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Irrigation Water Management for the Texas High Plains: A Research Summary

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IRRIGATION WATER MANAGEMENT FOR THE TEXAS HIGH PLAINS: A RESEARCH SUMMARY

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CHAPTER I

WATER RESOURCES FOR THE HIGH PLAINS

Introduction

The High Plains of Texas accounts for over 1/3 of the total cropland, nearly 2/3 of the irrigated acreage, and almost 1/3 of the agricultural income in the state (Clarke, 1986). Irrigation which began in the 1910's reached a peak in the mid 1970's (Knowles, 1985). Irrigation has created a system of agriculture that has allowed more persons to remain in the agricultural sector (Haney, 1985). The groundwater supply upon which irrigated agriculture is based, however, has been slowly declining for several decades.

Increasing pumping lifts, higher unit energy costs and much lower well yields in recent years have contributed to a gradual decline in irrigated acreage and irrigation water use per acre. In some areas of the High Plains, a significant transition to lower producing dryland farming has occurred and may continue with greater dependence on precipitation in the future. Farmers are generally becoming acutely aware of the need and opportunities for sound water management, both for precipitation and irrigation water. Considerable progress has been made both in technology development and on-farm adoption. Continued or accelerated adoption of the best available water management technologies may be hampered by high capital cost and low farm profitability.

Abundant research on water management in the Texas High Plains has been conducted for several decades, primarily by the Texas Agricultural Experiment Station and the Agricultural Research Service/U.S. Department of Agriculture at research centers near Lubbock, Halfway, Bushland, and Etter.

Texas Tech University has also been involved. This research knowledge has been and is being developed into general practice and transferred to farmers by education and technical assistance programs of the Texas Agricultural Extension Service, the USDA Soil Conservation Service, and underground water districts, most notably the High Plains Underground Water Conservation District No. 1 in Lubbock.

Purpose and Scope

The purpose of this report is to review and summarize major findings of research on irrigation and precipitation water management for the Texas High Plains that provides a basis for present and future guidelines. Much of the research on efficient irrigation systems was conducted in the last two decades and is continuing, while a significant portion of the crop research (on cotton in particular) has an earlier history in the region. Chapter II provides a summary of soils information, and Chapter III explains some of the irrigation water use efficiency concepts used in the remainder of the report. Chapter IV deals with managing moisture deficits and crop stress in irrigation scheduling. Research on precipitation harvesting, principally using tillage practices, is reviewed in Chapter V. Furrow irrigation research that is specific to the Texas High Plains and sprinkler irrigation system are the subjects of Chapters VI and VII, respectively.

Finally, a summary of research results from water management concepts and practices for the four major crops in the region--cotton, wheat, grain sorghum and corn--is presented in Chapter VIII.

Description of Region

The High Plains of Texas covers about 35,000 square miles (90,000 km^2) at the southern end of the Great Plains. This semi-arid region includes the upper reaches of the Red, Brazos, and Colorado River basins (Forster, 1985) and is traversed by the Canadian River. The region comprises about 11% of the state's land area.

The High Plains of Texas sits at an elevation of 3,000-4,000 feet (900-1,200 m), and it contains approximately 10.8 million acres (4.4 million ha) of planted cropland and 10.4 million acres (4.2 million ha) of range and pastureland in 42 counties (Clarke, 1986). Annual rainfall ranges from 12 to 22 inches (300-560 mm) (Figure I-1) and the growing season lasts from 180-220 days. About 5 million acres (2 million ha) of the cropland is irrigated with groundwater from the Ogallala Aquifer. In addition, more than 3.5 million head of cattle were marketed annually from cattle feedlots on the Texas High Plains, and these feedlots are a major user of grain and cotton by-products from the region.

Rainfall Patterns

Average monthly precipitation for Lubbock and Amarillo for 1911-1985 is shown in Table I-1 (Carver et al., 1985). Approximately two-thirds of the annual precipitation occurs just before or during the summer growing season. However, large variations from the mean monthly rainfall are usually experienced, and actual conditions can range from arid to humid. The amount of precipitation exceeded in 75, 50 and 25% of the 104 years of record for Amarillo show large discrepancies between average and median values, and between the wettest and driest 25% of the years, as depicted in Figure I-2 (Stewart et al., 1984).

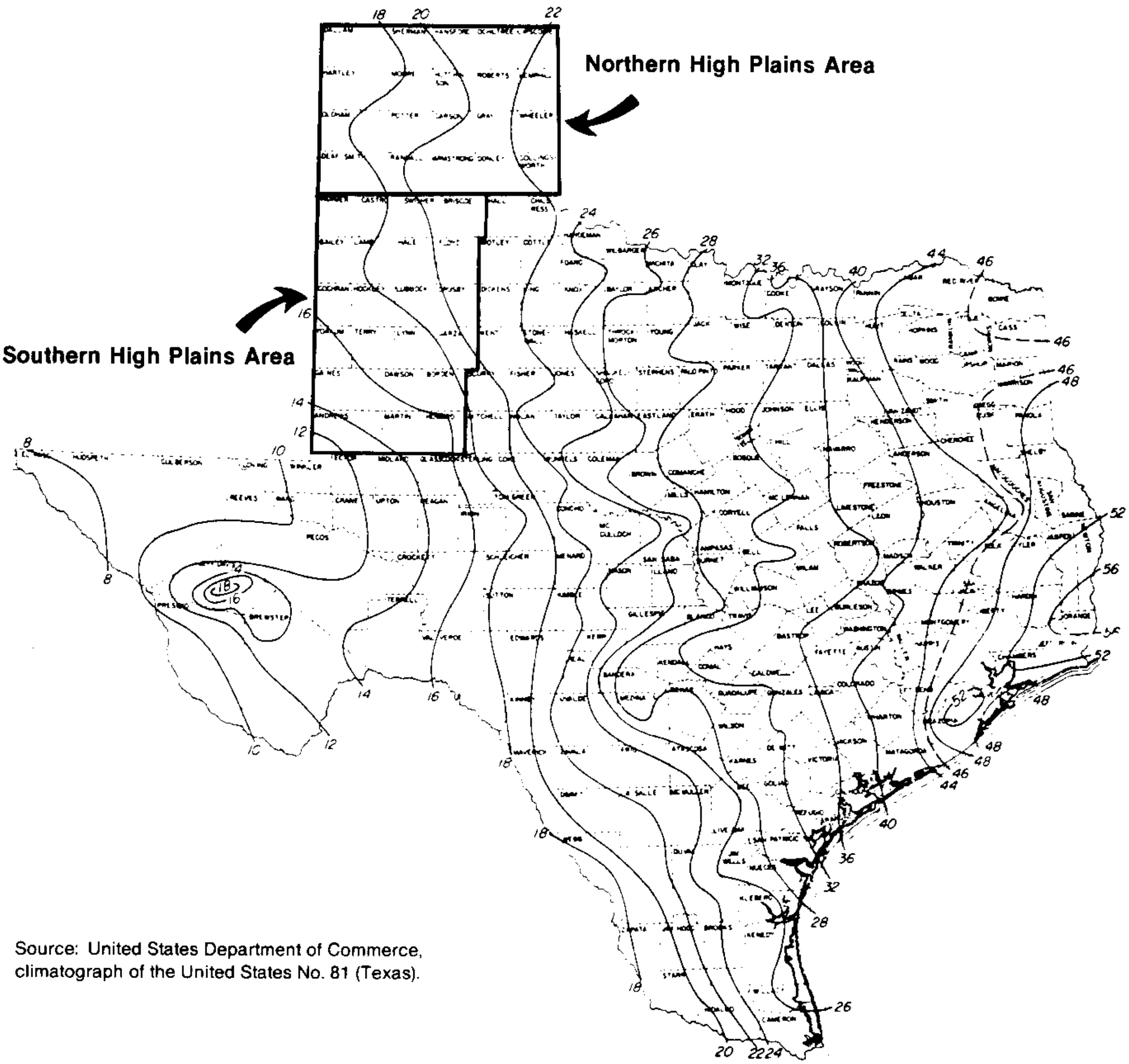

Figure I-1. Texas High Plains study region and mean annual precipitation for the region and the state (Clarke, 1986).

Table I-1

Average Monthly Precipitation at National Weather Service Stations in Amarillo and Lubbock, Texas 1911-1985

Month	Amarillo		Lubbock	
	inch	mm	inch	mm
January	0.55	14.0	0.51	13.0
February	0.64	16.3	0.63	16.0
March	0.95	24.1	0.85	21.6
April	1.32	33.5	1.25	31.8
May	2.82	71.6	2.60	66.0
June	3.19	81.0	2.60	66.0
July	2.55	64.8	2.15	54.6
August	3.05	77.5	2.08	52.8
September	2.07	52.6	2.43	61.7
October	1.73	43.9	2.17	55.1
November	0.76	19.3	0.63	16.0
December	0.66	16.8	0.62	15.7
Annual Average	20.29	515.4	18.52	470.4

Source: Carver et al., 1985.

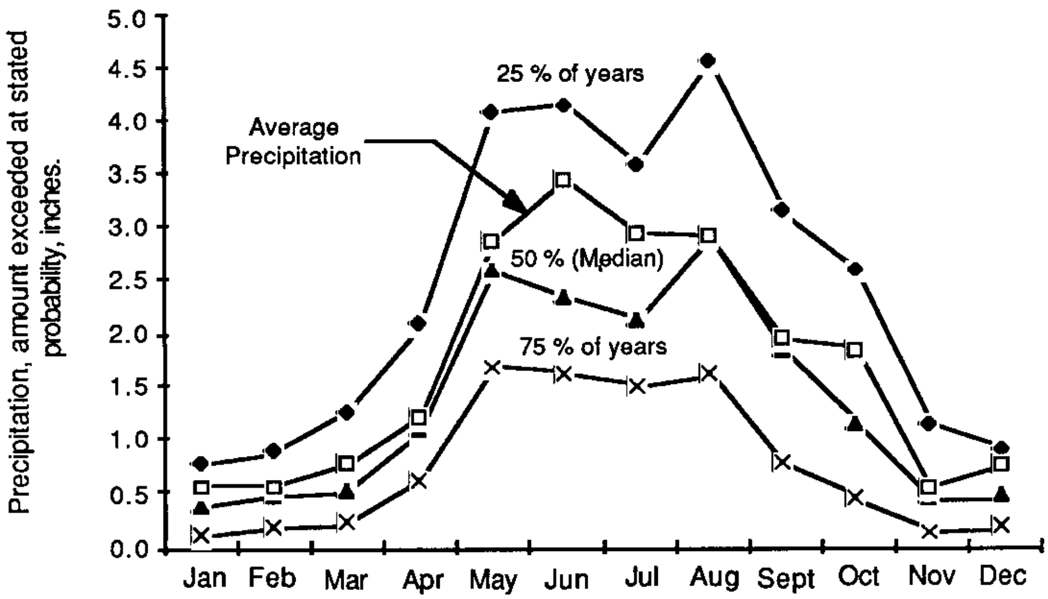

Figure I-2. Average precipitation and amount exceeded in 25, 50, and 75% of years at Amarillo, Texas, based on 104 years of data (Stewart et al., 1984).

The maximum annual precipitation in the region usually approaches 200% of the average, and minimum precipitation is about 50% of the average (Stewart and Musick, 1982). More years have below-average than above-average rainfall. Drought years provide both less rain and higher evaporation than average years. An irrigation system designed assuming near-average rainfall will be unsatisfactory both in drought and wet years (Stewart and Musick, 1982).

Rainfall probabilities are more important than average rainfall as a basis for decision making in water management, especially for dryland farming where it is almost imperative to take advantage of favorable years. Rainfall occurring in amounts of less than one inch account for about two-thirds of the annual rainfall (Carver et al., 1985). For example 20-year rainfall data for Bushland showed that 95.2% of the rainfall events were less than 1.0 inches, and they yielded 65.8% of the total precipitation (Stewart et al., 1984), as shown in Figure I-3. The remaining precipitation occurs in 3 to 5 events per year with 1 to 5 inches (25-127 mm) of rainfall (Carver et al., 1985), and these events generally create some runoff. These small precipitation events are generally absorbed by the soil, although soil storage efficiency may be low due to evaporation in hot or windy conditions (Stewart et al., 1984). As shown in Figure I-4, periods of peak rainfall are similar to the periods of maximum solar radiation and air temperature in the region (Musick and Dusek, 1980). Tillage and cultural practices to increase soil moisture storage are important.

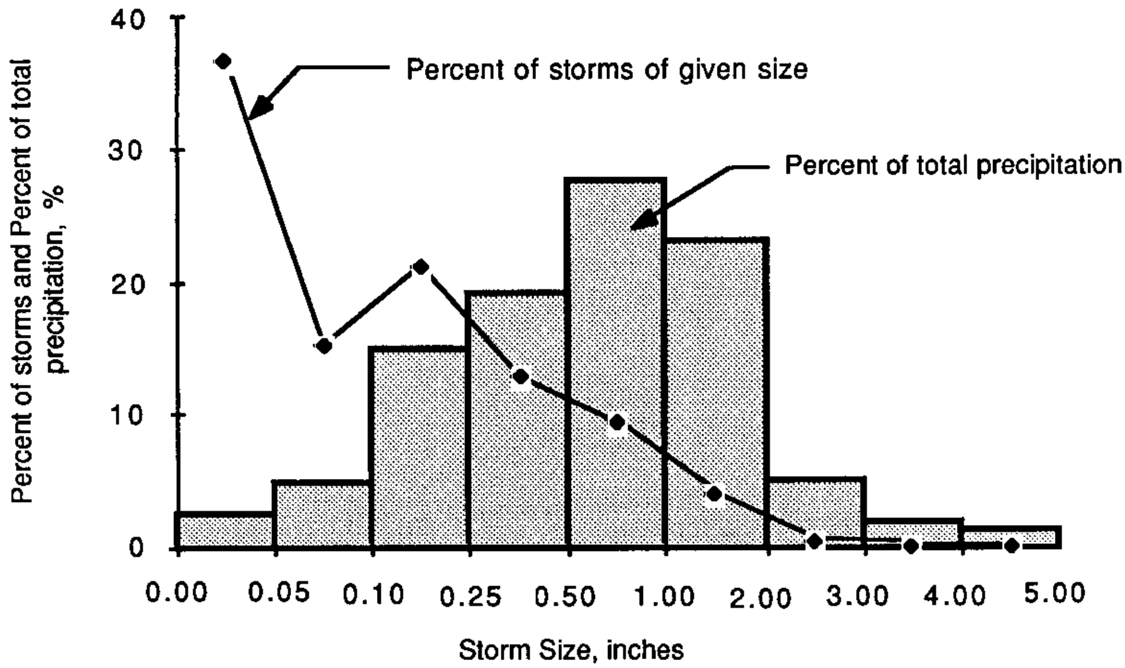

Figure I-3. Percentage of total precipitation and number of storms of given size, Bushland, Texas, 1960-1979 (Stewart et al., 1984).

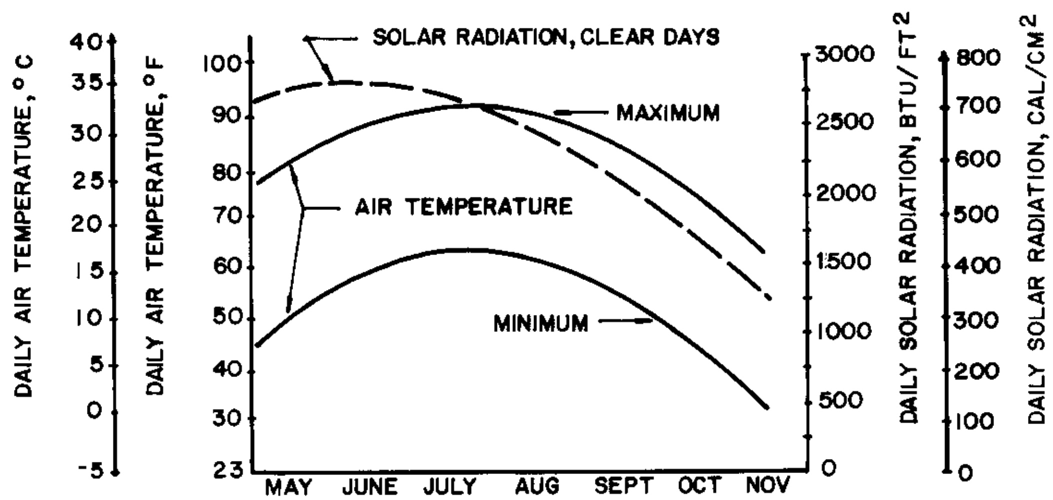

Figure I-4. Maximum and minimum air temperatures (37-year average) and daily solar radiation for clear days (10-year average) for Bushland, Texas (Musick and Dusek, 1980).

The Ogallala Aquifer

The Ogallala Aquifer which extends from Texas through Nebraska is the major component of the High Plains Aquifer, and underlies about 35,000 square miles (90,000 km^2) of the Texas High Plains (Knowles, 1985). Over 70,000 irrigation wells have been completed into this aquifer which also serves as the municipal water supply for many towns and most rural residents. Well yields are commonly 100 to 500 gallons per minute (6.3-31.5 L/s) (Schefter, 1984). Irrigation accounts for 95% of the total water used (Knowles, 1985). Total pumpage for irrigation reached a peak of 8.1 million acre-feet (10.0 km^3) in 1974 and declined to 5.6 million acre-feet (6.9 km^3) in 1979. The 1984 irrigation inventory showed pumpage at 5.0 million acre-feet (6.2 km^3).

Saturated thickness of the High Plains (Ogallala) Aquifer ranges from less than 50 feet to more than 300 feet (15-91 m) (TWDB, 1986). The thickness is primarily controlled by the topography before the Ogallala sediments were deposited and subsequently buried by later alluvial deposits (Knowles, 1985). The thicker sections are in the Northern High Plains and the thinner sections are in the Southern High Plains. The average saturated thickness is 112 feet (34 m) (Knowles, 1985). Regarding depth to water table, 30% of the water is within 100 feet (30 m) of the surface and 81% is within 400 feet (122 m).

