation applied.

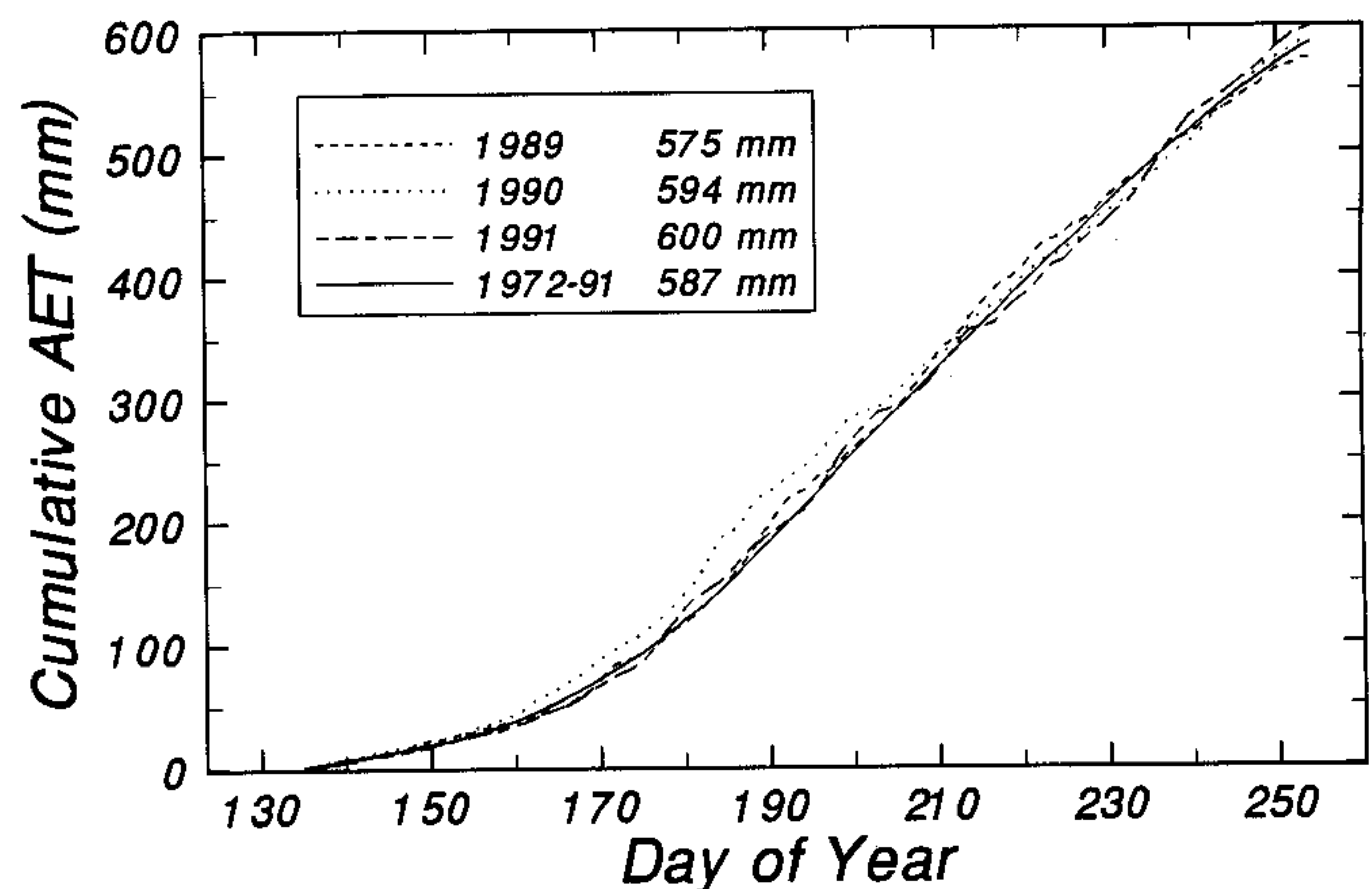


Figure 2—Cumulative calculated AET for well-watered corn for 15 May to 11 September (120) at Colby, Kans. (1989 to 1991).

UTILIZATION OF AVAILABLE SOIL WATER

A time series progression of available soil water in the 2.4-m soil profile for the three years (fig. 3) shows a distinct separation between the bottom three treatments and the top three treatments, apparently reflecting the respective inabilities and abilities of the treatment groupings to meet the ET needs of the corn crop. In essence, the top three treatments maintained high and adequate levels of available soil water, whereas the bottom three treatments "mined" the soil water. Mining the soil water to a low level would be acceptable and even desirable, if corn yield could be maintained. However, yields were drastically lower with the bottom three irrigation treatments (table 1).

