Reducing Tailwater Runoff for Efficient Irrigation Water Use

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ABSTRACT

TAILWATER runoff from 570-m graded furrows was varied from 0 to 8 hr to determine the variability of grain sorghum yield with length of run. During the first 3 to 4 hr, cumulative infiltration into the Pullman clay loam is 5 to 7 cm. Infiltration into the slowly permeable soil then approaches the steady-state rate of less than 0.25 cm/hr. Continuing to irrigate after the entire furrow reached the steady-state infiltration rate did not significantly increase the field average yield. The root zone at the tail end of the field was not fully wetted, but the soil water was sufficient for normal plant growth, and tailwater runoff was less than 10 percent of the applied water. As a result, the irrigation water-use efficiency varied inversely as the duration of tailwater runoff. By reducing the duration of tailwater runoff, additional land could be irrigated with the limited groundwater supply.

Allowing irrigation tailwater runoff is a method of achieving more uniform water distribution along graded irrigation runs. Criddle et al. (1956) recommended an irrigation advance time equal to one-fourth of the total application time. With this guideline, they also recommended a cutback or reduced furrow stream, after water advances to the end of the irrigation run. Irrigation tailwater recovery systems are an alternate method of reducing tailwater runoff losses. Bondurant (1969) presented design criteria for these systems and showed how they can be operated to simulate a cutback furrow stream. Most irrigation system design criteria have been developed for the alluvial soils of the Western US. Irrigated soils in the Great Plains are often fine-textured with much lower infiltration rates.

Pullman and related soils of the Southern Great Plains have a slowly permeable subsoil that determines the steady-state infiltration rate. During the first 4 to 6 hr, the infiltration rate is relatively high, but deceases rapidly as the topsoil is saturated. Subsequently, the slowly permeable subsoil limits the steady-state infiltration rate to less than 0.25 cm/hr. Musick et al. (1973) showed that the flow rate 540 m down irrigated furrows became steady within 4 hr after the wetting front passed. The unique infiltration characteristics of Pullman clay loam allow 800-m-long graded furrows to be irrigated without large, deep-percolation losses (Aronovici and Schneider 1972). Most of the irrigation run is adequately irrigated, but the lower end usually has a soil water deficit, even after tailwater has run off for several hours.

In irrigation water management, the crop must be considered in addition to the soil and irrigation practices. Musick and Dusek (1971) showed that grain sorghum in level borders effectively utilized small irrigations throughout the growing season. During 7 treatment-years, reducing the size of each irrigation from 10 to 5 cm increased the irrigation water-use efficiency from 148 to 226 kg/ha-cm. Musick et al. (1973) presented water-use and grain sorghum yield data from three equal-length segments of 540-m irrigated furrows. Water-use efficiencies for the three segments down the irrigation run were 135, 165, and 211 kg/ha-cm, respectively. The potential for efficient water use throughout an irrigation run exists even if the irrigation water distribution is quite nonuniform.

The study reported here was conducted to determine the feasibility of a graded-furrow irrigation system on Pullman clay loam with limited or no tailwater runoff.

RESEARCH PROCEDURE

Irrigation Treatments

The variable irrigaton tailwater runoff study was conducted in 1967

TABLE 1. EXPERIMENTAL DESIGN AND IRRIGATION TREATMENT VARIABLES.

	1967	1971
Plot length, m	570	570
Plot width, m (rows)	6 (8)	12 (12)
Subplot width, m (rows)	—	6 (6)
Furrow spacing, cm	75	100
Grain sorghum hybrid	RS 626	RS 671
Seeding rate, kg/ha	8	10
Preseason irrigation date	Not applied	May 12
Seasonal irrigation dates	July 25 to 27	I_2 & I_4 — July 6 & 7
	Aug. 8 & 9	I_4 — July 22 & 23
	Aug. 28 & 29	I_2 & I_4 — Aug. 5 & 6
		I_4 — Sept. 2 & 3
Application time for seasonal irrigations, hr	T_0 — 15.1	T_0 — 22.0
	T_4 — 17.4	T_3 — 24.0
	T_8 — 21.8	T_6 — 27.0
Furrow stream size, l/min	*38	†38

*First irrigation = 47 l/min.
†Preplant irrigation = 47 l/min.