The USGS has estimated that before significant irrigation development the High Plains Aquifer in Texas contained 3,230 million acre-feet (3990 km^3) of saturated material and 1,100 million acre-feet (1,360 km^3) of water assuming 40% porosity (Knowles, 1985). Specific yield is about 15%; hence, prior to development of irrigation, the total drainable water supply was around 500 million acre-feet (620 km^3). The drainable water was estimated at 505 million acre-feet (620 km^3) in 1960 and 420 million acre-feet (520 km^3) in 1980, of which 91% was recoverable by wells. In comparison all the lakes and reservoirs in the state have a combined conservation storage of only 32 million acre-feet (39 km^3), or only one-thirteenth of the storage of the Ogallala Aquifer in Texas. According to Knowles (1985) water surface gradient averages 15 feet per mile (0.0028 m/m) to the east-southeast or east. Rate of water movement is about 7 inches (180 mm) per day, specific yield averages 16 percent, and the hydraulic conductivity averages 400 gallons per day per square foot (16 m/day). Jones and Schneider (1969) measured specific yield of the Ogallala Aquifer at Bushland and determined a value of 22 percent using a neutron meter versus 14% using pumping tests.

According to Reddell et al. (1985), porosity of the aquifer is about 40 percent, which is filled with water when saturated. However, only about 15 percent of the aquifer volume is available water (i.e. specific yield is 15 percent) while the other 25 percent (specific retention) is held by capillary forces and is not available for pumping. This means there is only 1.8 inches of available water per foot (150 mm/m) of saturated thickness.

According to USGS estimates, the aquifer in Texas has been depleted by almost 23 percent since irrigation was first developed. Nevertheless, water levels actually rose in a large portion of the Southern High Plains during recent years. Possible reasons may include reduced pumpage due to economics and conservation technology, infiltration of earlier irrigation waters, soil modifications and above-normal precipitation.

Earlier estimates of recharge were 0.2 inches (5 mm) per year or 372,000 acre-feet (0.46 km^3) per year. But according to Knowles (1985), there is reason to believe that greater recharge could be occurring, a possibility that is currently being investigated.

The Texas Department of Water Resources developed a computer model of the aquifer and used it to project future conditions based on certain assumptions. Even with expected decreases in withdrawals, the volume of water stored in the Ogallala Aquifer in Texas would be decreased by 38 percent from 1980 to 2030, according to one set of projections (Knowles, 1985). Nevertheless, the aquifer could continue to supply substantial amounts of groundwater at least for several decades. The most significant reductions would occur in the southern part of the aquifer.

Decreased well yields are the result of lowered water levels because of and reduced aquifer transmission capacity. Well yields in the Southern Great Plains have generally decreased in relation to declining water levels according to an inverse square relationship (Hughes and Harman, 1969). Thus a 50 percent reduction in aquifer thickness would reduce well yields to only 25 percent of their initial capacities. Many wells have been retrofit with smaller pumping plants to match the smaller well yields.

Natural Recharge Rates

Natural recharge to the Ogallala Aquifer is believed to average only about 0.2 inches (5 mm) per year in Texas and New Mexico (Heath, 1984; Knowles, 1985) which is 1-2 percent of annual rainfall. The subsoil permeability is low in much of this region due to a caliche and/or hardpan layer and evapotranspiration is high, so that significant recharge occurs only during years of above normal rainfall (Heath, 1984). By contrast, the Nebraska Sand Hills portion of the Ogallala Aquifer experiences about a

4-inch (100 mm) per year recharge rate (20% of annual rainfall) due to much greater soil permeability and lower evapotranspiration.

Judd (1980) estimated that natural recharge was about 185,000 acre-feet (0.23 km^3) per year while pumpage was 4-6 million acre-feet (4.9-7.4 km^3). In other words, recharge rate was 3 to 5% of the rate of withdrawal. However, the 0.2 inch per year (5 mm) natural recharge rate does not include a potentially large amount occurring as return flow from deep percolation on irrigated land (Musick, 1987).

Water table depletions of 10 to 50% have resulted for about one third of the Texas High Plains Aquifer (Heath, 1984). However, the rate of groundwater depletion in the 15-county area (with 5.22 million acres, or 2.1 million ha) served by the High Plains Underground Water Conservation District No. 1 has slowed dramatically since 1979 (Redeker, 1984). The general trend for water in storage is shown in Figure I-5. For example, the average decline in water level measured in wells was 1.90 feet (0.58 m) per year from 1974-79. However, the average decline for 1979-84 was only 0.88 feet (0.27 m) per year. In 1985-86, zero average decline in the water table was reported (HPUWCD, 1986). The greatest average water table decline for 1974-84 of 1.8-2.6 feet (0.55-0.79 m) per year was in Castro, Parmer, Lamb and Deaf Smith Counties. Finally, in 1986 the High Plains Underground Water Conservation District No. 1 documented the first net rise in general water levels in observation wells throughout the service area (HPUWCD, 1987). Twelve of 15 counties encountered aquifer water table increases of 0.03 to 3.27 feet (0.009-1.0 m), while three counties had net declines of 0.16 to 0.38 foot (0.05-0.12 m). Total decline in water table averaged 1.0 foot (0.3 m) from 1982-87 and 7.4 feet (2.3 m) from 1977-87.

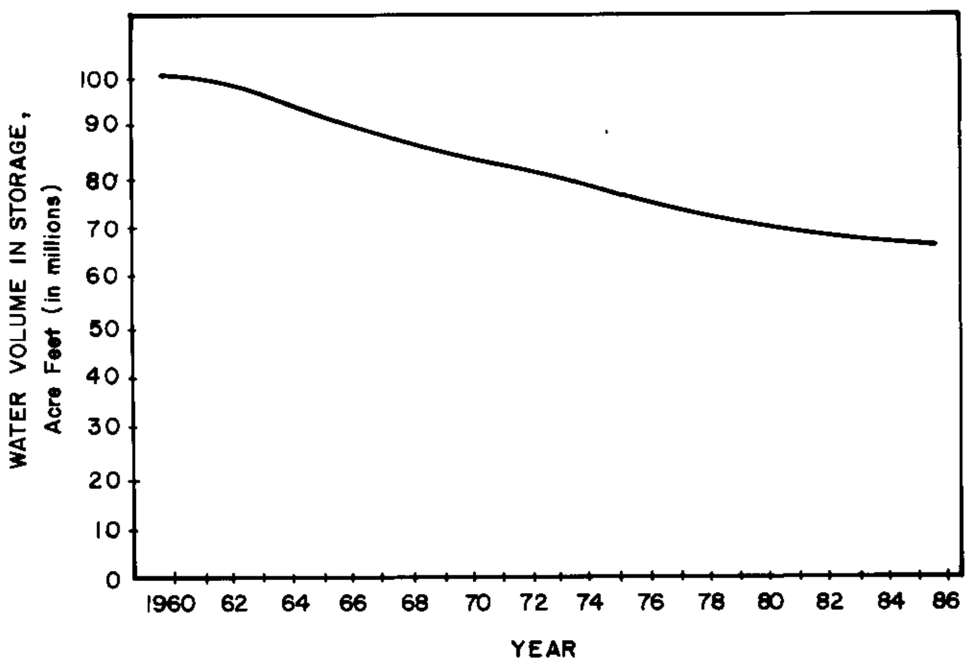

Figure I-5. Estimated volume of water in storage in the Ogallala aquifer and estimated rate of depletion, 1960-1985 in the 5.2 million acre (2.1 million ha) service area of High Plains Underground Water Conservation District No. 1, Southern High Plains of Texas (HPUWCD, 1985A).

Water Quality in Ogallala Aquifer

One of the significant attributes of the Ogallala Aquifer in the Texas High Plains is the relatively high water quality for irrigation purposes. The farmers have been able to avoid soil salinity problems, which are of major concern in many irrigated areas of the Southwest such as California, Arizona, and the Texas Rio Grande Valley. Consequently, high application rates to achieve proper leaching are rarely needed using Ogallala water.

Water quality data from public and private water supply wells in 44 contiguous counties that include the Texas High Plains and the Ogallala Aquifer were reported by the Texas Department of Health (Anderson and Bernstein, 1983). These data are summarized in Table I-2. These data show that total dissolved solids (TDS) average less than 600 ppm, which could be translated into an electrical conductivity (not reported) of approximately 400 micromhos per cm (μmhos/cm), which is low enough for nearly all irrigation uses.

The mean sodium (Na) and chloride (Cl) contents averaged 86 and 100 mg/l, respectively. Nitrates were about one-third the U.S. Enivronmental Protection Agency's public drinking water standard of 10 mg/l NO_3-N, reflecting no widespread contamination from fertilizers. Indeed recent soil testing data reveals a gradual lowering of soil nitrogen and phosphorus levels throughout the region (Wyatt, 1987). The wide variability in water quality parameters in Table I-2 are believed to reflect regional differences from north to south in the High Plains. Generally higher values of Na and TDS and lower pH values were found in the southern tier of counties (Ector, Midland, Glasscock and Howard) in the 44 counties represented in the data. In fact, some of the reported wells may

Table I-2

Summary of Chemical Water Quality in the Ogallala Aquifer, Based on Samples from 449 Public and Private Water Supply Wells [1, 2]

Constituent	Concentration		
	Mean mg/1	Standard Deviation mg/1	Range for all 449 Samples, mg/1
Calcium, Ca	67	28	1-563
Magnesium, Mg	38	21	<1-302
Sodium, Na	86	63	8-605
Carbonate, CO_3	0.42	0.89	0-18
Bicarbonate, HCO_3	281	42	126-545
Manganese, Mn	<0.026	--	<0.02-0.44
Iron, Fe	<0.093	--	<0.02-2.5
Sulfate, SO_4	126	105	3-1821
Chloride, Cl	100	93	4-788
Fluoride, F	2.3	1.3	0.2-28
Nitrate, NO_3-N	3.2	2.6	<0.01-34.8
Total Dissolved Solids (TDS)	591	294	195-4736
P. Alkalinity	0.4	0.7	0-25
Total Alkalinity	231	35	103-437
Total Hardness	322	136	5-2652
pH	8.05	0.13	7.3-9.1

[1] Data are mean values for 44 counties based on from 1 to 65 wells per county (greater well numbers for the more populated counties).

[2] Data are summarized from Anderson and Bernstein, Texas Department of Health, 1983).

have been outside the Ogallala boundaries, which could have accounted for certain extreme values that inflated the averages in Table I-2.

Nevertheless, most of the wells show very good water quality for irrigation purposes.

Secondary Recovery from Unsaturated Zone

The Ogallala Aquifer is comprised of alluvium deposited by ancient streams flowing east-southeast from the Rocky Mountains and consists of clay, silt, sand, and gravel capped by caliche (Reddell et al, 1985). The Ogallala is a water table aquifer with an unsaturated zone above the water table (saturated zone). This unsaturated zone has enlarged in recent years as the water table has declined due to depletion.

The volume of water stored in the unsaturated zone was estimated at 840 million acre-feet (1,040 km^3) in 1980 (USGS, 1981) and this would increase to 1,465 million acre-feet (1,810 km^3) at ultimate depletion. Hence, almost four times more water could remain in the unsaturated zone of the Ogallala than is presently recoverable by wells. A small reduction in specific retention from 25% to 20% would release approximately 300 million acre-feet (370 km^3) of additional water for pumping. At the 1974-1984 irrigation water use rate, this would be equivalent to several more decades of irrigation pumping.

The High Plains Underground Water Conservation District No. 1 conducted a two-year study which indicated that water recovery from the unsaturated zone by air injection can be accomplished (Reddell et al., 1985). Under laboratory conditions, applying an air pressure of 2 to 3 pounds per square inch (psi) (or 14-21 kPa) to wet sands from the Ogallala resulted in 20% more water yield than obtained only by gravity. The air injection zone must be capped with a confining layer (soil of low permeability) to restrict loss of air and pressure. To test the concept, four field investigations were conducted near Slaton (2 test sites), Idalou, and Wolfforth. Wells were drilled for air injection, air pressure testing and water level observation.

The Slaton and Idalou tests involved injecting 8.5-12.7 million cubic feet (240,000-360,000 m^3) of air in 3.5-9 days (Reddell et al., 1985). Only the Idalou site had a true pressure-confining layer above the unsaturated zone. Water levels rose 1-2 feet (0.3-0.6 m) within a few days after air injection at both sites and continued to rise gradually for almost a year. The total rise in water level ranged from 0-4.5 feet (0-1.4 m) within ½ mile (0.8 km) of the air injection well at Slaton and 3-9 feet (0.9-2.7 m) within ½ to 1¼ mile (0.8-2.0 km) at the Idalou site.

Data from the Wolfforth test (HPUWCD, 1985B) revealed a 0 to 2 foot (0-0.61 m) rise in water level for a radius of 4-8 miles (6.4-13 km) around the air injection site. The volume of water released to the saturated zone was 8,660 acre-feet (0.011 km^3). A mathematical model is being developed to predict the potential effects of air injection on water recovery from the unsaturated zone.

Surface Water to Augment Groundwater for Irrigation

Surface Runoff

Runoff volume from watersheds on Pullman clay loam near Bushland averaged 4.4, 9.3, and 8.7% of precipitation (i.e. 0.8-1.7 inches (20-43 mm) per year for a 26-year period) for wheat, sorghum and fallow watersheds, respectively. Runoff volume from these cropland watersheds was

3 to 5 times higher than for rangeland watersheds (Jones et al., 1985). The cultivated watersheds were managed with water conservation practices--terracing, contouring, and conservation (stubble-mulch) tillage--that reduced sediment loss. Consequently, runoff quality from both the cultivated and rangeland watersheds was of little or no importance as a nonpoint source of pollution with regard to sediment and nutrients.

As compared to the soil loss tolerance (T) value of 5 tons per acre (11 mt/ha), soil loss in the year with highest runoff (1978) was only 2.7-2.9 tons/acre (6.0-6.5 mt/ha) from the cropland and 0.14 tons per acre (0.31 mt/ha) from the rangeland watershed (Jones et al, 1985). Simultaneously, the nitrogen losses (total Kjeldahl nitrogen) ranged from 0-10 pounds per acre per year (0-11 kg/ha/yr) for cropland and 0-1 lbs/ac/yr (0-1.1 kg/ha/yr) from rangeland. Phosphorus losses were 0-4 lbs/ac/yr (0-4.5 kg/ha/yr) for cropland and 0-0.3 lbs/ac/yr (0-0.34 kg/ha/yr) for rangeland. Wheat produced lower runoff amounts and losses of sediment and nutrients than sorghum, while fallow fields produced the highest. Annual soil loss predicted by the Universal Soil Loss Equation (USLE) was over twice the actual 6-year average of 0.8 tons per acre per year (1.8 mt/ha/yr) for the wheat-sorghum fallow rotation.

Virtually all the surface runoff on the Texas High Plains accumulates in approximately 17,000-19,000 playas (wet weather lakes) that provide an important water resource for irrigation water management (Jones and Schneider, 1972). The volume of storm water runoff that accumulates annually in the playas has been estimated variously at 1.3 to 3.0 million acre-feet (1.6-3.7 km^3) (Hauser and Signor, 1967; Urban and Claborn, 1985).

Playas range in size from a few acres at shallow depth to a few that cover more than 200 acres (80 ha) with 10-20 feet (3-6 m) depth (Claborn et al., 1985). Typical playas may have a drainage area of 230 to 6100 acres (93-2,500 ha) and store 16-470 acre-feet (19,700-580,000 m^3) of water within the bottom clay liner. The larger playas are generally found in the northern part of the region.

The bottoms of the playa basins are characterized by an almost impermeable natural liner of clay or silt/clay (Claborn et al., 1985). Typically, this liner is classified as Randall clay. Upslope, the clay liner becomes thinner and finally disappears.

Transmission losses of runoff enroute to playas and initial filling of deep cracks in the Randall clay lake bottom can drastically reduce the available water stored in playas (Musick, 1987).

Even when pumped for irrigation, over half the collected runoff water may be lost to evaporation (Jones and Schneider, 1972). Evaporation loss from a playa surface exceeds an average of 500 gallons per minute (32 L/s) from a 100-acre (40 ha) playa (i.e. 5 gpm/acre or 0.78 L/s/ha) from May through August (Hauser, 1966). Estimated water loss by evaporation ranges from 85% with no management to only 15% with playa modification and recharge.

Using data from Reddell and Rayner (1962), Hauser (1966) calculated seepage loss from five playas near Lubbock. Seepage rate increased linearly as water depth increased, from 53% loss at 1.75 feet (0.53 m) water depth to 84% seepage loss at 6.67 feet (2.0 m) water depth.

Hauser (1966) determined that evaporation losses could be reduced by modifying playas to confine water in a smaller basin with greater depth. A detention reservoir in one corner of the playa was proposed. He estimated that 75-85 percent of the playa water could be saved by utilizing detention storage in conjunction with irrigation and groundwater recharge.

Whenever runoff is sufficient, the water level rises above the clay liner and natural recharge can occur through the surrounding sloping soil profile, which is typically a silty sand or silty loam with a relatively high permeability (Claborn et al., 1985). Recent studies have suggested that a considerable volume of water may be recharged naturally through the permeable soil surrounding the playa clay bottoms.

Quality of runoff caught in playas generally is excellent for irrigation (Lehman and Hauser, 1970). Water quality was monitored in 5 playas near Bushland during a 4-week period following a spring rainfall event. Initial water quality values of collected runoff from surrounding crop and pastureland were as follow: specific conductance or electrical conductivity--90-165 μmhos/cm; pH--6.8-7.2; nitrate--0.9-8.2 mg/l; suspended solids--890-1920 mg/l; chemical oxygen demand--57 mg/l (one playa only); and alkalinity--0.7-1.2 mg/l. With storage time of 2-3 weeks, concentrations of nitrate, chemical oxygen demand, and suspended solids generally decreased. However, specific conductance increased due to evaporation to levels of 135-285 μmhos/cm (still quite low), and pH and alkalinity likewise increased with storage time. The runoff water in playas is turbid and requires 3-5 days to settle (Urban and Claborn, 1985).

The playas are also useful for capturing tailwater runoff from irrigation. Rayner (1970) estimated that with 100% capture and reuse of irrigation tailwater runoff, almost 20% of the irrigation water pumped in a 4-county area could be saved. New (1970) estimated that 3000 playas were equipped for capturing irrigation water.

Aquifer Recharge with Playa Water

The concept of enhancing recharge of the Ogallala Aquifer with playa lake water has been studied by several investigators. Groundwater can be artifically recharged either by injection or percolation (Schneider, 1975).