Generally, yields begin to decrease rapidly when the seasonal soil water decreased below approximately 325 to 350 mm (56 to 60% of field capacity) for extended periods in July and August (table 1 and fig. 3). This may lend additional credibility to the use of 0.60 for B in equations 2a and 2b. If yield is dependent on the independent variable ET and yield is reduced when ASW falls below 60%, then it follows logically that ET is reduced when ASW falls below 60%.

The 1990 and 1991 data indicated soil water was highest at the dripline and lowest in the center of the furrow (data

Table 1. Summary of corn yield and water use data from an irrigation scheduling study of drip-irrigated corn, KSU Northwest Research-Extension Center, Colby, Kans., 1989 to 1991

Irrigation Trt. §	Corn Grain Yield				In-season Irrigation				Available Soil Water*				AET _{asw} †				PERC‡			
	1989	1990	1991	Mean	1989	1990	1991	Mean	1989	1990	1991	Mean	1989	1990	1991	Mean	1989	1990	1991	Mean
	(Mg/ha)	(Mg/ha)	(Mg/ha)	(Mg/ha)	(mm)	(mm)	(mm)	(mm)	(mm/2.4 m)	(mm/2.4 m)	(mm/2.4 m)	(mm/2.4 m)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1. 1.25*ET	10.5ab	12.3b	14.9a	12.6ab	500	579	542	541	442a	387a	420a	416a	574	588	597	586	129	89	132	117
2. 1.00*ET	11.3a	13.9a	14.7a	13.3a	394	456	425	425	406a	365a	353b	375b	574	588	597	586	58	23	59	47
3. 0.75*ET	11.0ab	12.1b	14.3a	12.5b	258	343	347	316	359b	328b	330b	339b	574	578	597	583	19	6	31	19
4. 0.50*ET	10.0bc	10.5c	10.9b	10.4c	174	198	184	185	295c	213c	200c	236c	549	517	560	542	14	4	18	12
5. 0.25*ET	8.9cd	7.9d	6.8c	7.8d	50	87	84	73	211d	185cd	179c	192d	506	459	517	494	12	4	17	11
6. No irrigation	7.9d	6.0e	4.3d	6.1e	0	0	0	0	199d	170d	154c	174d	482	411	485	459	11	3	16	10

* Available soil water in 2.4-m profile measured after harvest on 25 September 1989, 19 September 1990, and 19 September 1991.

† Total calculated AET corrected for soil water availability for the 120-day period (15 May to 11 September).

‡ Total calculated long-term drainage for the 120-day period, (15 May to 11 September).

§ Within columns, means followed by the same letter are not significantly different according to LSD means separation test at P = 0.05.