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and 1971 at the USDA Southwestern Great Plains Research Center, Bushland, TX. Duration of tailwater was the main treatment in a randomized block experimental design with two replicates. In 1967, the treatments were 0, 2, 4, and 8 hr of tailwater runoff. Data from the 2- and 4-hr runoff treatments were similar, so they were averaged as an intermediate treatment. The resulting three treatments are referred to as T_0, T_4, and T_8. In 1971, the treatments were 0, 3 to 4, and 6 to 8 hr of tailwater runoff which are referred to as T_0, T_3, and T_6, respectively (New 1974). A range of runoff times was specified because the recession flow time could not be accurately predicted with the wide range of soil water levels. The 1971 tailwater runoff treatments were split into two irrigation levels—two seasonal irrigations (I_2) and four seasonal irrigations (I_4). Plot dimensions are shown in Table 1. The field had a uniform, 0.3 percent furrow slope and negligible cross slope.

Irrigation Scheduling and Measurement

The variation in irrigation levels and rainfall provided a wide range of water-use and yield potential during the two crop years. In 1967, soil water was adequate for seed germination, and no preseason irrigation was applied. A large preseason irrigation was applied to establish the 1971 crop. The dates of the preseason and seasonal irrigations are listed in Table 1. Growing-season rainfall averages 230 mm, but it was 170 mm during 1967, and 330 mm during 1971. Most of the below-average rainfall in 1967 occurred during the early part of the growing season. Much of the 1971 rainfall occurred during late-August and September. Thus, both crops went through critical growth stages without effective rainfall.

Irrigation furrow streams were individually measured with a bucket and stopwatch, and tailwater runoff was measured with 30-cm, type-H flumes, equipped with water stage recorders. Furrow stream sizes are listed in Table 1. All treatments in a replicate were irrigated from the same aluminum pipeline. When the runoff duration for a treatment was completed, irrigation input was stopped. Furrow streams for the other treatments were then readjusted. Tailwater runoff was measured from five furrows per plot during 1967 and from four furrows per subplot during 1971. The lower ends of the T_0 plots were diked during both years to prevent irrigation runoff. Application times for the seasonal irrigations are listed in Table 1. Application times for the 1971 preplant irrigation were 34.8, 38.1, and 43.2 hr for T_0, T_3, and T_6, respectively.

TABLE 2. IRRIGATION WATER APPLIED AND TAILWATER RUNOFF.

1967			1971				
				I_2		I_4	
Treatment	Irrigation applied	Tailwater runoff	Treatment	Irrigation applied	Tailwater runoff	Irrigation applied	Tailwater runoff
			cm				
T_0	25.4	0	T_0	36.9	0	48.6	0
T_4	29.1	2.7	T_3	40.4	2.0	52.6	2.1
T_8	36.6	7.5	T_6	44.6	2.6	60.0	5.1

Soil

Pullman clay loam, described by Taylor et al. (1963), is a member of the fine, mixed, thermic family of Torrertic Paleustolls of the order Mollisols. The A horizon is clay loam, 10 to 18 cm deep, and underlying clay Bt horizons extend to about the 120-cm depth. A calcareous zone containing up to 50 percent $CaCO_3$ occurs between the 120- and 180-cm depths. Bulk density ranges from 1.3 to 1.4 g/cm^3 in the topsoil and from 1.5 to 1.6 g/cm^3 in the subsoil.

Soil Water Measurement

Soil water was determined gravimetrically by 30-cm increments, and bulk densities from earlier studies were used to convert the values to volumetric water contents. Measurements were made to the 180-cm depth before and after both growing seasons and after the 1971 preseason irrigation. Soil water was measured to the 120-cm depth before all growing season irrigations and after the 1967 growing season irrigations. Sampling locations were 30, 150, 270, 390, 480, and 540 m from the head-end of the field.

Crops and Yields

Grain sorghum was selected for the minimal tailwater-runoff irrigation system because it is a drought-tolerant crop that can effectively utilize small irrigations. The sorghum was planted one row per 75-cm bed in 1967 and two rows per 100-cm bed in 1971. The double rows were spaced 20 cm from the center of the beds or 40 cm apart. Seeding rates and grain sorghum hybrids are listed in Table 1.

Grain yield was determined from hand samples collected at each soil water sampling location. All yields were adjusted to 13 percent moisture by dry weight.

The water-use efficiency terms presented are a measure of the crop yield per unit of water used. Irrigation water-use efficiency (IWUE) is:

$$\text{IWUE} = \frac{\text{Irrigated yield - Dryland yield}}{\text{Irrigation Water Applied}}$$

Seasonal water-use efficiency (SWUE) is:

$$\text{SWUE} = \frac{\text{Irrigated yield}}{\text{Seasonal Water use}}$$

Seasonal water use includes net irrigation water applied, rainfall from planting to crop maturity and the change in soil water storage to the 180-cm depth.