The primary difficulty has been removal of suspended sediment in order to reduce groundwater contamination and plugging of recharge systems. In an early attempt, Schneider et al. (1971) reduced the specific capacity of a dual purpose (irrigation/recharge) well near Lubbock from 6 gpm per foot (0.0012 m^2/s) to only 3.8 gpm per foot (0.00079 m^2/s) in recharging only 0.58 acre-feet (715 m^3) of untreated playa lake water. Only 20 percent of the injected sediment was subsequently recovered by pumping. Hauser and Lotspeich (1968) developed a chemical flocculation and sedimentation system that achieved 90 percent removal of suspended solids, which had an initial concentration of 210 mg/l, primarily in the form of colloidal clay.

Aronovici et al. (1972) developed a promising system of aquifer recharge consisting of excavating small recharge basins around the playa into more permeable subsoils. The percolation rate with turbid playa water peaked at 3.3 feet (1.0 m) per day but diminished and stabilized at about 1 foot (0.3 m) per day after 60 days. By contrast, similar recharge basins with clear water (pumped from the Ogallala for test purposes) showed much higher recharge rates (up to 6.6 feet (2.0 m) per day).

A system of filter underdrains buried under the playa and discharging laterally into a nearly recharge well has been developed by Urban and Claborn (1985). Horizontal wick filters that were fabricated of geotextiles arranged in different configurations were tested. Water percolates through a layer of soil in the playa bottom and into the filter unit before flowing laterally to an injection well. Approximately 20 percent of the water in the playa passed through the filtration and metering system and was recharged in one test. The flow rate decreased with time due to decreased head and sediment deposition. With the exception of hardness, the filtrate met the USEPA primary drinking water standards for inorganic chemicals, and met secondary drinking water standards except for iron and manganese. Three new filter systems installed in 1985 produced more than 97 percent reduction in suspended solids from playa water (from 172 mg/l to less than 5 mg/l), even though total dissolved solids increased more than 100 mg/l as lake water percolated through the soil and filters (WRC, 1986).

In a 0.1-acre (0.04 ha) recharge basin, Goss et al. (1973) showed that 92 percent of the suspended solids in playa water were filtered out within 1 inch (25 mm) of the basin surface. These sediments were mechanically removed after surface drying (Jones et al., 1974). During eleven recharge cycles with turbid playa water, a total of 432 feet (132 m) were recharged at an average rate of 1.42 feet (0.43 m) per day. In some tests, surface cracks appeared in bottom sediment even while inundated, which enhanced recharge. Management practices were developed to increase recharge rates of playa water and reduce surface sealing (Jones et al., 1981). Management practices that increase recharge rates include (a) increased depth of flooding; (b) soil incorporation of cotton gin trash (organic matter); and (c) addition of cationic polyelectrolyte flocculent.

Schneider and Jones (1983) operated a 0.5 acre (0.2 ha) recharge basin from 1971-78 in a 40-acre (16 ha) playa over a 7-year period. During eight extended tests totaling 187 days of flooding, the average recharge rate ranged from 0.77-1.82 feet (0.23-0.55 m) per day averaging 1.22 feet (0.37

m) per day. No maintenance was performed on the basin bottom after the first year. The basin was excavated above one side of the playa to a depth of 4 feet (1.2 m) through slowly-permeable Pullman clay loam soil into a caliche layer overlying permeable sediments. The bottom was sloped and corrugated with 40-inch (1.0 m) furrows and a basin drain was installed at the lower end to remove sediment-laden water when desired. Suspended solids concentrations in the recharged water averaged 73-638 mg/l among tests, with 38 tons of sediment (34.6 metric tons) filtered through the basin floor in the 8 tests. Highest recharge rates were achieved with the highest flooding depths. Recharge rates generally decreased with time for each test. A temporary groundwater mound developed above the caprock layer as was also observed by Jones et al. (1974), but the underlying Ogallala water table rose as much as 9 feet (2.7 m) after recharge events. Because of the gravity drain, basin maintenance was not required during the last 6 years.

Schneider et al. (1977) studied the movement and recovery of three herbicides incorporated in aquifer recharge water through an injection well. The three herbicides--picloram, atrazine, and trifluralin--were injected with a tracer for 10 days. Two herbicides (atrazine and picloram) moved freely through the aquifer and were detected in observation wells 65 feet (20 m) away but not at 150 feet (45 m) distance. After a 10-day pause, over 90 percent of the herbicides and nitrate tracer were recovered by pumping from the injection well for 12 days. The volume pumped was 1.66 times the volume of recharge water. This research indicated that accidental injection of these herbicides could be overcome with swift action, monitoring, and presence of a dual-purpose well.

Claborn et al. (1985) used runoff simulation analysis based on historical rainfall data to estimate the amount of natural aquifer recharge in playas and the amount of playa water that is potentially available for artificial recharge. Depending upon the assumptions and simulation procedures, the amount of runoff water naturally recharged through permeable sediments surrounding the clay bottom liner could range from approximately 27 percent to 43 percent. Artifical recharge would reduce evaporation loss of the remaining water.

It appears that recharge basins can be an effective method of returning playa water to the aquifer during fallow seasons. However, playa water can be more economically utilized directly for irrigation during many seasons of the year (Schneider and Jones, 1983).

Economic Response to Water Levels and Energy Prices

Economic impacts of declining groundwater levels in the High Plains of Texas have caused sharply higher pumping costs and reduced usage of irrigation water. Schefter (1984) reported, for example, that water levels in a Floyd County observation well decreased from 60 feet (18 m) in 1945 to 245 feet (75 m) below the land surface in 1984, mainly in response to irrigation withdrawals. The saturated thickness was reduced from about 300 feet (91 m) to approximately 100 feet (30 m). Meanwhile, the energy cost of pumping water from the USGS observation well increased by almost 600 percent (in constant dollars), from \$3.82 per acre-foot (\$0.0031/m^3) in 1952 to \$26.47 per acre-foot (\$0.021/m^3) in 1981. Simultaneously, the index of farm prices increased only 116 percent. Over the 30-year period, declining water levels contributed slightly more to increased pumping cost than did the increased energy prices, which actually decreased the first 22 years but increased by 233 percent the last 8 years (1973-81).

Between 1969 and 1979, total irrigated acreage in the Southern High Plains of Texas dropped 10 percent, and the average annual water application rate decreased 15% from 1.2 to 1.0 acre-feet per acre (0.37 to 0.30 m) (Schefter, 1984). Decreased annual withdrawals can be attributed to higher pumping costs, declining well yields, and resulting changes in irrigation practices.

Economic factors decreased irrigated acreage statewide from 7.8 million acres (3.2 million ha) in 1979 to 6.7 million acres (2.7 million ha) in 1984 (TWDB, 1986). By 1984, the High Plains had nearly 4.6 million acres (1.9 million ha) of irrigated land, accounting for 68 percent of the total irrigated acreage in the state. Graded furrow irrigation was practiced on 2.81 million acres (1.14 million ha) in 1984, as compared to 4.60 million acres (1.86 million ha) in 1974 (Musick et al., 1987). Sprinkler irrigation decreased from 1.73 million acres (0.70 million ha) in 1979 to 1.68 million acres (0.68 million ha) in 1984. Together, graded furrow and sprinkler irrigation accounted for nearly all the irrigated crop acreage in the region. The transition to dryland is primarily occurring on land that was furrow irrigated. This transition is generally concentrated in counties that have experienced major groundwater declines or the decline has reached critical economic limits because of lower irrigation well yields.

Summary

The High Plains region comprises about 11 percent of Texas and contains more than 21 million acres (8.5 million ha) of agricultural land, of which approximately half is cropland. Nearly 50 percent of the cropland is irrigated with groundwater from the Ogallala Aquifer, which has been depleted by 23 percent since irrigation began in the region around World War II. Precipitation averages 12-22 inches (300-560 mm) of which almost two-thirds falls just before or during the 200-day summer growing season, and therefore this precipitation is largely available for crop utilization. Average precipitation is highly misleading, however, due to wide variation among years, and farmers should base decisions mainly on probabilities of rainfall above a specified amount rather than count on average values.

Irrigation water withdrawal from the Ogallala Aquifer is currently about 5 million acre-feet (6.2 km^3) per year. The drainable water in storage has recently been estimated at 420 million acre-feet (520 km^3), which is 12 times greater than the conservation storage in all the lakes and reservoirs in Texas.

Graded furrow irrigation diminished by almost 40 percent from 1974-84 to 2.81 million acres (1.14 million ha) while sprinkler irrigation decreased only 3 percent to 1.68 million acres (0.68 million ha) in the same time span. The reduction in graded furrow irrigation has generally occurred on the more permeable soils and in counties that have experienced the greatest groundwater decline.

Water use on irrigated cropland averages 12 inches (300 mm) per year. The relatively recent reduction in water use is attributable to economic response to energy and commodity prices, increased pumping lifts, and widespread adoption of available water conservation technology.

Natural recharge rates to the Ogallala Aquifer have been estimated at only 0.2 inches (5 mm) per year average or 0.37 million acre-feet (0.46 km^3). However, recent observers believe greater recharge may be occurring. The general water table decline has apparently almost ceased in many counties, presumably in response to reduced ground water useage.

Researchers have made numerous successful attempts on a limited scale to enhance the rate of recharge to the aquifer by injecting surface water caught in natural playa lake through basins or wells. Successful attempts have also been made to enhance the water table by secondary recovery methods by injecting compressed air that releases capillary water allowing it to percolate to the water table.

Despite some loss of sediment and nutrients through runoff and soil erosion, quality of surface runoff is good, especially from rangeland watersheds. Sediment losses are generally far below the so-called T-values of 5 tons per acre per year (11 Mg/ha). Nevertheless, surface runoff collected in playas requires settling, chemical treatment, and/or filtration prior to attempted artificial aquifer recharge. Groundwater in the Ogallala Aquifer has excellent quality for irrigation purposes which makes limited irrigation feasible and leaching for salinity control unnecessary. Consequently, water conservation practices have been and should continue to be strongly encouraged for both short and long term economic benefit.

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CHAPTER II

SOILS IN THE HIGH PLAINS

Soil Infiltration

Infiltration rate of cropland soils is primarily affected by soil properties such as texture, structure, aggregate stability, surface crusting tendencies, sediment migration, moisture content, type of clay, organic matter content and salinity status. Restrictive clay layers with poor structure are a dominant factor in controlling infiltration rate and consequent irrigation application rates in many soils. High soil density in the lower tillage zone (plow pan) restricts hydraulic conductivity and enhances runoff. Irrigation water quality also influences infiltration rate over time, especially with regard to total salinity, sodium concentration, and (for wastewater irrigation) organic matter content. Infiltration rates can vary significantly within a field and over time due to cultural practices.

Soil Moisture Storage

Soil water is essential for tillage and planting, seed germination, root development, nutrient absorption by roots, and transpiration (Stegman et al., 1983). Soil moisture is also important for chemical and microbial processes that result in plant residue decomposition and mineralization of nutrients. While leaching is necessary to maintain a favorable salt balance in many irrigated soils, Ogallala Aquifer water is low in salts and does not require application of excess water for leaching.

In semi-arid regions, as much water as possible should be stored in soil for subsequent crop use. Water storage in soil is increased when evaporation and rainfall runoff are minimized, soil conditions are conducive to rapid water infiltration, and weeds are effectively controlled (Unger, 1984).

The amount of water that can be stored in a soil is affected by various factors, with the most important being depth and texture (Unger, 1984). More water can potentially be stored in a deep soil than in a shallow soil, but the amount extracted will depend on the effective rooting depth. A deep-rooted crop would potentially extract more water from a deep soil than from a shallow soil, while a shallow-rooted crop is less affected by soil depth.

Soil texture affects the amount of water retained by a soil, which usually increases with increasing amounts of silt and clay (USDA, 1955). For soils of equal depth, sandy soils have much lower total water-holding capacity than clay soils. Soils with loam, silt loam, light clay loam, and clay loam textures generally have the highest capacity for holding water in the plant-available range (Unger, 1984).

Ratliff et al. (1983) at Temple, Texas determined the extractable soil moisture from 401 soil samples representing essentially all soil textural classifications. The survey included 13 soils from the Texas High Plains. The soil water limits (percent by volume) that were investigated were:

a. Drained upper limit--highest field-measured water content of a soil after wetting and complete drainage;
b. Lower limit--lowest field-measured water content of a soil after plants had stopped extracting moisture; and
c. Potential extractable soil water--difference between drained upper limit and lower limit.

In addition, water contests at -0.33 bar and -15.0 bar (-33 and -1,500 kPa) matric potential levels were measured in the laboratory.

Field-measured values of potential plant-extractable soil water are summarized in Figure II-1, in which the mean and standard deviation are plotted versus soil textural class. The data showed, for example, that for clay loam soils, the potential extractable soil water is 12.5 ± 3.2% by volume as compared to 13.2 ± 2.2% for sandy loam and only 8.0 ± 3.1% for sand. Experiments with Pullman clay loam soil showed that water extraction varied slightly with crop. Sunflowers, wheat and sorghum extracted 9.7, 9.0, and 7.9 inches (246, 230, and 200 mm), respectively, from a 6.9 foot (2.1 m) deep soil profile between the drained upper and lower limits defined above. This indicates average values of potential extractable soil water of 11.7, 10.9, and 9.6% by volume for the Pullman clay loam.

For dryland crops, the amount of water stored in soil at the time of planting is extremely important. For instance, at Bushland on Pullman clay loam soil, grain yields of wheat, sorghum and sunflowers increased an average of 164, 385, and 158 lbs/acre, respectively, for each additional inch (i.e. 0.72, 1.70, and 0.70 kg/m^3) of plant-available water in the soil at planting time (Unger, 1984). And, in 1983 when total rainfall during the growing season averaged only 2.0 inches (51 mm), dryland grain sorghum yields averaged 1,960 lbs/acre (2,200 kg/ha) because the soil was filled nearly to capacity at planting time and the plants extracted 6.9 inches (175 mm) during the growing season.

Conversely, the amount of soil moisture remaining after a crop season is an important factor in the moisture budget for the next crop, together with fallow season precipitation and irrigation (if any). Stewart (1984) determined the historical level of soil water remaining in the top 4 feet

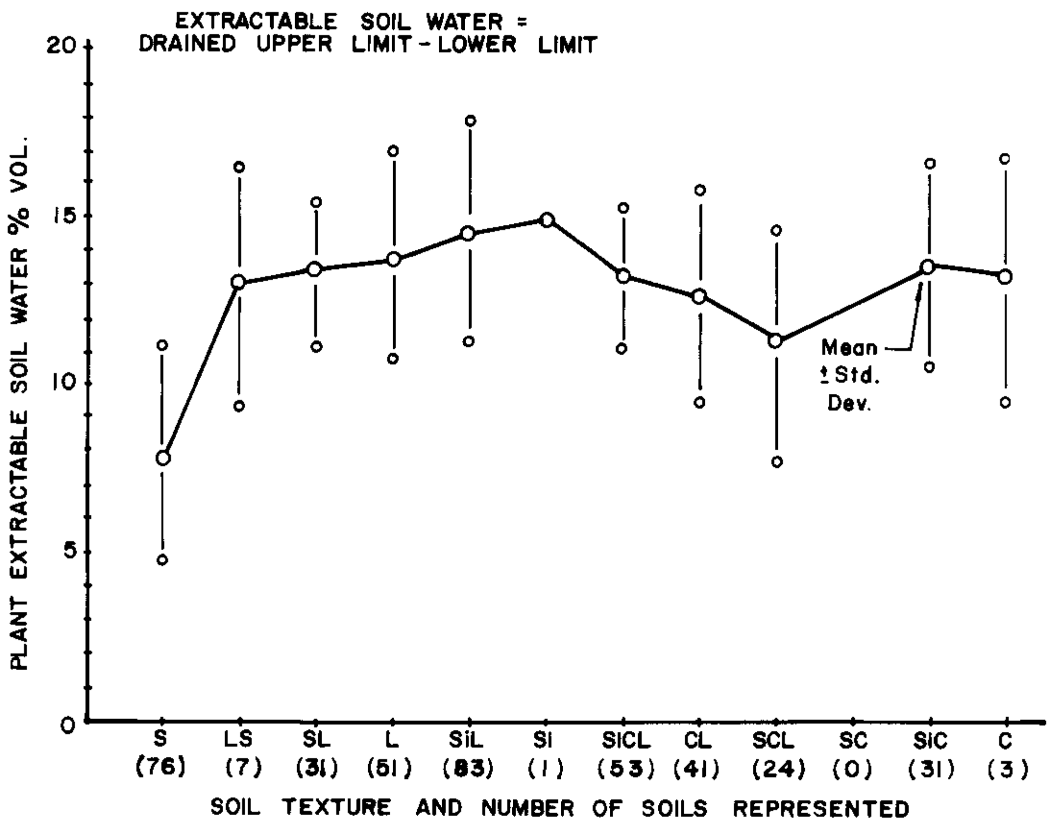

Figure II-1. Field measured potentially extractable soil water as a function of soil textural class based on 401 soil samples (Ratliff et al., 1983). S = sand, L = loam, Si = silt, C = clay.

(1.2 m) following harvest of dryland wheat and grain sorghum at Bushland on a Pullman clay loam. As shown in Figure II-2, the total soil moisture equaled or exceeded 10 to 12 inches (254-305 mm) after harvest in approximately 52% of the years. Post-harvest soil moisture was above the wilting point of about 9 inches (230 mm) in over 90% of the years, but was always below field capacity of about 15.5 inches (394 mm).

Major Soil Series

Soils of the High Plains (Table II-1) have formed under grass cover in Rocky Mountain outwash and sediment of variable sand, silt, clay and lime content (Runkles, 1968). Calcium carbonate and to some extent gypsum are present in most soil profiles, and rainfall has been insufficient to leach these bases from the soil profiles. Many of the surface soils are neutral to slightly acidic to calcareous and low in organic matter.