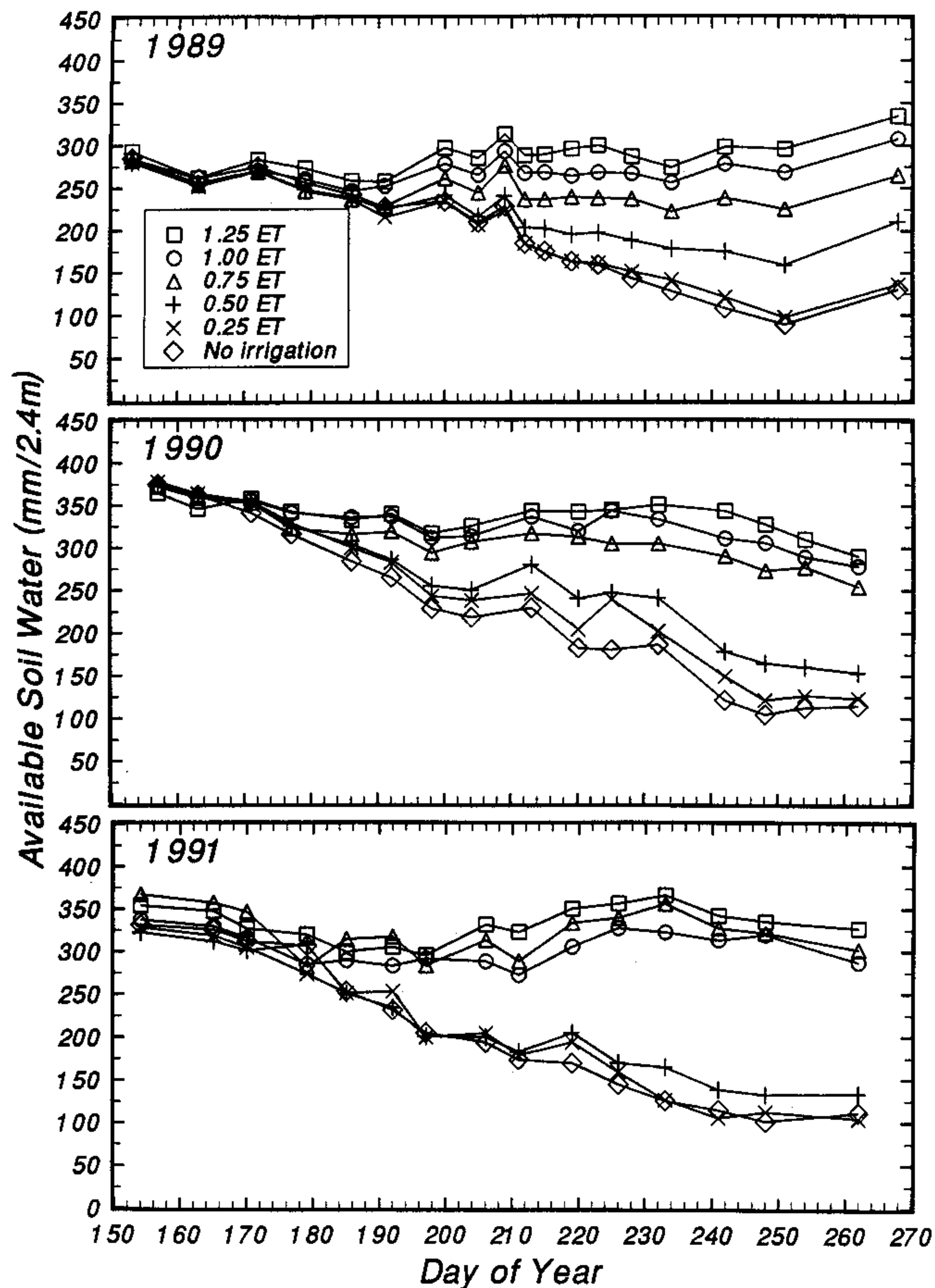


Figure 3—Seasonal progression of the available soil water in the 2.4-m soil profile for the six irrigation treatments (1989 to 1991).

not shown). However, the soil water measurement at the row location was nearly equal to the integrated mean of the three locations, which gives evidence that the single 1989 soil water measurement location was acceptable.

COMPARISON OF WATER USE MODEL TO FIELD MEASUREMENTS

Although the corn emerged on 15 May in each year, the initial soil water measurements were not made until 2 June 1989, 6 June 1990, and 3 June 1991. The installation of neutron access tubes is normally delayed until uniform crop stands are obtained and is also often further delayed by wet soil conditions.

The available soil water amounts on the June dates were used as the initial soil water amounts in the model to compare the calculated sum of AET_{asw} and PERC to the sum of IRR, RAIN, and the change in ASW from then to approximately the first week in September. The sums of the calculated and measured water balance components compares reasonably well (fig. 4) considering that each of the components has some associated error in calculation or measurement. Each of the 18 data points represents one treatment average for a particular year. It is not known why the 1989 data vary from the 1:1 unity line, though slopes are similar. It is possible that precipitation at the field site in 1989 (a wet year) did not match the data obtained from