RESULTS AND DISCUSSION

Irrigation and Tailwater Runoff

Seasonal crop-water use varied considerably between the 2 yr and between the irrigation levels in 1971. Seasonal irrigation application and tailwater runoff data for all treatments are listed in Table 2. The lowest irrigation level occurred in 1967 when the total water application from three irrigations ranged from 25.4 cm on T_0 to 36.6 cm on T_8. In 1971, the irrigation applications ranged from 36.9 to 60.0 cm. The larger irrigation water application was partially due to preseason irrigations of 16.8, 18.4, and 19.8 cm for the T_0, T_3, and T_6 plots, respectively. The I_4 subplots were adequately irri-

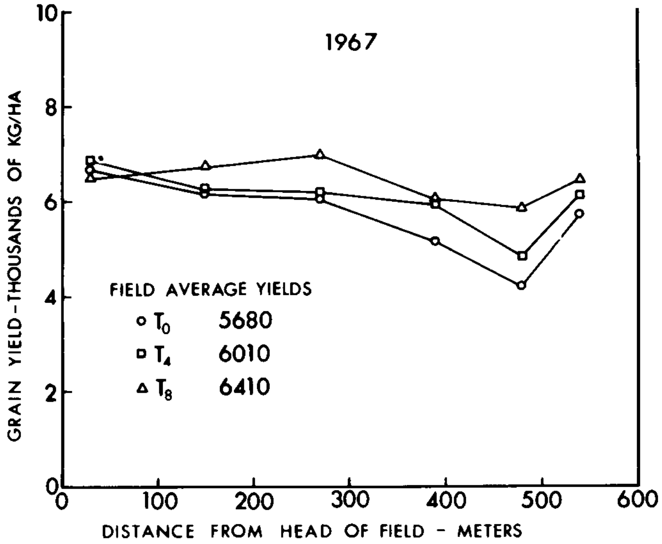

FIG. 1 Grain yield as a function of distance down the irrigation furrows.

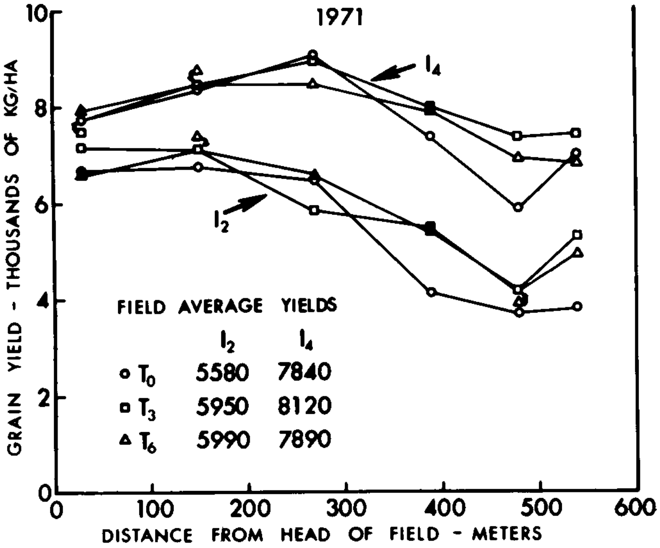

FIG. 2 Grain yield as a function of distance down the irrigation furrows.

gated for maximum grain sorghum production at the Research Center. The I_2 irrigation level and the 1967 treatments were limited water levels.

Total tailwater runoff varied with the furrow width as well as with the duration of tailwater runoff. During both years, the furrow stream size was 38 l/min, but furrow spacings were 75 cm in 1967 and 100 cm in 1971. Thus, the irrigation input per unit-width of furrow was one-third greater in 1967. That year, tailwater runoff for T_4 and T_8 was 9.3 and 20 percent, respectively, of the total irrigation water applied. In 1971, the maximum tailwater runoff was 8.5 percent of the water applied to the higher irrigation level of T_6. Irrigation runoff from the other treatments was less than 6 percent of the applied water. Twenty percent runoff from graded furrows is typical for Pullman clay loam irrigated from a good water supply.

Yields

The 1967 crop was severely stressed by limited soil water before the first irrigation and slightly damaged by the herbicide, 2,4-D. The herbicide was applied before the tailwater runoff treatments were initiated so yield differences should be due to the treatments. The grain sorghum came under severe soil water stress while repairs on the irrigation well delayed the first irrigation until July 25-27. Only three seasonal irrigations were applied, and seasonal water use for T_8 was 14 cm less than the average consumptive use by grain sorghum in the area. Thus, none of the 1967 plots reached the maximum yield potential for grain sorghum.