Dark colored to brown clayey to loamy soils extend over 5 million acres (2.0 million ha) in the northern part of the area. They include Pullman, Sherm, and Randall series, and are commonly referred to as "hardlands" (Runkles, 1968). Brown, slightly acidic soils with loamy to sandy surface layers with finer textured subsoils occupy about 7 million acres (2.8 million ha) in the central portion of the area (Table II-1). These soils comprise the "mixed lands" and include the Amarillo, Olton, Dalhart, and Richfield series. The Brownfield series is the most extensive soil with a sandy surface underlain by finer texture subsoil and is found mainly in the southern half of the region in the so-called "sandy lands." Other productive soils include the Mansker, Portales, Zita, and Berthoud series that occupy another 3 million acres (1.2 million ha). They are

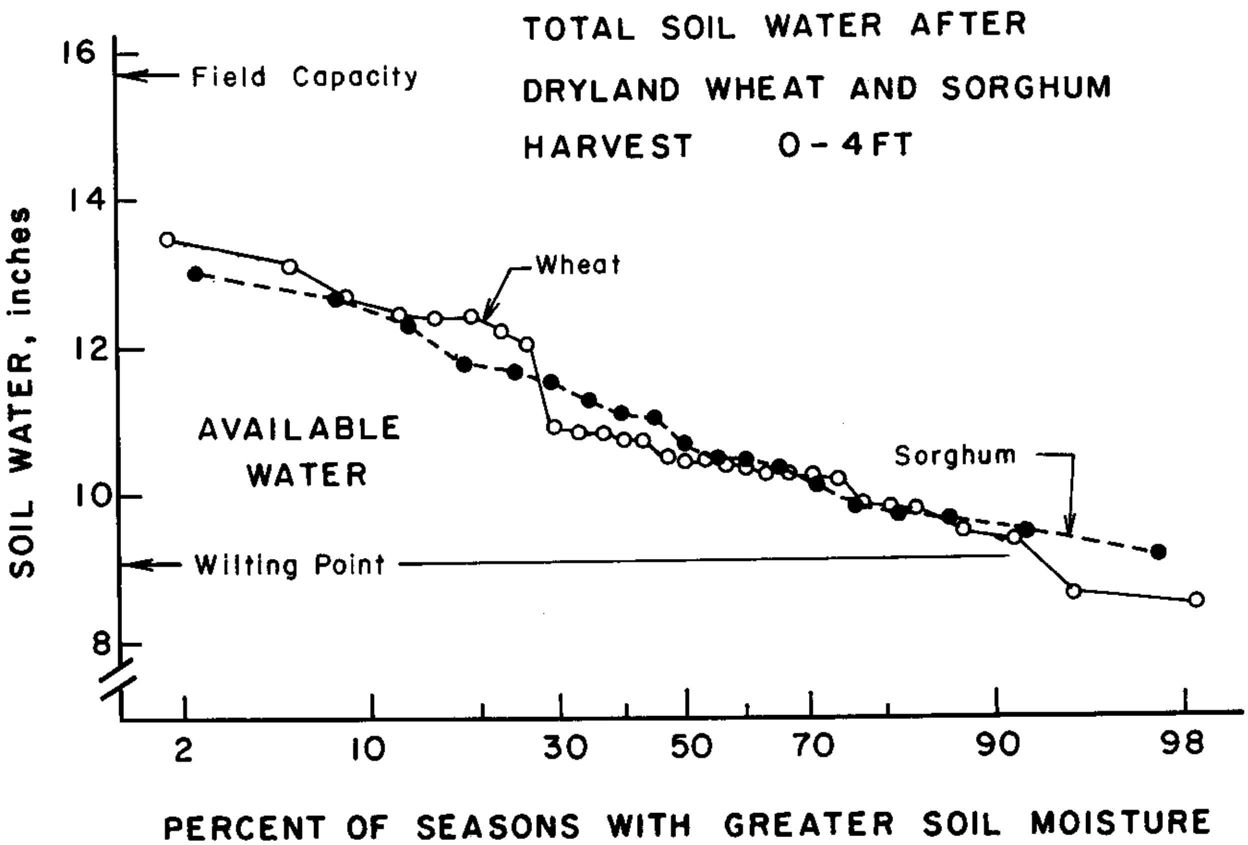

Figure II-2. Plant available soil water remaining in the soil profile after harvest time for dryland wheat and sorghum, Bushland, Texas (Stewart, 1984).

Table II-1

Soils of the High Plains
(Runkles, 1968)

Major Soil Series	Description	Acreages,[1] 1,000 acres
Pullman/Sherm Randall	Dark colored to grayish brown clayey and loamy soils - firm clayey subsoils.	5,000.0 200.0
Amarillo Olton Dalhart Ulysses Richfield	Brown loamy soils - friable loamy to clayey subsoils.	4,000.0 600.0 700.0 300.0 100.0
Mansker Portales Zita Kimbrough Arvana Berthoud Bippus	Brown moderately deep clayey and loamy soils - very limy subsoils.	1,500.0 700.0 100.0 100.0 150.0 600.0 150.0
Potter Rough Broken Lands Arch	Light colored shallow soils over limy earths or limestone.	1,000.0 100.0 100.0
Brownfield Tivoli Likes Vona	Brown sandy soils over loamy subsoils and deep sandy soils.	1,500.0 500.0 200.0 100.0
Spur	Brown loamy alluvial soils.	100.0
Miscellaneous other soils		223.2
	TOTAL	18,023.2

[1] Does not include approximately 4 million acres below the caprock escarpment along the Canadian River Valley.

generally loamy and clayey soils of moderate depth and limy subsoils. Several of these soils are described in this chapter.

Pullman Soil Series

Pullman clay loam is a fine-textured, slowly permeable soil which constitutes about 3.8 million acres (1.5 million ha) of irrigated land on the High Plains of Texas (Allen et al., 1980; Unger and Pringle, 1981). The Pullman series is the most extensive arable soil in Texas (Unger and Pringle, 1981). It is a member of the fine, mixed, thermic family of Toretic Paleustolls of the order Mollisols (Musick and Dusek, 1974). Typical physical characteristics of Pullman soils are summarized in Table II-2 (Undersander et al., 1985).

The Pullman series consists of deep, well drained, very slowly permeable clayey soils on nearly level to gently sloping uplands (National Cooperative Soil Survey, 1977B). This type of soil erodes easily. The surface tillage zone is a very dark grayish brown clay loam, underlain by moderate to strong blocky clay to about 3 feet (0.9 m) depth. Below this depth is clay loam which is interspersed with 40 to 60 percent calcium carbonate in the 5 to 6 feet (1.5-1.8 m) depth. The B horizon extending from about 10 to 24 inches (150-610 mm) is slowly permeable which causes the soil to have basic intake rates of 0.05 to 0.10 inches per hour (1.3-2.5 mm/hr). Pullman soil is a swelling clay which develops shrinkage cracks upon drying. Bulk densities are 81 to 87 lbs/ft^3 (1.3 to 1.4 g/cm^3) in the surface foot and 94 to 100 lbs/ft^3 (1.5 to 1.6 g/cm^3) in the clay subsoil.

Water intake characteristics of the Pullman soil also affect efficient irrigation water management. Initial intake has been found to be 2 to 3

Table II-2

Physical Characteristics of Pullman and Sherm Clay Loam Soils[1]
(Undersander et al., 1985)

Soil Type	Layer	Depth, inches	Sand %	Silt %	Clay %	Bulk Density lbs/ft^3	Bulk Density g/cm^3	% OM
Pullman	Ap	0-6	17.0	53.0	30.0	78.6	1.26	2.06
series	Bt1	6-16	13.0	38.8	48.2	92.4	1.48	1.29
(Bushland)	Bt2	16-29	13.0	40.0	47.0	99.8	1.60	0.95
	Bt3	29-44	15.0	40.8	44.2	98.6	1.58	0.76
	Bt4	44-58	19.3	37.2	43.5	103.0	1.65	0.39
	Bt5k	58-80	--	--	--	--	--	--
Sherm	Ap	0-6	16.8	47.2	36.0	78.6	1.26	2.17
series	Bt1	6-19	12.0	41.3	46.7	88.0	1.41	1.13
(Etter)	Bt2	19-34	13.9	48.0	38.1	94.2	1.51	0.56
	Bt3	34-54	26.5	41.2	32.3	98.6	1.58	0.30
	Bt4k	54-72	18.2	56.2	25.1	86.1	1.38	0.24

[1] Data from Unger and Pringle (1981) and (1984).

Table II-3

Soil Moisture Content of Pullman Clay Loam at
Various Tension Values (Unger, 1970)

Profile Depth, Ft.	Field Capacity, Field-Determined	Wilting Point	1/3-Bar Tension	15-Bar Tension
	------------Soil water, inches/foot----------------			
0-1	4.08	2.09	4.15	2.47
1-2	3.82	2.46	4.39	2.80
2-3	3.67	2.37	4.20	2.69
3-4	3.68	2.43	4.21	--

inches (51-76 mm) during the first 2 hours after surface flooding and ponding in plots (Hauser and Taylor, 1964; Jensen and Sletten, 1965), which indiates 1.0-1.5 inches per hour (25-38 mm/hr) initial intake rate. After 2 to 4 hrs when shrinkage cracks and large voids are filled, the intake rate drops to less than 0.1 inch per hour (2.5 mm/hr). The low basic intake rate of 0.05 to 0.10 inch per hour (1.3-2.5 mm/hr) is caused by the slowly permeable clay B horizon below the major tillage zone. The major restricting zone is the 12 to 15 inch (300-380 mm) depth, where the hydraulic conductivity was found to be 0.047 inches per hour (1.2 mm/hr) (Musick and Dusek, 1974). Slower initial intake is experienced in graded furrows due to lateral wetting requirements (Musick, 1987).

New (1985) found that the permeability of Pullman clay loam soil was only 0.0052 to 0.046 inches per hour (0.13-1.17 mm/hr) after 24-48 hours of water application in ring infiltrometers at six locations. The permeability decreased to 0.01 inch per hour (0.25 mm/hr) or less after 108 hours of continuous submergence.

On Pullman clay soil, soil moisture conditions have been determined at field capacity, wilting point, 1/3-bar (33 kPa) tension, and 15-bar (1,500 kPa) tension relative to grain sorghum (Jensen and Sletten, 1965; Unger, 1970). These values are shown in Table II-3. Unger and Pringle (1981) stated that the Pullman soil at Bushland holds 4.1-4.25 inches of total water per foot (340-350 mm/m) and about 1.85 inches per foot (150 mm/m) is available to plants (i.e. 7.7 inches (200 mm) in 4-foot (1.2 m) rooting depth).

The low water infiltration rate of Pullman clay loam allows the use of long irrigation furrows with little deep percolation (Unger and Pringle, 1981). However, tailwater runoff may be high unless a reduced (cutback) furrow stream is used during the irrigation set. Tailwater recovery pits and a return pumping system may be attractive. With sprinkler systems, irrigation application rates should be consistent with infiltration rates to reduce runoff.

Olton Soil Series

The Olton series consists of deep, well drained, moderately permeable soils on nearly level to gently sloping uplands (National Cooperative Soil Survey, 1982). The Olton soil is a fine, mixed thermic family of Aridic Paleustolls. According to Musick (1985), the Olton soil has a reddish-brown, neutral, clay loam surface layer about 8 inches (0.2 m) thick. The subsoil is blocky clay loam to a depth of 47 inches (1.2 m). It is reddish brown in the upper part and yellowish red below 31 inches (0.8 m). From 47 to 71 inches (1.2 to 1.8 m), the Olton soil is pink clay loam containing about 50% by volume calcium carbonate. Below 71 inches (1.8 m), it is reddish-yellow clay loam with about 25% calcium carbonate. The average available water capacity is 16% by volume or approximately 8.8 inches (224 mm) in the 0 to 55 inch (0 to 1.4 m) profile depth to caliche.

Olton soils have a permeability of 0.6 - 2.0 inches per hour (15-51 mm/hr) in the upper 8 inches (0.2 m), and 0.2 - 0.6 inches per hour (5-15 mm/hr) in the 8-80 inch (0.2-2.0 m) depth range (National Cooperative Soil Survey, 1982). The available water holding capacity is 1.7 - 2.4 inches per foot (140-200 mm/m) in the top 48 inches (1.2 m), decreasing to 1.2 - 1.9 inches/foot (100-160 mm/m) for the 48-80 inch (1.2-2.0 m) depth. This soil is favorable for irrigation. Bulk densities are 78 to 90 lbs/ft^3 (1.25 - 1.45 g/cm^3) in the tillage zone and 81 to 103 lbs/ft^3 (1.30 - 1.65 g/cm^3) below 8 inches (0.2 m).

Sherm Soil Series

The Sherm series consists of deep, gently sloping to level well drained soils with very slow permeability on uplands north of the Canadian River (National Cooperative Soil Survey, 1971). Sherm soils occupy about 1.3 million acres (0.52 million ha) in Texas (Unger & Pringle, 1986). It is a member of the fine, mixed mesic family of Torrertic Paleustolls. Physical characteristics of the Sherm soil are shown in Table II-1 (Undersander et al., 1985).

The soils have a brown clay loam A horizon that has a thickness of 0-5 inches (0-0.13 m) with granular structure, permeability of 0.06-0.2 inches per hour (1.5-5.1 mm/hr) and water holding capacity of 1.8-2.4 inches per foot (150-200 mm/m), according to the National Cooperative Soil Survey (1971). From 5-35 inches (130-890 mm) depth, the Sherm soil is a clay with blocky structure, permeability of less than 0.06 inch per hour (1.5 mm/hr), and available water capacity of 1.6-2.2 inch per foot (130-180 mm/m). The subsoil between 35-84 inches (0.9-2.1 m) consists of light brown to reddish yellow clay loam with subangular blocky structure, 0.06-0.2 inches (1.5-5.1 mm/hr) permeability, and 1.2-2.0 inch per foot (100-167 mm/m) available water holding capacity. Unger and Pringle (1986) stated that total water storage is 4.1 inches per foot (340 mm/m) of which 2.1 inches per foot (175 mm/m) is available for use by plants. The percolation rate is slow, and the soil erodes easily.

The Sherm series is very similar to a Pullman clay loam in terms of water management and irrigation due to the presence of a thick restrictive clay layer just below the tillage zone. Because the soil is slowly permeable, relatively long periods of water application are needed to add large amounts of irrigation water to Sherm soils (Unger and Pringle, 1986). Furrow irrigation, the most commonly used method, usually generates considerable amounts of tailwater before adequate water is stored in the soil profile at the lower end of the field. This tailwater runoff reduces irrigation water use efficiency unless tailwater recovery systems are used. Center pivot sprinkler systems have reduced runoff compared to furrow irrigation.

Amarillo Soil Series

The Amarillo series, typically fine sandy loam, consists of deep, well drained, moderately permeable soils on nearly level uplands (National Cooperative Soil Survey, 1977A). The soil belongs to the taxonomic class of fine-loamy, mixed, thermic Aridic Paleustalfs. The top one-foot (0.3 m) contains only 5-18% clay, has a permeability of 2.0-6.0 inches/hour (51-152 mm/hr), and an available water holding capacity of only 0.7-1.8 inches per foot (58-150 mm/m) with low shrink-swell potential. The 11-80 inch (0.3-2.0 m) depth or below consists of sandy clay loam with permeability of 0.6-2.0 inches per hour (5-51 mm/hr), 1.2-2.2 inches plant available water per foot (100-180 mm/m), and 20-35% clay fraction. The bulk density is 81-100 lbs/ft^3 (1.3-1.6 g/cm^3) for the top foot (0.3 m) and 81-112 lbs/ft^3 (1.3-1.8 g/cm^3) for the next 6 foot (1.8 m) depth. For water management purposes, the Amarillo soil series has several properties that are similar to the Olton and Portales series.

Portales Soil Series

The Portales series consists of deep, well drained calcareous soils with moderate permeability. It is a member of the fine, loamy, mixed thermic family of Aridic Calciustolls. It is both favorable and widely used for irrigation and dryland farming in the High Plains of Texas and eastern New Mexico (National Cooperative Soil Survey, 1972). Principal associated soils include the Olton and Arch series. Portales soils are found in nearly level to gently sloping uplands. The top 8 inches (0.2 m) is a grayish brown loam with platy or granular structure with 10 to 35 percent clay, 0.2 to 2.0 inch per hour (5-51 mm/hr) permeability (depending on clay content), and plant available water of 1.6 to 2.3 inch per foot (130-190 mm/m). Typically, the depth of 8 to 25 inches (0.2-0.6 m) is a brown, light clay loam with moderate structure, 0.6 to 2.0 inches per hour (15-51 mm/hr) permeability, 18 to 35% clay and 2.2 to 2.4 inches per foot (180-200 mm/m) plant available water. A soft, white, massive clay loam with 15 to 40 percent calcium carbonate lies between about 25 to 50 inches (0.6-1.3 m), and it has similar hydraulic characteristics as the 8 to 25 inch (0.2-0.6 m) zone, as does the underlying pale brown, massive clay loam at 50 to 80 inches (1.3-2.0 m), approximately.

Arch Series

The Arch series consists of deep, well-drained, light gray or grayish brown shallow calcareous soils of loam and fine sandy loam texture around playa lakes on the Texas High Plains with slopes of 0 to 8 percent. Typically, the light gray loam surface layer is 7 to 10 inches (0.18-0.25 m) thick with 5 to 25 percent clay, 0.6 to 6.0 inches per hour (15-150 mm/hr) permeability, and plant available water of 1.0 to 1.9 inches per foot (83-160 mm/m). Beneath the topsoil at 7 to 17 inches (0.18-0.43 m) is a light gray loam or clay loam layer with 0.6 to 2.0 inches per hour (15-51 mm/hr) permeability and 18 to 35 percent clay fraction. The 17 to 60 inch

(0.43-1.5 m) subsoil consists of white, chalky soft material that is 50 percent or more calcium carbonate. It has a permeability of 0.6 to 2.0 inches per hour (15-51 mm/hr) and plant available water of about 1.7 inches per foot (140 mm/m).

Summary of Soil Permeability Data

A summary of the reported permeability information for the six predominant soil series discussed in this chapter is provided in Table II-4. The Olton, Amarillo, Portales and Arch series have greater permeability than the Pullman and Sherm soils. The Pullman and Sherm series have obvious restrictive layers, and the Sherm series has lower permeability in the topsoil than the Pullman series. Because leaching would be practically nonexistent for these two soils, it is important that they be irrigated only with high quality irrigation water (such as found in the Ogallala Aquifer) to prevent soil salinity.