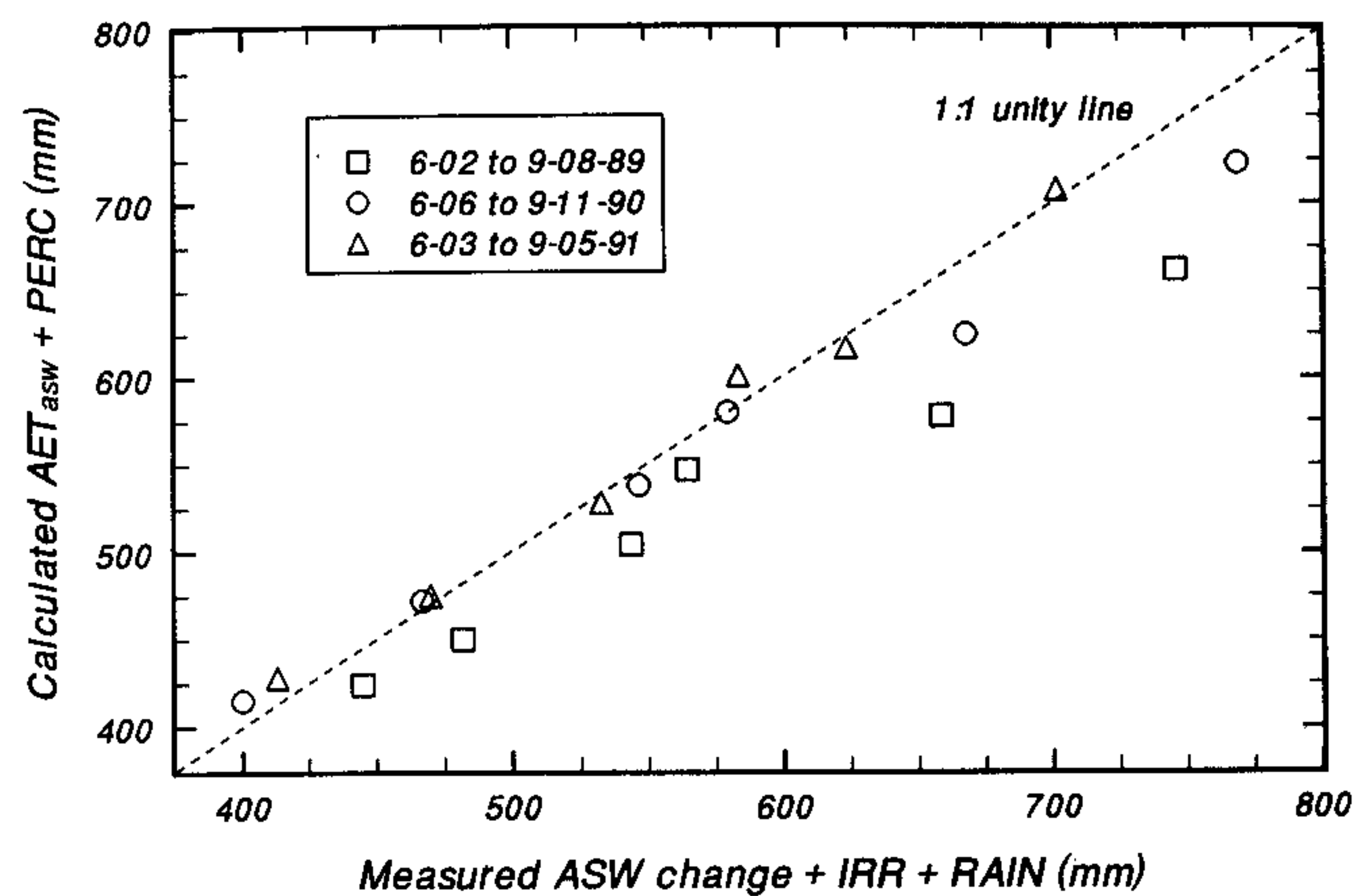


Figure 4—Relationship between the cumulative calculated and measured water balance components for approximately 95-day periods (1989 to 1991).

the official weather station 400 m to the east. Another possibility might be the different corn hybrid used in 1989.

DRIP IRRIGATION AND WATER USE EFFICIENCY

In a thorough review of crop yield response to water, Howell et al. (1990) enumerates four methods to increase water use efficiency: 1) increase the harvest index (ratio of crop economic yield to total dry matter production); 2) reduce the transpiration ratio (ratio of transpiration to dry matter production); 3) reduce the root dry matter amount and/or the dry matter threshold required to initiate the first increment of economic yield; or 4) increase the transpiration component relative to the other water balance components, for example, through reductions of evaporation, drainage, and runoff. Clearly, some of these four methods are more difficult than others. Tanner and Sinclair (1983) in a review of studies from the early 1900s to the 1980s conclude that there is very little hope for significantly improving the transpiration ratio (method 2). The use of SDI to increase water use efficiency has greatest possibilities with method 4, reducing the nonbeneficial components of the water balance.

Based on the relatively good agreement between the modeled and the measured water balance components, the model was used to calculate the cumulative AET_{asw} and PERC for a 120-day period beginning at emergence on 15 May and ending on 11 September for each of the three years. In the model, the initial available soil water level in the 2.4-m soil profile was assumed to be at 60% of field capacity for all treatments on 15 May. Although surface soil layers are usually near field capacity at planting, the entire 2.4-m soil profile is seldom this wet at planting. Irrigation amounts for the various treatments and climatic data were used to drive the model. Results from these calculations are summarized in table 1.