The yield distribution with length of run was similar for each of the irrigation water levels (Figs. 1 and 2). Within each irrigation water level, yields did not vary appreciably at the 30-, 150-, and 270-m sampling locations. At the three lower samling locations, yield was directly related to the duration of tailwater runoff. The yield reduction on T_0 was appreciable at the 390- and 480-m sampling locations. Since water was ponded behind the H-flumes on the runoff treatments and behind the dikes on T_0, the yield of all treatments increased at the 540-m sampling location. Some yield reduction occurred at the lower end of the field even with 6 to 8 hr of tailwater runoff.

The field average grain yield indicated that yield reduction with reduced tailwater runoff was not large (Figs. 1 and 2). The field average yield increased significantly for the longest runoff treatment only in 1967 when the irrigation level was limited. In 1971, the T_3 and T_6 field average yields were approximately equal for the intermediate irrigation level. With the adequate irrigation level, the field average yield was 230 kg/ha higher for T_3 than for T_6.

Water-Use Efficiency

Irrigation and seasonal water-use efficiencies varied inversely with the duration of tailwater runoff (Table 3). Water-use efficiencies were highest in 1967 when a preseason irrigation was not required. The intermediate and no tailwater runoff treatments increased the irrigation water-use efficiency 15 and 28 percent, respectively, over the 8-hr tailwater runoff treatment. Seasonal water-use efficiencies varied much less because 170 mm of precipitation was included in the seasonal water use for all treatments. During 1971, water-use efficiency was similar for the I_2 and I_4 irrigation levels. Irrigation water-use efficiency with no tailwater runoff, was 13 percent higher for I_2 and 22 percent higher for I_4

TABLE 3. IRRIGATION AND SEASONAL WATER-USE EFFICIENCIES BASED ON TOTAL IRRIGATION WATER APPLIED.

1967			1971				
				I_2		I_4	
Treatment	Irrigation* water-use efficiency	Seasonal water-use efficiency	Treatment	Irrigation† water-use efficiency	Seasonal water-use efficiency	Irrigation† water-use efficiency	Seasonal water-use efficiency
			kg/ha-cm				
T_0	207	124	T_0	151	80	161	96
T_4	187	118	T_3	147	81	154	95
T_8	162	111	T_6	134	77	132	85

*Dryland yield of 430 kg/ha used in calculations.
†Zero dryland yield used in calculations.

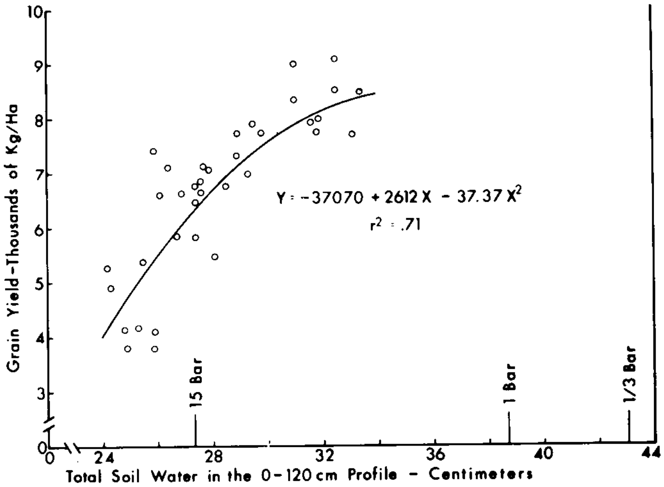

FIG. 3 Grain yield as a function of the lowest soil water content measured during the 1971 growing season.

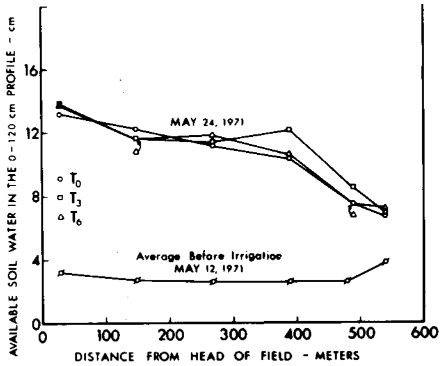

FIG. 4 Available soil water before and after the 1971 preplant irrigation.

than with 6 hr of runoff. Seasonal water-use efficiency did not vary appreciably for the I_2 irrigation level and varied 11 percent for the I_4 irrigation level.