Soil Permeability and Types of Irrigation Systems

To enhance understanding of soil resources as related to irrigation, Musick et al. (1987) grouped soil series in the Texas High Plains into two broad permeability classifications (Figure II-3):

a. Slowly Permeable Soils--Pullman and Sherm;

b. Moderately Permeable Soils--Acuff, Amarillo, Dallam, Estacado, Olton, and Gruver.

Slowly permeable soils constituted 41% of the total irrigated area, and moderately permeable soils occupied 59% of the irrigated area. For these two major soils groups, the total crop areas irrigated by furrow and sprinkler systems are presented in Table II-5 (Musick et al., 1987).

Table II-4

Summary of Permeability Characteristics for Major High Plains Soils

	Depth		Permeability		Available Water Holding Capacity	
Soil Series	in	m	in/hr	mm/hr	in/ft	mm/m
Pullman	0-6	0-0.15	0.2-0.6	5-15	1.2-1.5	100-125
	6-38	0.15-0.97	<0.06*	<1.5	0.7-1.9	58-158
	38-78	0.97-2.0	0.06-0.2	1.5-5	1.3-1.8	108-150
Sherm	0-5	0-0.13	0.06-0.2	1.5-5	1.8-2.4	150-200
	5-35	0.13-0.89	<0.06*	<1.5	1.6-2.2	133-183
	35-80	0.89-2.03	0.06-0.2	1.5-5	1.2-2.0	100-167
Olton	0-8	0-0.20	0.6-2.0	15-51	1.7-2.4	142-200
	8-48	0.20-1.22	0.2-0.6	5-15	1.7-2.4	142-200
	48-80	0.22-2.03	0.2-0.6	5-15	1.2-1.9	100-158
Amarillo	0-11	0-0.28	2.0-6.0	51-150	0.7-1.8	58-150
	11-38	0.28-0.97	0.6-2.0	15-51	1.2-2.2	100-183
	38-80	0.97-2.03	0.6-2.0	15-51	1.2-2.2	100-183
Portales	0-8	0-0.20	0.2-2.0	5-51	1.6-2.3	133-192
	8-80	0.20-2.03	0.6-2.0	15-51	2.2-2.4	183-200
Arch	0-10	0-0.25	0.6-6.0	15-150	1.0-1.9	83-158
	10-17	0.25-0.43	0.6-2.0	15-51	1.7-1.9	142-158
	17-60	0.43-1.52	0.6-2.0	15-51	1.5-1.8	125-150

* Restrictive clay layer.

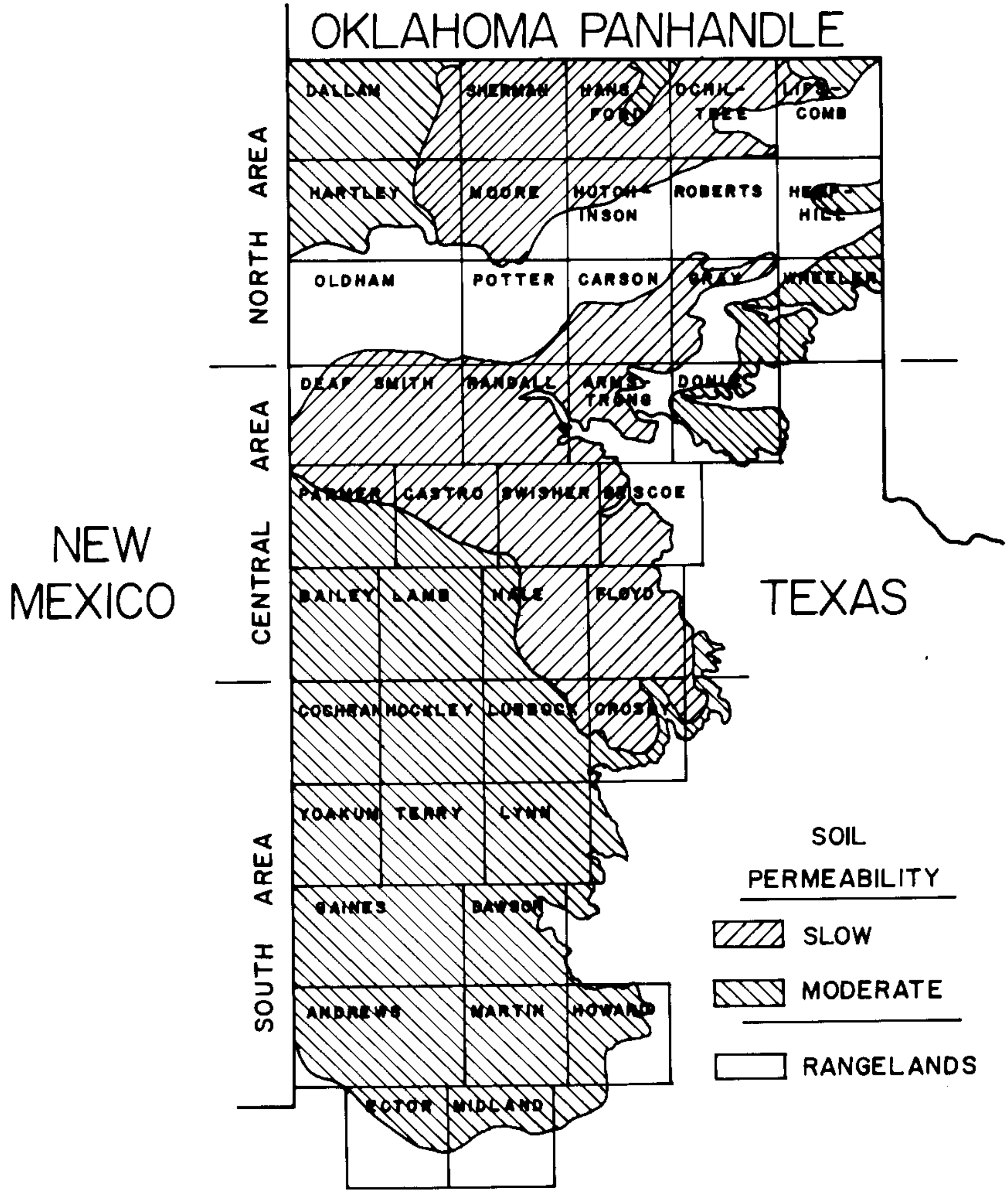

Figure II-3. The 41-county irrigated area of the Texas High Plains overlying the Ogallala aquifer divided into the North, Central, and South areas and into the major soil permeability groups (Musick et al., 1987).

Table II-5

Crop Area in 1984 Irrigated by Sprinkler and Furrow Systems on Slowly and Moderately Permeable Soils for 41-County Area of the Texas High Plains (Musick et al., 1987)

Area	Sprinkler		Furrow	
	Slowly Permeable	Moderately Permeable	Slowly Permeable	Moderately Permeable
	acres			
North	67,450	279,200	626,990	208,160
Central	76,160	358,390	931,270	676,440
South	3,660	828,450	128,860	248,580
Total	147,270	1,466,040	1,687,120	1,133,180
% of Total Acres	3.3	33.1	38.0	25.6

On the slowly permeable soils (1.83 million acres or 0.74 million ha), furrow irrigation was practiced on 92% of the irrigated acreage. Of the 2.60 million irrigated acres (1.05 million ha) of moderately permeable soils, 56% was sprinkler irrigated and 44% was furrow irrigated. A very high percentage (91%) of all the sprinkler irrigation was on the moderately permeable soils.

Soil Nutrient Status

Nutrient status of soils in the High Plains are routinely determined by analysis of soil samples submitted to the Soil/Water/Plant Testing Laboratory of the Texas Agricultural Extension Service at Lubbock. In spring and summer 1986, the USDA Soil Conservation Service and the High Plains Underground Water Conservation District No. 1 collected 853 soil samples to a depth of 0-4 feet (0-1.2 m) in one foot (0.3 m) increments from 217 farms in the 15-county service area of the Water District. The chemical analysis data provided by the Extension Soil/Water/Plant Testing Laboratory is summarized in Table II-6 (Wyatt, 1987) for the 0-12 inch (0-0.3 m) and 12-24 inch (0.3-0.6 m) depth increments. These mean values may indicate reasonably good nutrient levels for most nutrients, but nitrogen levels are low to medium for irrigated grain sorghum and wheat. However, the mean values obscure a very wide range of soil nitrogen values (from 3 to 504 pounds per acre, or 3.3-565 kg/ha) in which 40% of the farms represented had less than 21 pounds per acre (24 kg/ha) of N in the top 2 feet (0.6 m) of soil which is rated as low for irrigated cotton and very low for irrigated wheat and grain sorghum. Only nitrogen and phosphorus were commonly low enough to limit crop production and water use efficiency of field crops grown in the area (Redeker and Snell, 1987).

Summary

Major soils in the Texas High Plains include Pullman, Sherm, and Randall series ("hardlands"); Amarillo, Olton, Dalhart and Richfield series ("mixed lands"); and Brownfield, Tivoli and Likes series ("sandy lands"). The finer textured soils are generally found in the northern half of the region. Two major soils--Pullman and Sherm--have a restrictive horizon below the plowed layer which greatly reduces water intake after initial wetting to below 0.06 inches per hour (1.5 mm/hr) and profoundly affects soil management and irrigation practices. Root zone permeabilities for most other soils are usually well above 0.2 inches per hour (5 mm/hr). Plant available water holding capacities (i.e. difference in water content between field capacity at -0.33 bars matric potential and wilting point at -15 bars) varies from 0.7-2.4 inches per foot within the root zone. Soils with loam, silt loam, and clay loam textures generally have higher water holding capacities than sandier soils. Each additional inch of plant available water in the soil at planting time can boost crop yields significantly. Therefore soil moisture storage during fallow season is an important consideration.

Table II-6
Soil Nutrient Status (0-2 ft depth) for 15 Counties in Southern High Plains, 1986 (Wyatt, 1987)

County	No. Samples	Soil Depth	pH	N	P	K	Na	Ca	Mg	Salinity	Zn	Fr	Mn	Cu
		ft		lbs/acre										
Armstrong	(3)	0-1	7.6	28	49	2,760	267	13,079	2,220	1,785	1.4	58	89	--
		1-2	7.6	19	11	1,893	587	22,280	2,220	2,375	0.13	53	67	5.0
Bailey	(3)	0-1	8.0	83	41	1,533	373	14,029	2,220	2,096	2.9	29	41	--
		1-2	8.1	45	8	1,120	427	14,068	2,040	2,011	0.32	37	22	2.6
Castro	(13)	0-1	7.9	55	53	1,618	382	22,373	2,220	1,719	2.0	39	72	8.9
		1-2	8.0	36	34	1,970	751	30,386	2,220	1,582	0.45	40	35	3.0
Cochran	(17)	0-1	8.0	33	44	1,513	250	15,107	1,760	1,321	1.0	25	45	1.6
		1-2	8.0	33	23	1,448	390	17,381	1,986	1,369	0.44	29	28	2.1
Crosby	(12)	0-1	8.1	54	45	1,817	760	15,219	2,062	1,631	1.4	31	48	3.4
		1-2	8.2	46	18	1,633	1,400	21,210	1,942	1,690	0.42	39	25	3.6
Deaf Smith	(12)	0-1	7.9	146	78	2,300	540	17,471	2,192	2,799	2.1	38	75	3.1
		1-2	8.1	67	58	1,913	680	30,991	2,220	2,218	0.31	37	39	3.9
Floyd	(28)	0-1	8.1	72	49	1,823	389	16,249	2,220	1,830	3.2	28	46	3.9
		1-2	8.2	44	42	1,926	919	32,684	2,220	2,091	0.45	26	24	3.7
Hale	(16)	0-1	8.1	36	33	2,252	591	12,607	2,160	1,665	1.6	30	40	2.2
		1-2	8.2	40	15	1,828	1,391	22,511	2,220	1,951	0.46	40	25	3.3
Hockley	(26)	0-1	8.2	24	38	2,032	411	16,944	1,801	1,316	1.2	22	37	2.4
		1-2	8.2	31	22	2,103	671	21,165	1,975	1,641	0.69	26	28	2.7
Lamb	(24)	0-1	8.0	36	57	1,608	352	10,401	1,955	1,500	1.6	24	38	2.5
		1-2	8.0	25	24	1,466	440	15,887	2,114	1,517	0.32	26	32	2.2
Lubbock	(38)	0-1	7.9	37	38	2,000	378	14,455	1,954	1,482	1.2	26	46	2.5
		1-2	8.1	28	16	1,781	708	22,870	2,065	1,604	0.54	32	32	3.2
Lynn	(18)	0-1	8.3	57	44	2,227	427	16,729	1,920	1,444	2.2	22	27	2.5
		1-2	8.3	34	14	1,989	924	23,641	1,942	1,584	0.64	27	16	2.7
Parmer	(16)	0-1	7.8	72	68	1,518	570	11,609	2,220	1,940	2.1	41	65	2.8
		1-2	7.8	46	17	1,052	542	18,055	2,220	1,772	0.25	39	38	3.1
Potter	(3)	0-1	7.8	83	49	2,000	427	20,689	2,220	2,088	2.8	27	72	--
		1-2	7.9	67	21	1,227	640	25,063	2,220	1,993	0.16	27	30	5.0
Randall	(18)	0-1	7.8	79	29	2,323	446	15,049	2,220	2,550	2.1	52	83	4.6
		1-2	8.0	41	29	1,725	811	26,564	2,220	2,340	0.12	45	42	4.8
Grand Mean	(247)	0-1	8.0±0.2	60±32	48±13	1,959±366	437±131	15,467±3,176	2,090±167	1,811±430	1.9±0.7	33±11	55±19	3.4±2.0
		1-2	8.1±0.2	38±16	23±13	1,672±335	752±307	22,983±5,499	2,122±117	1,849±315	0.38±0.19	35±8	32±12	3.4±0.9

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CHAPTER III

WATER USE AND IRRIGATION EFFICIENCY

Water Use Efficiency

General Concepts and Definitions

The concept of water use efficiency provides a useful index for comparing alternative irrigation systems and water management methods. Water use efficiency can be calculated in several ways and can be misinterpreted unless the specific usage of the term is clearly stated (Stewart, 1985). There are four bases for calculating water usage by crops and hence water use efficiency (Schneider et al., 1976; Stewart et al., 1981):

a. Irrigation water applied.

b. Irrigation water retained in soil (i.e. amount applied minus runoff).

c. Seasonal water available (including rainfall, irrigation and soil moisture depletion).

d. Seasonal water use or evapotranspiration (ET), including rainfall + irrigation + soil moisture depletion - runoff - deep percolation.

Water use efficiency as used herein is defined as the crop yield per unit of water applied, or, alternatively, crop yield per unit of water actually used by the crop. It is expressed in units of pounds of crop per acre-inch of water, or pounds per acre-inch (kg/m^3).

Therefore, irrigation water use efficiency (IWUE) can be defined, and is most commonly expressed, as follows:

$$\text{Irrigation Water Use Efficiency (IWUE), lbs/ac-in.} = \frac{\text{(Irrigated Crop Yield - Dryland Yield), lbs/ac}}{\text{Irrigation Water Applied, inches}} \quad \text{(III-1)}$$

Seasonal water use efficiency (SWUE), or simply WUE, is the more common term, computed either for dryland or irrigated crops. It takes into account the seasonal rainfall (from planting to crop maturity), rainfall runoff, irrigation application, irrigation water runoff, and the change in soil water storage in the top 6 feet (1.8 m) of soil profile:

$$\text{SWUE, lbs/ac-in} = \frac{\text{Crop yield, lbs/acre}}{\text{Seasonal Water Use or ET, in.}} \quad \text{(III-2)}$$

In this equation, the seasonal water use is calculated from the following expression:

$$\begin{aligned}\text{Seasonal Water Use, ET} = {} & [(\text{Seasonal Rainfall - Rainfall Runoff}) \\ & + (\text{Irrigation - Irrigation Runoff}) \\ & + \text{Soil Moisture Depletion - Deep Percolation}].\end{aligned} \quad \text{(III-3)}$$

Seasonal water use (ET) is primarily dependent on climatic factors and type of crop. Deep percolation is usually negligible for Pullman or Sherm soils besides being difficult to measure, so it is often ignored in reporting research results.

For most crops, there is a linear relationship between ET and yield (Stewart and Skidmore, 1985). The highest water use occurs at the highest yield. Seasonal water use efficiency is improved by management factors such as soil fertility that increase yield.