Measured yields were highly linearly related to the cumulative AET_{asw} in all three years (fig. 5), although the slopes and intercepts varied. The slopes are the water use efficiencies (WUE) of the different treatments and near linearity denotes equal WUE. The different slopes and intercepts are to be expected, because other factors

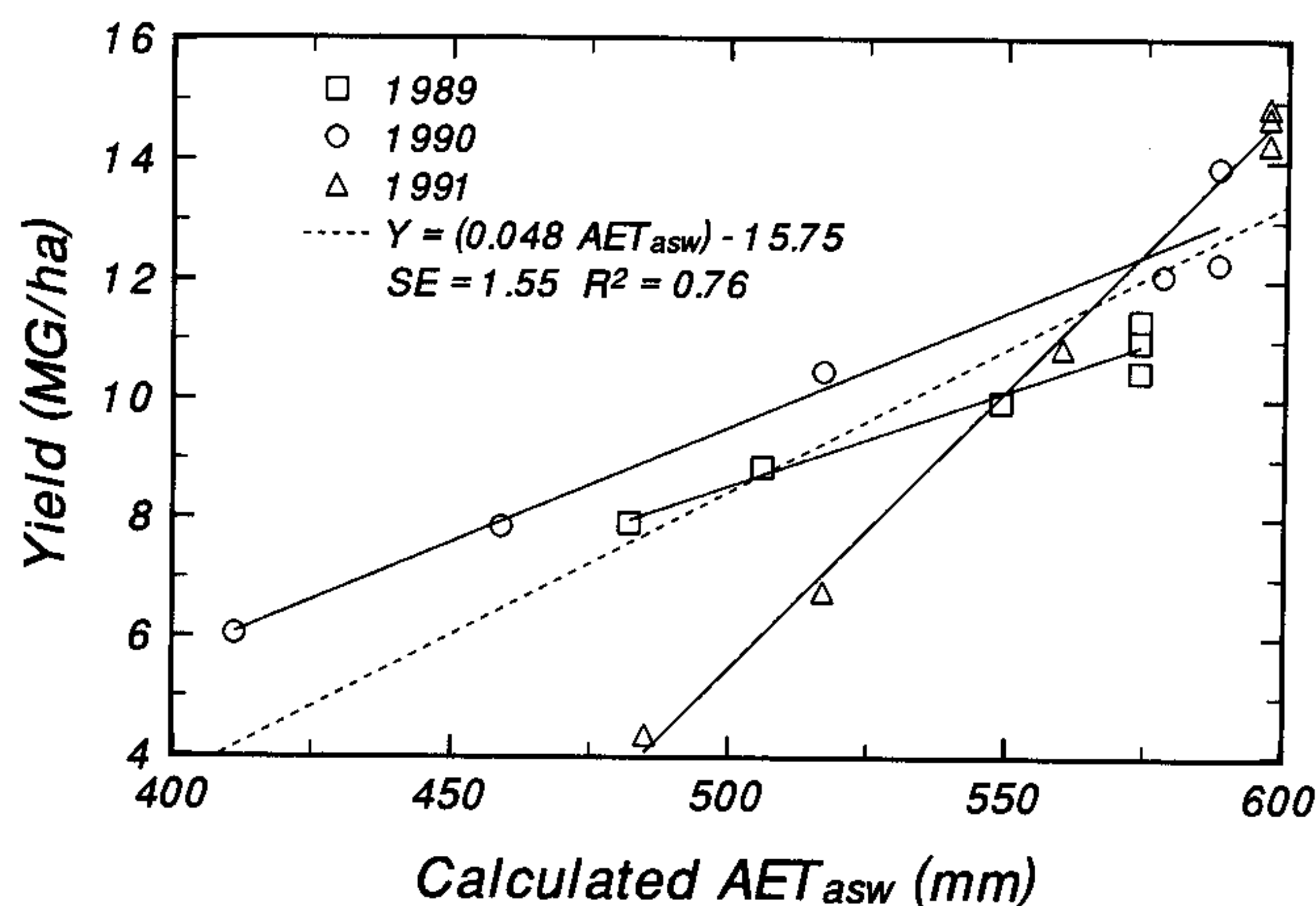


Figure 5—Relationship of corn grain yield and the cumulative calculated evapotranspiration corrected for soil water availability (AET_{asw}) (1989 to 1991).

influence yields besides water use. These linear relationships should not be confused with the typical curvilinear relationships found when the nonbeneficial water use components are included in the crop water use. The calculation of water use for the top three treatments ($0.75*ET$ to $1.25 ET$) resulted in nearly identical values within a given year. This indicates that irrigation, precipitation, and available soil water were sufficient to meet all crop water needs. Irrigation and precipitation applied above the necessary amount to meet crop water needs had no positive effect on yield. In fact, in two of the three years, yields were reduced by irrigation in excess of the amount required to meet $1.00*ET$. This yield reduction is probably attributable to poor aeration caused by the high irrigation frequency or leaching of nutrients. This contrasts sharply with previous results from basin studies in which no yield depression occurred with overirrigation (Lamm and Rogers, 1985). However, the frequency of irrigation for the basin studies was much less, which would allow for better aeration.