Soil Water

The 1971 grain yield was highly correlated with the lowest soil water measured during the growing season. The soil water content on the I_2 subplots was extremely low before the August 5 irrigation. It was lowest on the I_4 subplots before the September 3 irrigation. Soil water to the 120-cm depth is plotted vs. yield in Fig. 3 for each of the 36 replicated sampling locations. The quadratic equation fitted to the data showed that the minimum soil water content was quite important in the lower range. The yield increase per cm of additional soil water decreased from 900 kg/ha at 24 cm, to 360 kg/ha at 30 cm. Minimum soil water contents above 32 cm had little effect on yields. For example, the yield increase per cm of additional soil water was only 87 kg/ha at 33 cm. The 1967 data did not follow the same trend, because of the severe soil water stress before the first irrigation. All treatments were depleted to approximately the same soil water content, and subsequent soil water levels caused the yield variation.

Fig. 4 shows the plant-available soil water before and after the 1971 preplant irrigation. After the irrigation, the available soil water varied little between runoff treatments but decreased nearly 50 percent from the head- to the tail-end of the field. Soil water measurements, after the 1967 seasonal irrigations, were similar although not as consistent. Very long intervals of tailwater runoff would have been required to fully wet the Pullman clay loam profile at the lower end of the irrigation run.

Irrigation Water Management

On Pullman clay loam, irrigated with graded furrows, specifying tailwater runoff in hours rather than as a percent of the application time is more practical. Because of the low steady-state infiltration rate, minimal deep percolation losses are not difficult to obtain (Aronovici and Schneider 1972). The major objective in irrigation design and management is to minimize the yield reduction at the lower end of the field without excessive tailwater loss. The one-fourth irrigation advance time guideline of Criddle et al. (1956) would be difficult to justify. For example, the irrigation advance times for the 1971 preplant irrigation ranged from 86 to 100 percent of the application time. Twelve days after the irrigation, there was little difference in soil water distribution among the runoff treatments. To use the one-fourth irrigation advance time, furrow streams would have to be decreased to a small fraction of their initial flow rate.

A schedule of frequent irrigation is best adapted to a minimal-tailwater-runoff system. The most uniform yield distribution during the study occurred on the I-4 irrigation subplots in 1971. With more frequent irrigation, the cumulative infiltration for each irrigation is smaller at the upper end of the field (Musick et al. 1973). The tail-end of the field remains drier and has a higher initial infiltration rate. As a result, irrigation water application varies less between the ends of the irrigation run.

Rainfall distribution during the growing season will affect the success of a reduced-tailwater-runoff system. When Pullman clay loam is wetted by rainfall, the plant-available soil water is uniformly distributed (Musick et al. 1973). In the Southern Great Plains, precipitation may furnish one-third or more of the water requirement for grain sorghum. The uniformly distributed rainfall is combined with the nonuniformly distributed irrigation water. If rainfall is timely, soil water distribution during critical growth periods can be fairly uniform.

Use of Limited Water Supplies

Minimizing or eliminating tailwater runoff is an effective way to utilize a limited irrigation water supply. If the time of irrigation sets is reduced by one-fourth to one-third, considerably more land can be irrigated with a fixed flow rate or volume of water. Since changes in the irrigation system are not required, tailwater runoff can be reduced during all or part of the cropping season. In the Southern Great Plains where supplemental irrigation water is pumped from low-producing wells, this will provide flexibility in meeting critical water demands. During extended intervals without rainfall, tailwater runoff can be decreased to permit irrigation of larger acreages. When rainfall is near average, the crop can be irrigated for a higher yield level.

Schneider (1976) developed an irrigation tailwater model showing the relative effect of the variables affecting tailwater loss. When tailwater recovery systems are utilized, total water loss varies with the fraction of irrigation water running off the field and the fraction of runoff lost during recycling. With many tailwater recovery systems, as much as 40 percent of the runoff will be lost to evaporation and seepage during the recovery process. This loss, plus the added percolation during long intervals of runoff, could be applied to additional land. This further illustrates why irrigated acreages and irrigation water-use efficiencies can be increased by decreasing irrigation tail-water runoff.

CONCLUSIONS

The field study showed the feasibility of graded-furrow-irrigating Pullman clay loam with limited or no tailwater runoff. Specific conclusions are:

1 Continuing to irrigate 570-m long furrows after the entire furrow reached the steady-state infiltration rate did not significantly increase field average grain sorghum yields.

2 Irrigating to achieve a minimum acceptable soil water level at the lower end of the graded furrows resulted in high yields and small tailwater losses.

3 Limiting or reducing tailwater runoff increased the irrigation water-use efficiency of grain sorghum on 570-m graded furrows. The results should be applicable to other drought-tolerant crops on soils with similar soil water characteristics.

4 A limited-tailwater-runoff irrigation procedure permits irrigating larger acreages with a limited water supply.

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