To illustrate, for sorghum grain (Figure III-1) the WUE value was about 159 pounds per acre-inch (0.7 kg/m^3) at a yield level of 1,800 pounds per acre (2,000 kg/ha) and about 249 pounds per acre-inch (1.1 kg/m^3) at a yield level of 4,500 pounds per acre (5,000/ha) (Stewart,

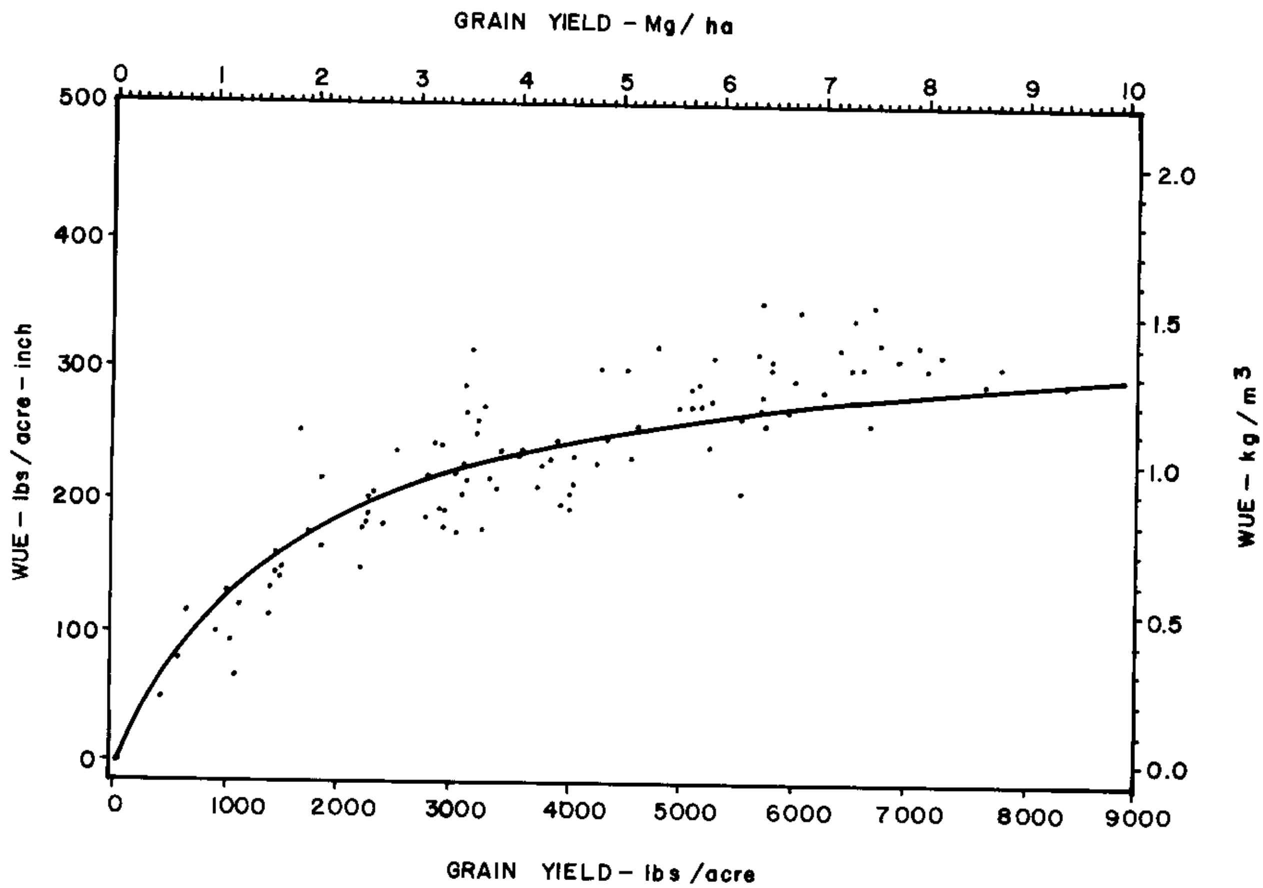

Figure III-1. Relationship between water use efficiency (WUE) and yield of grain sorghum at Bushland, Texas (Stewart, 1985).

1985), according to the regression line. It is obvious that conditions which favored higher grain yields also allowed the crop to make more efficient use of water.

Water Use Efficiency and Limited Irrigation

Water use efficiency is normally much lower for dryland than for irrigated crop production on the High Plains because the yields are much lower. For example, sorghum yields from dryland acreage averages about one-fourth the normal yields under irrigation, and the SWUE based on seasonal ET averages about one-half of the SWUE for irrigated sorghum (Musick and Dusek, 1982).

The major advantage of limited irrigation in the Southern Great Plains stems from using a limited water supply to irrigate a larger area and thus reduce the crop area that is in less efficient dryland production (Musick and Dusek, 1982). The Ogallala Aquifer is no longer adequate for full irrigation in the Southern Great Plains (Stewart et al., 1981). Irrigation wells are becoming less productive as the water level declines. According to New (1977), the average well in the Texas High Plains can irrigate about 80 acres (32 ha) today as compared to about 150 acres (61 ha) in 1950. Irrigation wells are usually pumped continuously during summer months, unless unusually wet periods occur (Stewart et al., 1981). The limited water supply, along with high pumping costs, makes it imperative to use irrigation water efficiently.

Plants utilize water through transpiration which mainly occurs through leaf surfaces. The amount of dry matter produced is related to the amount of water utilized by plants. Transpiration ratio is the weight of water transpired (T) per unit weight of above ground dry matter (DM) produced

(Unger, 1984). An efficient crop will have a low transpiration ratio (T/DM). Transpiration ratios for major crops range from 271 for sorghum to 858 for alfalfa (Table III-1). Corn, wheat, cotton and alfalfa require 37, 86, 107 and 217 percent more water than sorghum to produce equivalent amounts of dry matter. The total amount of water use or evapotranspiration (ET) is about 35-100 percent higher than the transpiration rate because of soil evaporation, which is around 25-50 percent of ET. Moreover, for grain crops, the grain may represent only 30-50 percent of total above-ground dry matter produced. Therefore, a high water use efficiency production system would have a high grain-to-DM ratio (harvest index) and a low value of E/ET.

Typical transpiration ratios and water use efficiencies for major crops in the Texas High Plains are shown in Table III-1, which was adapted from Unger (1984). The calculations show, for example, that for a high efficiency system, if grain is 50 percent of the total plant dry matter and evaporation (E) is only 25 percent of total evapotranspiration (ET), the seasonal water use efficiency of grain sorghum and corn are 314 pounds per acre-inch (1.38 kg/m^3) and 228 pounds per acre-inch (1.01 kg/m^3), respectively. Conversely, for 30 percent grain-to-dry matter ratio and E/ET of 0.5, the water use efficiencies will be much lower--for example, 125 and 91 pounds grain per acre-inch (0.55 and 0.40 kg/m^3) of water for grain sorghum and corn, respectively. These calculations represent estimates of the SWUE.

Irrigation Efficiency

Irrigation efficiency is determined from field measurements for purposes of comparing irrigation systems and equipment and determining

TABLE III-1

Typical Transpiration Ratios and Seasonal Water Use Efficiencies for Dry Matter Yield (DM) of Major Crops at Different Ratios of Soil Surface Evaporation (E) to Evapotranspiration (ET) (Unger, 1984)

Crop	Transpiration Ratio-- Ratio of Transpiration (T), lbs to Dry Matter (DM), lbs	Dry Matter/ET, lbs/acre-inch		Seasonal Water Use Efficiency (SWUE), Grain Dry Matter/ET, lbs/acre-inch			
		E/ET Ratios		(E/ET) = 0.25 Grain/DM Ratio		(E/ET) = 0.50 Grain/DM Ratio	
		0.25	0.50	0.3	0.5	0.3	0.5
Sorghum	271	627	418	188	314[1]	125[2]	209
Corn	372	456	304	137	228	91	152
Wheat	506	336	224	101	168	67	112
Barley	521	326	218	98	163	65	109
Cotton	562	302	202	--	--	--	--
Oats	634	268	179	80	134	53	89
Alfalfa	858	198	132	--	--	--	--

[1] High efficiency production system.
[2] Low efficiency production system.

needed improvements. There are several commonly-used measures of irrigation efficiency (TDWR, 1983; Burman et al., 1983). Four basic efficiency terms that have been widely used to express irrigation efficiency in Texas in recent years are discussed herein.

1. Application efficiency is the percentage of pumped water that remains in the root zone. Application efficiency is calculated as the ratio of the depth of water actually entering the soil root zone to the depth of water pumped. Depth of water pumped is measured with a flow meter. Factors that can lower water application efficiency include transmission losses (ditch seepage and pipeline leakage), spray evaporation, free water surface evaporation, deep percolation, and runoff.

2. Field application efficiency is defined as the percentage of applied water retained in the profile root zone (Musick et al., 1985). The two losses from the system are tailwater runoff and deep percolation. Tailwater may be partially recoverable.

3. Distribution or pattern efficiency is the uniformity with which water is applied across the field with sprinklers or along the length of the furrow or border.

4. System efficiency is the product of the application efficiency and the distribution or pattern efficiency. To have a high system efficiency, systems must have both high distribution and application efficiencies.

Computing Irrigation Efficiency for Sprinkler Systems

For a sprinkler system, depth of application is measured with numerous "catch cans." For rectilinear sprinkler systems (hand move, side roll, linear move, etc.), application efficiency is determined by:

$$\text{Application Efficiency, \%} = \frac{\text{Average Catch Over Entire Area, inches x 100}}{\text{Gross Amount of Water Pumped into System, inches}} \qquad \text{(III-4)}$$

For a center pivot irrigation system, the average catch must take into consideration the increased area represented by catch cans placed successively farther from the pivot point. Patterson (1970) devised suitable weighting factors to aid in calculating weighted average catch and application efficiency for center pivots. Values of weighing factors range from 1.0 at a distance of 90 feet (27 m) from the pivot point to 7.0 at the midpoint of 660 feet (201 m), to 13.8 at 1290 feet (393 m) from the pivot point.

One method of computing a pattern efficiency value for a sprinkler system is to compute a "lower one-quarter distribution uniformity" (DU), also known as the USDA-SCS pattern efficiency (Musick et al., 1987). The SCS pattern efficiency is based on the lowest average water depth collected in enough catch cans to represent just 25 percent of the irrigated area, and is calculated as follows:

$$\text{SCS Pattern Efficiency (DU), \%} = \frac{\text{Lowest Average Catch on 25\% of Area, inches}}{\text{Average Catch Over Entire Area, inches}} \times 100 \qquad \text{(III-5)}$$

For center pivot systems, both the numerator and denominator in the above expression must be weighted averages that are adjusted according to increasing area with distance from the pivot. This SCS method tends to ignore 75% of the application depth measurements closest to the mean and therefore gives low estimates of pattern efficiency.

Pattern efficiency for sprinkler systems is also frequently calculated with the Christiansen Uniformity Coefficient (Cu):

$$Cu = \frac{(1\text{-Average Deviation from Average Depth Caught, inches}) \times 100}{\text{Averge Depth Caught, inches}} \quad \text{(III-6)}$$

Values of Cu tend to be higher than DU values computed with the SCS formula. A relationship between DU and Cu has been developed by Warrick (1983) as follows:

$$DU = -60 + 1.6\ Cu \quad \text{(III-7)}$$

This expression indicates, for example, that a Cu value of 80 percent will be equivalent to a DU value of 68 percent.

The irrigation system efficiency is simply the product of the application efficiency and the measure of pattern efficiency that one choses as follows:

System Efficiency, % = Application Efficiency, % x Pattern Efficiency, %. (III-8)

Using the SCS pattern efficiency (DU) term, for example, the system efficiency is defined as:

$$\text{System Efficiency, \%} = \frac{\text{Lowest Average Catch on 25\% of Area, inches}}{\text{Gross Amount of Water Pumped into System, inches}} \times 100 \quad \text{(III-9)}$$

Data from 36 evaluations of stationary side-roll sprinkler systems on the High Plains and Rolling Plains was compiled by the Soil Conservation Service-SCS (TDWR, 1983). Results as summarized in Table III-2 were as follows: distribution efficiency--61 percent, application efficiency--74 percent, and system efficiency--47 percent.

Evaluations from 261 center-pivot sprinkler systems on the Texas High Plains showed an average system efficiency value of 62 percent. Application efficiency averaged 83 percent, and distribution (pattern) efficiency averaged 74 percent.

Table III-2

Summary of SCS-USDA Evaluations of Irrigation Efficiency in the Texas High Plains (TDWR, 1983)

Irrigation Systems (No. Evaluated)	Efficiency Factor	Mean %	Standard Deviation %	Range %
1. Side-roll Sprinklers (36)	Pattern	61.3	13.8	36-84
	Application	73.6	16.8	35-100
	System	46.5	17.3	14-79
2. Center Pivots (261)	Pattern	73.7	10.0	35-93
	Application	83.2	12.6	45-100
	System	61.6	13.3	31-92
3. Furrow (93)	Distribution	73.2	19.4	11-100
	Application	82.0	17.6	30-137
	System	59.3	18.3	6-93
4. Borders (3)	Distribution	86.4	4.1	82-89
	Application	56.2	27.5	30-85
	System	48.7	24.8	27-76

Irrigation Efficiency for Furrow Systems

Application loss with a furrow system is caused primarily by tailwater runoff or deep percolation. In evaluating a furrow system, furrow streams are measured with orifice plates or furrow Parshall flumes at the top and bottom of the furrow. Time measurements are made at five stations along the furrow to record the length of time water stood at each point (i.e. intake opportunity time). Then, using soil infiltration rate functions, the amount of water entering the soil at each station is estimated. The application efficiency is computed from this expression (TWDR, 1983):

$$\text{Application Efficiency, \%} = \frac{\text{Average Water Applied in Root Zone, inches} \times 100}{\text{Gross Amount of Water Pumped, inches}} \qquad \text{(III-10)}$$

As with sprinkler systems, the distribution efficiency is often computed with the SCS method from the average of the lowest one-fourth of the application depth estimates. Therefore, the distribution and system efficiencies are defined as follows:

$$\text{Distribution Efficiency, \%} = \frac{\text{Lowest Average Water Depth Applied to 25\% of area, inches} \times 100}{\text{Average Water Applied in Root Zone, inches}} \qquad \text{(III-10)}$$

As shown previously,

System Efficiency, % = Application Efficiency, % x Distribution Efficiency, %;

therefore:

$$\text{System Efficiency, \%} = \frac{\text{Lowest Average Water Depth Applied to 25\% of Area, inches}}{\text{Gross Amount of Water Pumped, inches}} \qquad \text{(III-11)}$$

Values of system efficiency for 93 field evaluations of furrow systems in the Texas High Plains averaged 59 percent (range of 6-93 percent) as shown in Table III-2 (TDWR, 1983). The average distribution efficiency was 73 percent, while the average application efficiency was 82 percent. The data indicated that a properly managed furrow irrigation system can be an efficient means of water application in many situations.

The results for both surface and sprinkler irrigation systems indicated very large variations in irrigation efficiencies between farms. In many instances, there was considerable opportunity for saving water through improved irrigation efficiency.

Summary

Water use efficiency by crops can be defined in several ways to provide a meaningful index for comparing situations and systems. Seasonal water use efficiency (SWUE) is the ratio of crop yield to the seasonal water use (evapotranspiration). The seasonal ET value is computed as the sum of precipitation, irrigation application, and soil moisture depletion minus the runoff from irrigation, rainfall runoff and deep percolation (often negligible). For most crops, yield varies directly with ET. Also, good correlation usually exists between crop yield and seasonal water use efficiency. Irrigation water use efficiency (IWUE) is usually defined as the yield increase due to irrigation (as compared to dryland) divided by the total amount (depth) of irrigation water applied. Transpiration ratio is the weight ratio of pounds of water transpired to pounds of plant dry matter produced.

Irrigation efficiency can be expressed in several ways also. Irrigation system efficiency is the product of application efficiency (i.e. percentage of the pumped water that enters the soil profile) and the so-called distribution or pattern efficiency. Several methods are available for measuring distribution or pattern efficiency for furrow and sprinkler systems, but basically this term represents an index (in percent) of the uniformity with which water is applied over a field. The method of measurement and data computation can bias the calculated values of distribution/pattern efficiency and hence irrigation system efficiency. Field-measured values of irrigation systems efficiency for the Texas High Plains have averaged approximately 60 percent for both graded furrow and center pivot irrigation systems. Extreme values have ranged from less than 10 percent to over 90 percent.

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CHAPTER IV

MOISTURE DEFICITS AND CROP STRESS IN RELATION TO IRRIGATION SCHEDULING

The water supply and distribution system must be capable of meeting the crop water needs, both in time and quantity, to reach genetic potentials for crop growth and yield (Hiler and Howell, 1983). Three promising areas for increasing water use efficiency are improved irrigation scheduling, improved water distribution and application systems, and application of systems analysis methods to optimize water allocation to crops. Numerous procedures are available for irrigation scheduling (Stegman et al., 1983). This chapter describes recent research on irrigation scheduling based on evapotranspiration, soil or crop moisture deficits, crop stress, and yield relationships.

Crop Water Requirements

Evapotranspiration

Evapotranspiration (ET) includes all water lost by evaporation from the soil surface and by transpiration from plant surfaces. Soil evaporation occurs in two phases: a constant rate phase when the soil surface is wet, and a falling rate phase which decreases with the square root of time in the soil drying phase (Kanemasu et al., 1983). Evaporation from the soil surface represents water lost from the potential transpiration reservoir and may be viewed as a "leak" in the system since only water transpired by the crop is coupled to photosynthesis and crop productivity.

Plants inevitably lose water by transpiration as they exchange gases between the outside air and the interior of their leaves (Stegman et al., 1983). A strong interaction exists between the plant and soil water flow systems to support transpiration. Water deficits in plants may not limit transpiration until the soil water reservoir is substantially depleted. Water stress induces stomata to close, which reduces transpiration and photosynthesis. Repeated brief stresses, such as daily periods of peak ET, may reduce yield potential very slightly; but if stresses are too great or too long, plant growth is affected, especially in determinate crops such as corn, sorghum, and small grains.

Crop yields are closely correlated with seasonal evapotranspiration, usually by linear relationships (Stegman et al., 1983; Stewart and Skidmore, 1985). For maximum water use efficiency, a maximum proportion of the precipitation or irrigation water should be expended by plant transpiration and a minimum proportion lost to evaporation, soil drainage or runoff.

Evapotranspiration rate (ET) of a crop is dependent mainly on characteristics of the cropland climate rather than on management practices (Stewart and Skidmore, 1985). The ET rate is related to the evaporative demand of the air, which can be expressed as "reference ET" (ET_r) or "potential ET" (ET_o). Values of ET_o represent the rate of evapotranspiration on a clear day from an extensive surface of actively growing and adequately watered green grass that is 3.1 to 5.9 inches (80 to 150 mm) tall, of uniform height, and completely shading the soil surface. Approximate ET_o values for a warm semi-arid, subtropical climate are about 0.30 in./day (7-8 mm/day) and for a warm, semi-arid temperate climate are 0.33 in./day (8-9 mm/day). Values of ET_r by comparison are based on alfalfa with more than 12 inch height and are somewhat greater than ET_o values (Musick, 1987).

When the soil surface is wet, the ET of nonstressed plants approaches the potential ET_o rate regardless of canopy development (Stegman et al., 1983). After the soil surface dries, soil evaporation rate is reduced (controlled by radiation energy reaching the soil surface and vapor diffusion through the dry soil surface layer), and ET is controlled mainly by vegetative transpiration. Under these conditions, the actual ET rate (ET_a) can reach or exceed ET_o only when the leaf area index (area of one side of all leaves divided by the ground surface area) becomes sufficiently large to effectively form a complete canopy cover, e.g. to 3.0 for some crops (Stegman et al., 1983).