Linear regression of all 18 data points (fig. 5) resulted in an equation for yield in milligrams per hectare:

$$Y = (0.048 * AET_{asw}) - 15.75 \quad (4)$$

where AET_{asw} is expressed in millimeters. The equation fits the overall data well with a standard error of the estimate, $SE_{y,x}$ (also called Root Mean Square of the Error) equal to 1.55 Mg/ha. The standard error of the estimate is an estimate of the variance about the regression line. The RSQUARE of the equation was 0.76, meaning that 76% of the variation about the regression line is explained by the equation. The dry matter threshold or the X intercept for the equation was 328 mm. This value is somewhat higher than the values of 232 mm for wheat and 257 mm for grain sorghum reported by Koelliker (1976) from studies in the Great Plains. However, Wenda and Hanks (1981) reported threshold values ranging from 200 to 340 mm for corn in Utah. Hook (1985) reported threshold values for corn of 230 to 240 mm in Georgia. The value found in this study falls within the range of values reported in the literature. The slope (WUE) of the regression line, though much greater than the 0.017 Mg/ha-mm reported by Musick and

Dusek (1980) for a three-year study near Bushland, Texas, is very near the 0.045 Mg/ha-mm reported by Hook (1985) for corn in Georgia. The value from this study seems reasonable considering the recent yield advances in corn hybrids.

NONBENEFICIAL COMPONENTS OF THE WATER BALANCE

As noted, the nonbeneficial components of the water balance were removed from the discussion of water use efficiency. These components are runoff, soil evaporation (above amount inherent in ET), and long-term drainage. The leaching requirement for salinity management has not been a concern in western Kansas due to the high water quality and moderate precipitation amounts, thus, long-term drainage is considered nonbeneficial in this discussion. Runoff was considered negligible in the study because of the low land slope, the presence of furrow dams in 1989 and 1990, and high residue levels in 1990 and 1991. Excessive soil evaporation, which occurs following irrigation and precipitation events, was considered to be reduced because the irrigation was applied at the 40 to 45 cm depth. Though long-term drainage can be reduced through irrigation management, it probably cannot be eliminated, at least during the early part of the season when precipitation exceeds ET. However, because SDI can apply the water at a deeper level than both sprinkler and furrow irrigation, for a given amount of water, a smaller "slug" of irrigation is required to put the water near the crop roots where it is needed. With a smaller "slug" in the soil profile, long-term drainage can be reduced, if irrigation and precipitation amounts are carefully matched to the crop water needs.

The cumulative calculated values of PERC and AET_{asw} as related to irrigation treatment for the three years are compared in table 1 and figure 6. PERC is nearly minimized for the $0.75*ET$ irrigation treatment while AET_{asw} is still at the maximum level required for high yields. The majority of the calculated PERC for the deficit-irrigation treatments occurred during the early part of the season when ASW was relatively high for the deficit-irrigated treatments.

YIELDS AND IRRIGATION

The previous sections have emphasized that highly efficient water use can be obtained with careful management of SDI. This careful management requires providing the necessary water to meet the total ET needs of the crop but avoiding increased irrigation above this point. Excessive irrigation not only increases the nonbeneficial components of the water balance, but may actually decrease yields for drip-irrigated corn in some years. Excessive irrigation has both economic costs, such as pumping costs, and social costs, such as waste of the water resource and excessive drainage of possibly chemical-laden water. Though some variation occurred among years, yields tended to plateau for the top three treatments (fig. 7). Significant differences ($P = 0.05$) in yield for the top three treatments only occurred in 1990 when the normal $1.00*ET$ treatment outyielded the $1.25*ET$ and the $0.75*ET$. A three-year average of 12.5 Mg/ha for the $0.75*ET$ treatment was obtained using 25.6% less water than the normal treatment, $1.00*ET$ (table 1). The $0.75*ET$ treatment required 316 mm of in-season irrigation which is

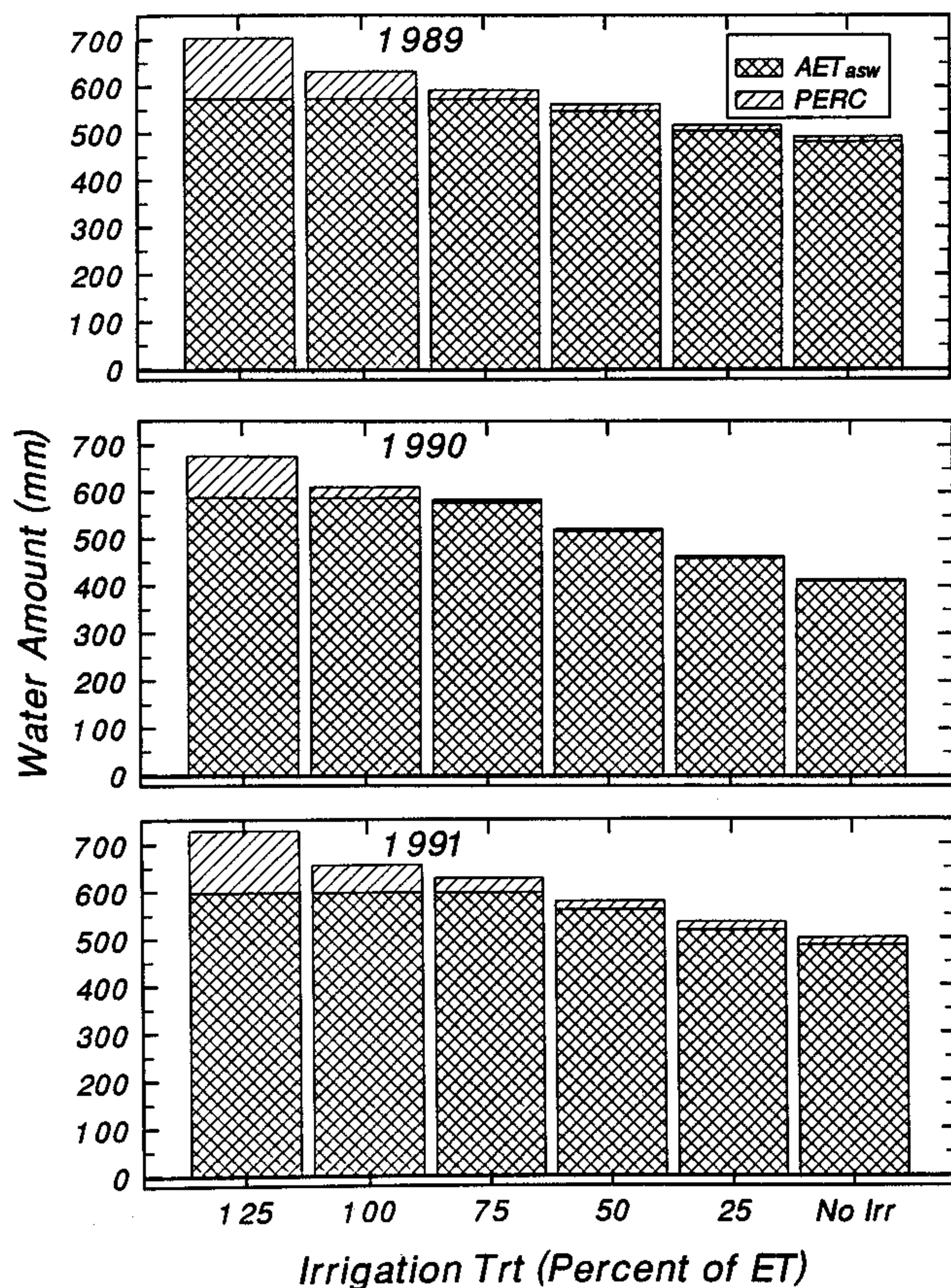


Figure 6—Cumulative calculated values of the AET corrected for soil water availability (AET_{asw}), and long-term drainage (PERC) as related to irrigation treatment (1989 to 1991).

considerably less than the long-term net irrigation requirement of 391 mm for Colby (based on 80% chance rainfall). It should be noted that the normal treatment ($1.00 \cdot ET$) had an average irrigation requirement during these three years, slightly above the long-term average net requirement. This indicates that the years were fairly representative. It should also be noted that the 316 mm value is a gross amount for the highly efficient SDI system,