Crop Coefficient

Measurement of actual ET is difficult, so it is usually correlated with climatic conditions using research data and then is computed for various conditions in relation to the potential evapotranspiration (Kanemasu et al., 1983). In many situations, actual evapotranspiration (ET_a) is related to potential evapotranspiration (ET_o) through a simple coefficient (Stewart and Skidmore, 1985). Therefore,

$$ET_a = K_c \, ET_o \qquad \text{(IV-1)}$$

The crop coefficient, K_c, is a dimensionless empirical factor that represents the combined effects of (a) resistance to water movement from the soil to evaporative surfaces, (b) resistance to diffusion of water vapor from evaporative surfaces to the air, and (c) radiant energy available relative to a reference crop (Jensen et al., 1971). Values of the crop coefficient vary with type of crop, development stage, wind speed, and humidity. The experimentally-determined K_c values increase from a low value at the time of crop emergence (when evaporation exceeds transpiration) to a maximum value as the crop reaches full development. Often, K_c decreases as the crop matures. Typical values of crop coefficients (K_c) for a grain and vegetable crop--sorghum and watermelons--are contrasted in Table IV-1.

For a given crop and climate, there is some maximum value of evapotranspiration termed as ET_m, which also depends on a crop canopy that essentially covers the soil (Musick, 1987). When the soil moisture supply fully meets the crop water requirements, the actual evapotranspiration is at this maximum value (i.e. $ET_a = ET_m$). As the available soil water is depleted, values of ET_a decrease at a rate that depends on the type of crop and soil texture. So, when water becomes limiting, ET_a is less than ET_m. Drought tolerant crops such as sorghum can withstand greater soil moisture depletion before ET_a falls below ET_m than can vegetable crops, for example.

Water Deficit

The water deficit of a crop can be expressed as the difference between actual and maximum ET divided by ET_m, as follows:

$$\text{Water Deficit} = \frac{ET_m - ET_a}{ET_m} = 1 - \frac{ET_a}{ET_m} \qquad \text{(IV-2)}$$

When water deficits occur during the vegetative or ripening periods, yield reductions are usually relatively small. However, relatively large yield reductions occur when water deficits occur during flowering periods.

To illustrate the effect of water deficits on crop yields, Doorenbos and Kassam (1979) developed generalized relationships for various crops for situations where (a) the deficit applies over the entire growing season,

Table IV-1

Comparison of Crop Coefficients (K_c) for Sorghum vs. Watermelons (Doorenbos and Kassam, 1979)

Crop Stage	Sorghum K_c	Watermelons K_c
1. Initial	0.30-0.40	0.40-0.50
2. Crop Development	0.70-0.75	0.70-0.80
3. Mid-Season	1.00-1.15	0.95-1.05
4. Late Season	0.75-0.80	0.80-0.90
5. At Harvest	0.50-0.55	0.65-0.75
6. Total Growing Season	0.75-0.85	0.75-0.85

and (b) a deficit occurs in individual plant growth periods. These relationships are illustrated in Figures IV-1 and IV-2.

Yields of most crops are generally more sensitive to water deficits at certain growth stages than others (Hiler and Howell, 1983). Water stress is the negative effect of excessive plant water deficit as measured in terms of reduced crop yield. The extent of yield reduction depends both on the stage of growth and magnitude and duration of the moisture deficit.

Soil Moisture Monitoring

Irrigation management involves two basic decisions: (a) when to irrigate; and (b) how much to apply (McFarland, 1984). A crop should be irrigated between the earliest date for efficient water application and the latest date to prevent an unacceptable level of moisture stress. The amount of water to apply depends on the effective root zone depth of crop, the capacity of the soil reservoir, and the degree of moisture deficit allowed by management. Knowledge of the amount of water in the soil reservoir is very important to determining when and how much to irrigate.

Pre-Season Soil Moisture Survey

Pre-season soil moisture surveys where available provide the irrigator with an estimate of (a) the amount and distribution of water stored in the root zone soil profile; and (b) the amount of water needed to recharge the root zone soil profile to field capacity (Risinger and Wyatt, 1985). By knowing the amount of stored soil water in the plant root zone prior to planting, irrigators can make important decisions such as crop selection, seeding rate, necessity of preplant irrigation or tillage practices.

The preplant soil moisture survey conducted annually by the High Plains Underground Water Conservation District No. 1 uses a network of permanent monitoring sites at 3 to 5 mile (5-8 km) intervals (Risinger and Wyatt, 1985). The monitoring stations are buried so that normal farming operations can take place above them. Soil moisture measurements are made annually during a 4 to 6 week period from late November to early January. Measurements are made using a neutron probe at 6-inch (150 mm) intervals to a soil depth of 7 feet (0.18 m). The neutron moisture meter measures the total water content. The plant-available water is considerably less than the total water content and is determined from these readings by knowing the soil type. Most soils in the High Plains hold 0.6 to 2.3 inches of plant-available water per foot of depth (50-190 mm/m).

Data published from pre-season soil moisture surveys are usually expressed in terms of moisture deficit, i.e. inches of water per foot of soil (mm/m) needed to wet the soil to field capacity within the root zone. This allows management decisions to be made for bringing the root zone up to field capacity prior to planting. Often, only the top half of the root zone may need additional moisture, and an irrigator may want to accept the probability that as much as half the needed amount will be received from precipitation (Risinger and Wyatt, 1985). For example, if the soil moisture survey shows only a 2-4 inch (50-100 mm) moisture deficit, the irrigator might choose to install furrow dikes to capture an expected 3 inches (75 mm) of precipitation rather than apply a pre-plant irrigation. On the other hand a large moisture deficit of 6-8 inches (150-200 mm) in the root zone would probably indicate the need for some level of pre-plant irrigation as well as utilizing precipitation.

Soil Moisture Sensing

Monitoring the water content of soil in irrigated fields throughout the growing season offers a potentially high return on investment by enabling farmers to possibly eliminate an unnecessary irrigation, to initiate irrigation before untimely stress conditions, and to determine root development (Henggeler, 1984). Soil moisture sensing devices are especially beneficial to producers with center pivot or drip systems because of the potential for rapid action to eliminate water stress.

Methods and devices for soil moisture sensing are well developed and are in widespread use. Methods of soil moisture sensing range from simple to relatively complex (Henggeler, 1984; McFarland, 1984):

1. Feel method--Consists of soil sampling with an auger and manual manipulation and inspection of soil sample to estimate water content based on cohesiveness, presence of free moisture, appearance, friability, and other sensory perceptions. Samples should be taken from each foot of depth. Guides to estimating soil water deficiency for different soil textures in inches per foot (or mm/m) are readily available (Risinger et al., 1985). All producers should be proficient in estimating soil moisture by the feel method. The time involvement for sampling soils to the four foot depth several times per week is excessive for widespread use.
2. Tensiometer--Water-filled air-tight plastic column with porous ceramic tip that is embedded in soil and with a vacuum gauge on the top end. Tensiometers measure tension or suction exerted on the water by soil particles. The permanent wilting point is the limit of soil moisture tension that plant roots can overcome in

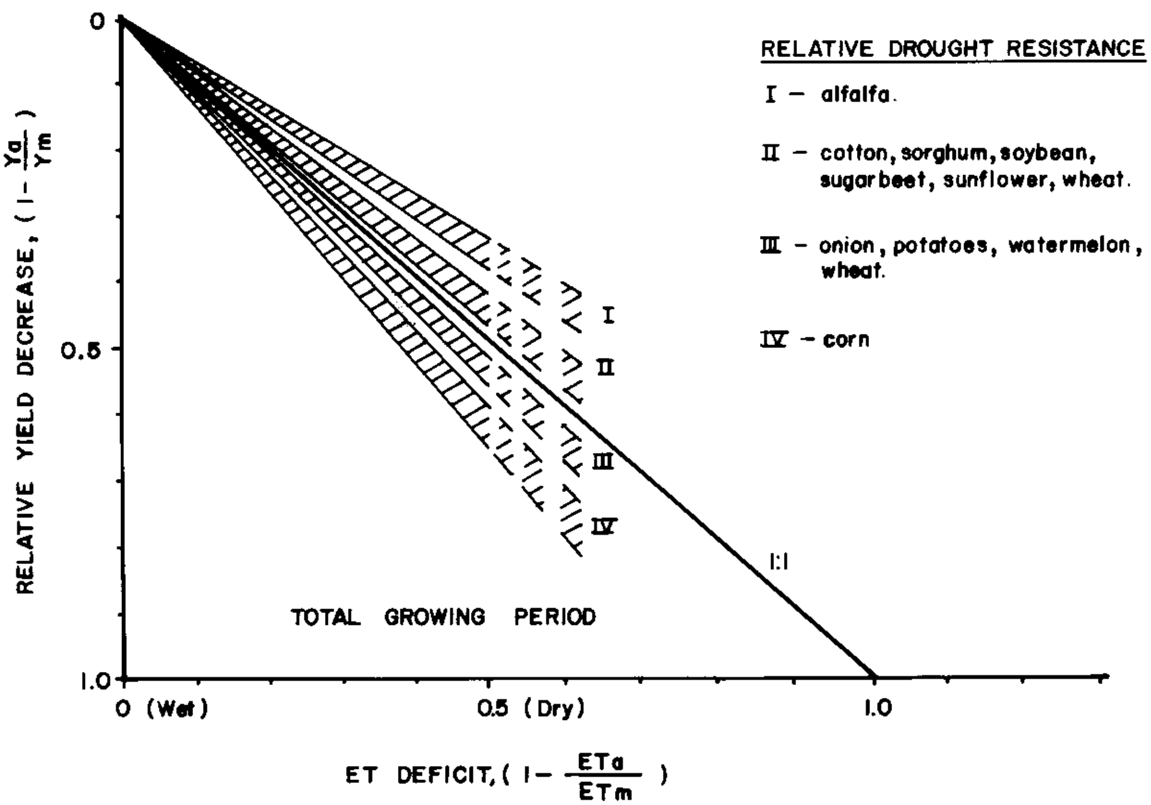

Figure IV-1. Generalized relationships for various crops of the effect of increasing evapotranspiration deficit on yield (Doorenbos and Kassam, 1979). ET_a is actual evapotranspiration, ET_m is maximum evapotranspiration, Y_a is actual yield, and Y_m is maximum yield.

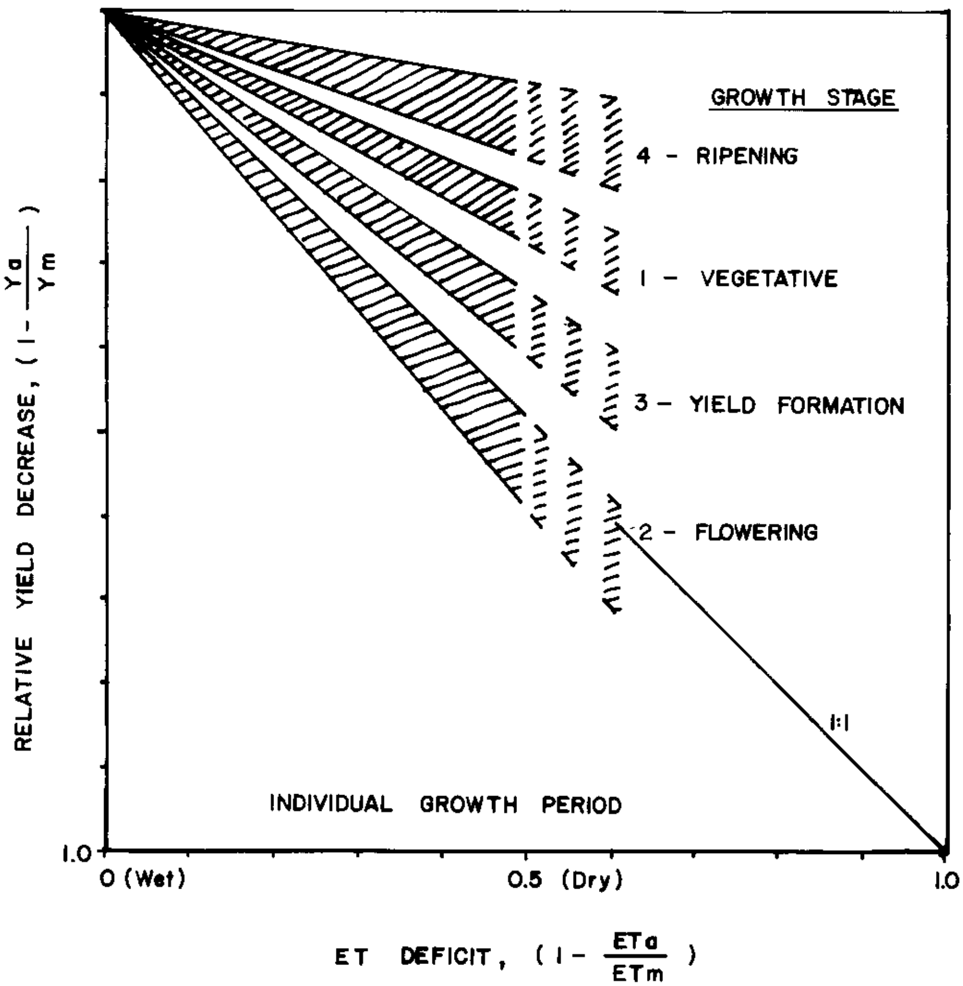

Figure IV-2. Relative effects of evapotranspiration deficit during specific growth stages on crop yields (Doorenbos and Kassam, 1979).

extracting water from small pore spaces and is near -15 bars or -1,500 centibars (-1,500 kPa). Soil tension will draw water through the ceramic tip and create a vacuum that registers on the gauge. Vacuum (suction) in the column varies according to soil moisture content at equilibrium with the tensiometer. After rain or irrigation, moisture moves from the soil back into the ceramic tip and reduces the tension. Correlation between matric potential (measured in bars or kPa) and percent depletion of available water has to be established for each soil series. The limit to the measurable tension is about one bar (100 cb, or 100 kPa). A separate tensionmeter is needed for each depth to be measured, with two depths recommended. The range of operation is about 0.7-0.8 bars (70-80 kPa) tension. When the soil dries above this level, the sensor will break suction and cease to operate correctly. After the tensiometer has broken suction, it may have a reading that indicates more moisture than is actually present.

3. Gypsum blocks--Permeable ceramic gypsum cylinders about 1 inch (25 mm) long with electrical wires cast around two stainless steel electrodes with electrical wires that lead to an ohm meter to measure electrical resistance. Electrical resistance of the block between the two electrodes increases as moisture content at equilibrium decreases and vice versa. The meter provides a scale of 0 to 10 or 0 to 100, and the manufacturer supplies a diagram showing the correlation between meter readings and the approximate moisture contents of soils of various textures. Gypsum blocks should be set at one foot intervals in the top 4 to

5 foot (100-125 mm) root zone at each measurement station. A gypsum block will measure soil moisture tension up to several bars. A step-by-step procedure for using gypsum blocks was outlined by Carver et al. (1985).

4. Neutron probe--Consists of a probe, a neutron source, a neutron counter, and a compiler/readout instrument (Risinger and Carver, 1985A). The probe is lowered into an aluminum tube inserted in a bored hole to a desired depth. The radioactive source emits "fast neutrons" which subsequently bounce off hydrogen atoms that are present in soil water. The number of deflected "slow neutrons" is detected by the counter and correlated with soil water content. The compiler/readout instrument calculates and displays the result, usually in inches of water per foot of soil. Neutron probes are perhaps the most accurate instrument but are also the most expensive method and are time consuming, perhaps out of the realm of consideration for individual farmers. The Texas Department of Health requires a license for possession and use of a neutron meter.

Other methods of soil moisture measurement include soil psychrometers and hygrometers and the gravimetric method. The latter method consists of determining the evaporation loss of soil sample upon heating to 220°F (105°C) for 24 hours.

Neutron probes are too expensive and impractical for most farm operations (Risinger and Carver, 1985B), and the feel method is too slow and labor intensive. Thus, the choice of soil moisture sensing equipment usually centers on tensiometers vs. gypsum blocks (McFarland, 1984). Tensiometers have a narrow range (up to 0.7 or 0.8 bars tension) that includes over 60 percent of the available water in a sandy soil but less than 50% of available soil water for clay loams and clays. Thus, tensiometers will not have sufficient operating range in a field crop on a clay soil to allow use of the commonly recommended criterion of irrigating when 50% of the soil water has been depleted. Tensiometers are most advantageous on high moisture demand crops such as corn or vegetables where the soil moisture content needs to be maintained at 50 to 75 percent of field capacity (Risinger and Carver, 1985C).

Gypsum blocks will measure soil moisture tension over a much wider range of available soil moisture, but they are not as sensitive at high moisture contents as tensiometers. Also, gypsum blocks require intimate contact with soil to give representative readings. This condition is more difficult with a coarse-textured soil such as loamy sand than with a fine-textured soil. Gypsum blocks work best when used with crops such as cotton, grain sorghum, and small grains that are resistant to water stress (Risinger and Carver, 1985B).

Each separate irrigation unit such as a center pivot system should have a dedicated set of soil moisture sensing devices with at least 3 stations per irrigation unit (Henggeler, 1984). At each station, soil water should be measured at several depths. One device or reading can be obtained at every foot (0.3 m) to the rooting depth to signal moisture movement and root development. Also, a sensing device or reading at a depth of one foot (0.3 m) below the root zone will detect deep percolation losses.

It is important to plot the data from each measurement station as a function of depth and time to observe trends in soil moisture depletion. This will enable the farmer to adjust irrigation frequency and amount to the extent feasible (Henggeler, 1984). A record of moisture levels and trends may help a producer decide whether or not to apply one more irrigation before shutting down for the season (McFarland, 1984).

Irrigation Scheduling

Irrigations should be scheduled before plants deplete deep soil moisture. Traditional methods of irrigation scheduling have been based on a fixed-level deficit, that involves irrigating when the soil moisture drops to a certain level (detected by "feel" or actual measurement). More recent methods have focused on the magnitude of water deficits at critical stages of crop development. Three such methods discussed below are (a) water balance method based on daily ET, (b) stress-day index approach, (c) optimal sequencing of evapotranspiration deficits; and (d) measurements of leaf temperature.

Water Balance Method

The most widely used method for irrigation scheduling is the water balance approach based on a USDA water depletion model (Jensen et al., 1971):

$$D = \sum_i (ET_a - P_e - I_{dn} + W_d)_i \qquad \text{(IV-3)}$$

in which D is the current level of water depletion in the root zone (inches or millimeters of soil moisture); P_e is effective precipitation (precipitation minus runoff); I_{dn} is net irrigation (gross irrigation times the irrigation efficiency); W_d is drainage loss; and i is the time increment, usually in days (Hiler and Howell, 1983).