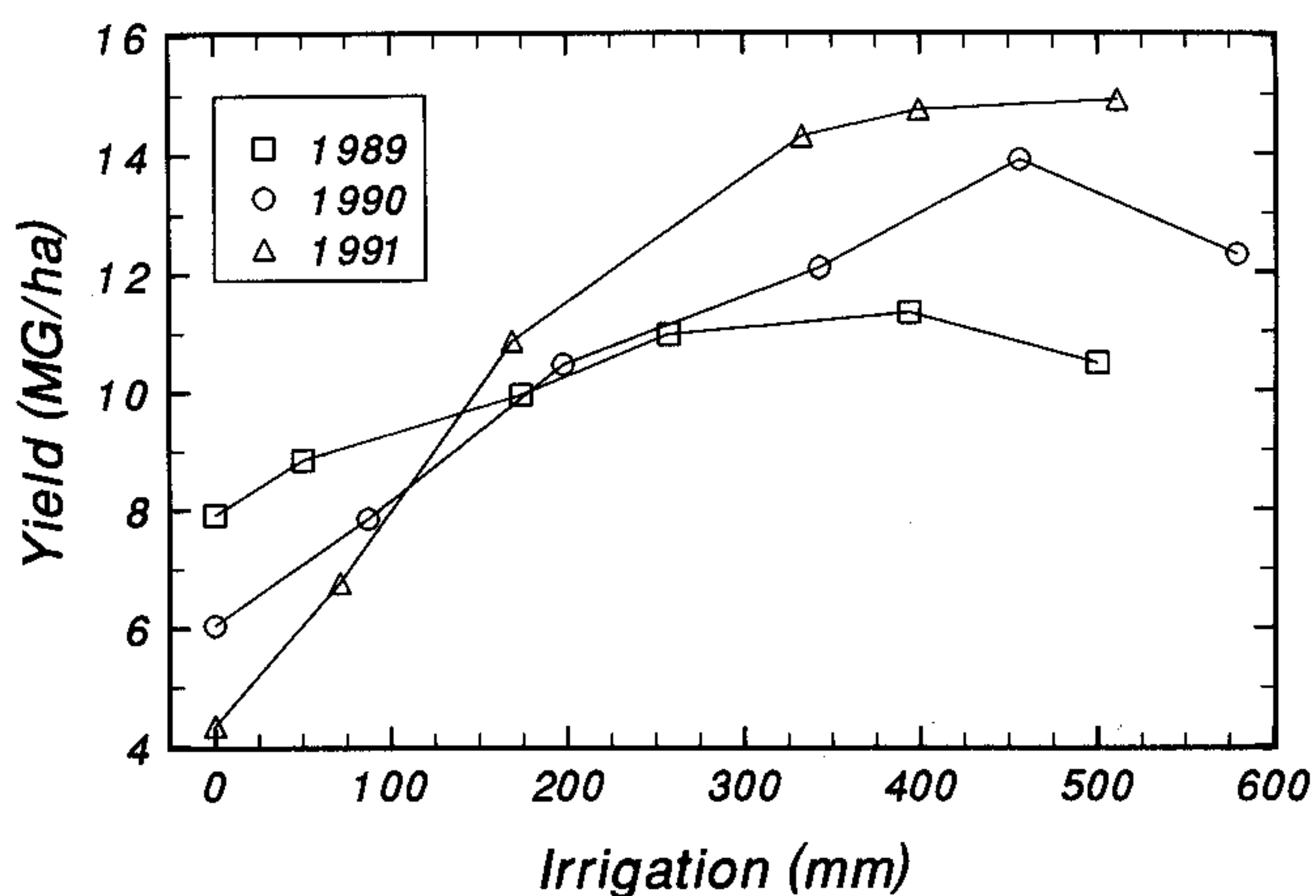


Figure 7—Relationship of corn grain yield and irrigation amount for 1989 to 1991.

whereas the 391 mm value is a net requirement, which would increase the gross requirement for less efficient irrigation systems.

CONCLUSIONS

Overall, the three years of this study had near normal precipitation and ET. However, each season had periods of low precipitation and/or high ET, which increased irrigation requirements above normal. The credibility of the results of this study is bolstered by the fact that these three years were fairly representative of climatic conditions in northwest Kansas.

Analysis of the soil water data revealed sharp differences in utilization between the well-watered (75, 100, and 125 of ET) and deficit-irrigated treatments (no irrigation, 25, and 50% of ET). Sufficient irrigation for the well-watered treatments maintained the 2.4-m soil profile above 60% of field capacity during most of the season while the deficit-irrigated treatments "mined" the soil water.

A water balance model constructed to estimate the actual ET of the crop corrected for soil water availability and long-term drainage agreed reasonably well with measured data for an approximately 95-day period of each season. After verification, the model was used to estimate the water balance components for the 120-day season beginning at crop emergence. Measured yields were linearly related to the cumulative AET (corrected for soil water availability) in all three years. Highest yields were obtained when ET was not limited by soil water availability. The yield plateau was reached by an irrigation treatment applying almost 26% less than the normal full irrigation amount. These water savings were obtained by minimizing the nonbeneficial components of the water balance while still maintaining the high levels of evapotranspiration necessary to attain high yields. Using careful management, the nonbeneficial water balance components (runoff, evaporation, and long-term drainage) are minimized with SDI, resulting in increased water use efficiency without sacrificing corn yields.

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