The crop evapotranspiration rate on a given day (ET_a, in./day) is estimated as in equation IV-1 (Hiler and Howell, 1983). Values of ET_o

are usually calculated from mathematical models (usually the Jensen-Haise equation or modified Penman equation), using daily weather measurements including air temperature, humidity, wind speed, solar radiation, etc. (Jensen et al., 1971). These weather data are determined locally, and ET_o values are subsequently calculated. Historical ET_o values calculated for Texas have been published by Dugas and Ainsworth (1983).

The California Irrigation Management Information System (CIMIS) which involves about 50 weather stations in irrigated regions of that state, provides daily updates of ET_o, K_c, and ET_a. These values are then used in the USDA water balance equation for irrigation scheduling on many farms.

Drainage loss from the root zone depends on soil water content in excess of field capacity (Hiler and Howell, 1983). To estimate drainage loss, the simplifying assumption is usually made that W_d is the amount by which an irrigation or rainfall exceeds the prevailing root-zone water depletion. It is easier to control drainage loss with sprinkler irrigation than with conventional gravity irrigation. It should be noted that W_d can have a negative value when upward flow (capillary rise) occurs due to a high water table.

Stegman et al. (1983) ignored drainage loss altogether in devising a simpler version of the USDA water balance equation. His proposed method would allow a farmer to keep a daily running tabular record of soil water depletion given ET_a estimates, rainfall, and irrigation amounts.

With the USDA water balance scheduling program, the estimated number of days (I) before the next irrigation is needed can be forecast as follows (Hiler and Howell, 1983):

$$I\text{, days} = \frac{D_o - D}{(ET_a - P_e)_i} \qquad \text{(IV-4)}$$

where D_o is the optimum level of soil moisture depletion and other quanities are as described for equation IV-3. The expected precipitation amount can be determined from rainfall probability estimates (Heerman et al., 1971), or zero can be assumed for arid climates. Data for Texas has been published by Dugas (1983).

Allowable levels of water depletion in the root zone between irrigations range from as low as 25 to 50 percent of available soil water content for certain vegetable crops to as high as 50 to 70 percent for field crops (Table IV-2), according to guidelines proposed by various authors (Stegman et al., 1983). Soil moisture depletion relative to field capacity can be estimated from how the soil feels or using soil moisture sensors, such as tensiometers or gypsum blocks. According to Musick (1987), irrigating clay soils at a depletion allowance that is too low (eg. 25 percent) can result in low water intake problems, while on moderately permaeble soils it can result in deep percolation.

The amount of water to apply during an irrigation (W_I) assuming an irrigation application efficiency value, e, is calculated from:

$$W_I = \frac{D_o}{e}\text{ ; or, } W_I = \frac{D}{e} \qquad \text{(IV-5)}$$

The greater of Do (optimum depletion) or D (current depletion) should be used to calculate W_I.

The USDA computer-based scheduling approach does not account for varying crop sensitivities with respect to growth stages. Either the

Table IV-2

Allowable Root Zone Water Depletion Between Irrigations for Near Maximum Yield as Applied to Scheduling of "Set Type" Sprinkler and Non-Automated Gravity Systems (Stegman et al., 1983)

Crop	Available Water Depletion percent	Root Zone Depth Normally Irrigated in Deep Soils	
		ft	m
Alfalfa	30-50	4-6	1.2-1.8
Corn	40-60	2.5-4	0.8-1.2
Cotton	50-65	3-4	0.9-1.2
Grain sorghum	50-70	3-4	0.9-1.2
Potatoes	25-50	2-3	0.6-0.9
Sugar beets	30-60	3-4	0.9-1.2
Soybeans	50-60	2-3	0.6-0.9
Wheat	50-70	3-4	0.9-1.2
Vegetable crops	25-50	2-4	0.6-1.2

stress day-index or the optimal sequencing approach could be incorporated for greater accuracy in scheduling irrigations.

Stress-Day Index Method

Hiler and Clark (1971) developed the stress day index (SDI) concept of irrigation scheduling to quantify the relative effects of water stress on a crop during its growing season. The stress day index is defined as follows (Hiler and Howell, 1983):

$$SDI = CS \times SD \qquad (IV\text{-}6)$$

where CS is the crop susceptibility factor, and SD is the stress day factor. Values of SD may be chosen to represent leaf water potential, soil water potential, or percent of available soil moisture. Units of SDI are the same as for SD (i.e. bars (kPa) or percent), since CS is a dimensionless term. Crop yield of grain sorghum and peanuts was found to decrease linearly as the stress-day index increased (Hiler and Clark, 1971).

The crop susceptibility factor (CS) indicates a plant's sensitivity to water deficits at different growth stages. It is the measured reduction in yield (expressed as a decimal fraction) resulting from applying a water deficit during a given growth stage. Values of CS are determined experimentally. For example, Lewis et al. (1974) determined crop susceptibility factors for grain sorghum at three growth stages using lysimeters. Crop yields under moisture stress conditions of -12 to -13 bars soil water potential at a soil depth of 200-300 mm were related to an unstressed control treatment. Resulting CS values, in terms of decimal fraction reduction in grain yield, were as follows: no water stress--0.0; late vegetative to boot stage--0.17; boot through bloom--0.34; and milk through soft dough stage--0.10. In this instance, an equal water stress resulted in a 34 percent yield reduction when applied during the early reproductive stage, but only a 10 percent yield loss when it occurred during grain filling.

Estimated values of crop susceptibility (CS) for various crops were calculated from research of numerous scientists (Hiler and Clark, 1971; Hiler et al., 1974). Typical CS values for grain sorghum, cotton, corn, and soybeans are shown in Table IV-3. The highest values occur at or near anthesis, indicating this is the most critical growth stage insofar as water deficit is concerned. In reality, values of CS also depend upon the magnitude of moisture deficit at each crop growth stage and on the "conditioning" of the crop to moisture deficits (i.e. pattern of deficits earlier in the growing season), but these relationships have not yet been quantified for the majority of crops.

The stress day factor (SD) is a measurement of plant water deficit (Hiler and Howell, 1983). Several different quantitative indicators can be used to express SD. These indicators include expressions of either plant water deficit (e.g. leaf water potential, leaf air-temperature difference, leaf diffusion resistance, stem diameter, etc.) or soil water deficit (e.g. soil water potential, percent depletion of available water, etc.).

Leaf water potential is a direct measure of plant water deficit and theoretically at least should be the best measure of SD; however, values may be impractical to obtain or unavailable. Higher correlations were obtained for grain sorghum when soil water potential was used to relate SD to crop yields rather than when leaf water potential was used (Hiler et al., 1974).

Table IV-3

Examples of Practical Applications of the Stress Day Index (SDI) Method of Irrigation Scheduling (Hiler and Howell, 1983)

Crop and Growth Stage	CS (Yield Reduction if Water-Stressed) %	Initial SD Value, % ASM	SDI (CS x SD) % ASM	SDI_o (Ave. SDI) % ASM	SD when time to irrigate, % ASM
1. Grain Sorghum					
a. Vegetative (6 to 8 leaf stage)	25	50	12.5	16	65
b. Boot to heading	36	50	18	16	45
c. Heading to soft dough	45	50	22.5	16	36
d. After soft dough	25	50	12.5	16	65
Average			16.4		
2. Cotton					
a. Before flowering	0	50	0	12	--
b. Early flowering	21	50	10.5	12	58
c. Peak flowering	32	50	16	12	38
d. Late flowering	20	50	10	12	61
Average			12.1		
3. Corn					
a. Vegetative	25	50	12.5	16	64
b. Silking and tasseling to soft dough	50	50	25	16	32
c. After soft dough	21	50	10.5	16	76
Average			16		
4. Soybeans					
a. Vegetative	12	50	6	10.5	88
b. Early-to-peak flowering	24	50	12	10.5	44
c. Late flowering, early pod development	35	50	17.5	10.5	30
d. Late pod to maturity	13	50	6.5	10.5	81
Average			10.5		

CS = Crop Susceptibility; SD = Stress Day Factor; ASM = Available Soil Moisture

Irrigation timing with the SDI concept involves irrigating when the daily SDI value (CS x SD) reaches a selected critical value, SDI_o. In periods of high crop susceptibility (CS), the crop would be irrigated frequently at low water deficit (SD) values. The costlier or scarcer the water, the higher the value of SDI that should be chosen in order to restrict irrigation to the most susceptible periods.

An example of the stress day index approach for irrigation timing is shown in Table IV-3 (Hiler and Howell, 1983). In this example, available soil moisture (ASM) was chosen as the stress day factor (SD), and a "standard practice" criteria was chosen as 50 percent ASM depletion. The table indicates that during the most susceptible water stress period for each crop, irrigation water should be applied when the available soil moisture has been depleted by only 36, 38, 32, and 30 percent for sorghum, cotton, corn and soybeans, respectively. However, either early or late in the growing season, the soil moisture depletion can be allowed to be much greater without crop damage.

In lysimeter and field plot studies with cotton and grain sorghum, Bordovsky et al. (1974) and Hiler et al. (1974) showed significant increases in irrigation water use efficiency following the SDI method as compared to irrigating at a water deficit value that remains constant throughout the growing season.

Optimal Sequencing of Evapotranspiration Deficits

A limitation of the stress day index method is the lack of data on the effects of "conditioning" certain crops to moisture deficits at different growth stages. Since crop yield increases linearly with seasonal evapotranspiration (ET), yield reductions can occur when actual ET falls below potential ET, resulting in a so-called ET-deficit.

Stewart et al. (1975) found that sequences of ET-deficits can have an effect on corn yield. "Optimal" and "suboptimal" ET-deficit sequences were identifiable. With optimal sequencing of ET deficits, there was a primary yield loss of 1.2% for each 1.0% seasonal ET deficit. Sub-optimal sequencing of ET deficits reduced yields even further, drastically in some cases. The effects of an ET deficit during corn pollination was especially severe when preceded by ample moisture during the vegetative stage (Stewart et al., 1975). But, when there had been an earlier ET deficit (in the vegetative period), the adverse effects of a pollination-period ET deficit was somewhat lessened because the crop was "conditioned" (i.e. plant size reduced). ET deficits during the pollination period reduced the corn's ability to utilize water supplied later during the grain filling period. However, the stress conditioning effect did not develop in corn on Pullman clay loam soil and is believed to be of minor significance for Texas High Plains conditions (Musick, 1987).

There was no indication that grain sorghum is affected by a conditioning function (Stewart et al., 1975). They determined that a significant decrease in grain sorghum yield occurred in all water deficit sequences in which there was an early ET deficit. During the vegetative stage (tiller initiation to boot stage), ET deficits of 26 to 45 percent clearly resulted in major yield reductions (16-29 percent) which were only partially recoverable by later irrigation. The maximum ET rate of grain sorghum was 10 percent less than for corn.

For a given magnitude of ET deficit, corn is much more sensitive to ET deficits than grain sorghum, in both vegetative and pollination stages

(Stewart et al., 1975). Corn was most sensitive during the pollination stage, and high yields of corn occurred only when there was little or no ET effect in the pollination period. Both corn and grain sorghum were somewhat insensitive to moderate deficits during the grain filling period. Late-season irrigation improved corn yields by only about 4 percent.

Canopy Temperature as a Guide to Irrigation Scheduling

Canopy temperature offers potential for determining plant stress and transpiration levels (Kanemasu et al., 1983). A stress degree-day index, which sums the daily positive values of canopy temperature minus air temperature (T_c-T_a), was developed by Jackson et al. (1979). If the observed canopy-air temperature differential (T_c-T_a) exceeded some critical value, an irrigation would be required. Using this approach, Geiser et al. (1982) determined that corn used 19 and 38% less water, and yields were not significantly different from irrigation treatments scheduled by electrical resistance blocks and by the water balance method, respectively. However, use of canopy-air temperature differential for irrigation scheduling appears tenuous at the present time because air and soil temperatures and cloud cover interfere with leaf temperature measurements. Because evaporative demand is influenced by atmospheric conditions such as vapor pressure deficit, canopy-air temperature values should be normalized using vapor pressure deficit or using a non-stressed crop area as a reference condition (Musick, 1987). Only the plant leaves should be measured to determine canopy-air temperature differential. This method is more applicable in aird regions than to humid regions.

Discussion of Irrigation Scheduling Research

Kanemasu and Raney (1982) compared corn yields over a 5-year period in Kansas with irrigations scheduled at 50 percent remaining available soil moisture content. The 50 percent ASM criteria was maintained using two methods: (a) neutron probe, versus (b) computerized water balance calculations of water deficit. Scheduling by using the neutron probe resulted in an average of 10 percent higher corn yields than the computerized water balance scheduling approach, but differences were not statistically significant (8,650 vs. 7,870 pounds per acre, or 9,700 vs 8,820 kg/ha). It was concluded that the water balance technique could be used to estimate soil moisture for irrigation. The treatments provided increased yields of 90 and 75 percent over dryland production.

Water use efficiencies resulting from three methods of timing irrigations on narrow-row cotton were compared by Bordovsky et al. (1974) for a humid part of Texas. These methods were (a) fixed-level soil water potential (SWP), (b) fixed-level leaf water potential (LWP), and (c) stress day index (SDI) with variable-level LWP as the stress day indicator. Water use efficiencies (based on irrigation plus rainfall input amounts) were 17 and 38 percent higher, respectively, for the LWP and SDI timing methods than for the soil-water potential method. Average increases in water use efficiency based solely on irrigation water (IWUE) averaged 30 and 84 percent higher for the LWP and SDI indicators, respectively. While yields were equivalent for the three methods, applied irrigation water was 23 and 43 percent less for the irrigations scheduled with the fixed-level soil water potential and the stress day index methods, respectively.

Field data comparing sorghum yields and water use efficiencies when irrigations were scheduled with fixed-level soil water potential versus the stress day index were reported by Hiler et al. (1974). The data, summarized in Table IV-4, indicate that the water use efficiency was significantly higher (by 66 and 80 percent) in two years for the SDI scheduling method than for the soil water potential method at fixed level of -0.7 bars (-70 kPa) at 11.8 inch (30 cm) depth. A leaf water potential method of irrigation scheduling (using a fixed level of -12 bars) also produced better results than the fixed soil water potential method. It should be noted, however, that a soil water potential of -0.7 bars (-70 kPa) is too dry for an irrigation threshold for tensionmeters, and -0.3 to -0.5 bars (-30 to -50 kPa) would be a more realistic threshold.

There was no significant difference in yields between scheduling methods for either year (Hiler et al., 1974). Total water uses (irrigation plus storage depletion minus drainage) were determined the first year only and totaled 12.5, 14.75 and 9.75 inches (317, 375, and 248 mm) for the three treatments. Seasonal water use efficiency values computed with these total water uses were as follows:

* Soil water potential method--483 pounds per acre-inch (2.13 kg/m^3)
* Leaf water potential method--519 pounds per acre-inch (2.29 kg/m^3)
* Stress day index method--728 pounds per acre-inch (3.21 kg/m^3)

These values indicate 51 percent improvement with the SDI and 8 percent improvement with the leaf water potential indicators as compared to the criteria of fixed soil water potential.

A sequential water stress study was performed on cotton using sheltered lysimeters (Clark and Reddell, 1986). Water stress was imposed during the peak bloom and late bloom periods during flowering days number 8-34 or 34-59 after first bloom,respectively. In addition, a sequential stress treatment was imposed that involved water stress during both peak and late flowering with one irrigation between stress cycles. All stress

Table IV-4

Comparison of Water Application, Yields and Water Use Efficiencies for Grain Sorghum With Three Criteria for Irrigation Scheduling (Hiler et al., 1974)

Irrigation Criteria	Water Applied		Sorghum Grain Yield	Irrigation Water Use Efficiency	
	in.	% Reduction	lbs/ac	lbs/ac-in	% Increase
1971					
1. Fixed-level soil water potential	10.6	--	6010	569	--
2. Fixed-level leaf water potential	13.0	-23	7663	592	4
3. Stress Day-Index	7.5	29	7110	945	66
1972					
1. Fixed-level soil water potential	10.0	--	3252	326	--
2. Fixed-level leaf water potential	7.2	28	3214	447	37
3. Stress Day-Index	5.6	44	3286	587	80

treatments significantly reduced yields. The peak bloom treatment reduced yield by 37 percent with respect to the control (well-watered, no stress), and the late stress treatment reduced yield by 33 percent. The sequential stress treatment reduced cotton lint yield by a total of 44 percent. Since yield reductions caused by the sequential stresses were not additive (i.e. were much less than 70 percent), the results indicated that cotton was conditioned by the first stress and was not as susceptible to the second stress cycle.

An additive model for the Stress Day Index predicted the effects of a sequential stress in cotton using both leaf water potential and available soil water factors (Clark and Reddell, 1986). Lysimeter cotton lint yields and seasonal water use efficiencies favored the control treatment, followed by the late bloom water stress period. Late bloom stress was more favorable than peak bloom or sequential stress cycles (Table IV-5).

Sternitzke and Elliot (1986) measured evapotranspiration rates for the Oklahoma Panhandle (Table IV-6). They calculated crop coefficients Kc from ET_a values for well-watered corn, grain sorghum, and soybeans using the expression $K_c = ET_a/ET_o$, where ET_o was determined from alfalfa. Regression equations were developed with two years of data relating crop coefficient (K_c) values to number of days after crop emergence (DAE). Results for corn, grain sorghum and soybeans are shown in Figure IV-3. Values of K_c ranged from 0.57-1.02 for corn, 0.15-0.88 for sorghum, and 0.15-1.07 for soybeans. Actual ET rates (ET_a) calculated from a water balance equation compared favorably with values found in research literature. The modified-Pennman equation predicted reference ET_o values based on alfalfa reasonably well, while neither the Priestley-Taylor or Jensen-Haise models were satisfactory for the conditions tested.

Table IV-5

Cotton Lint Yield and Seasonal Water Use Efficiencies from Sequential Water Stress Experiments (Clark and Reddell, 1986).

Treatment	Lint Yield		Seasonal Water Use Efficiency	
	lbs/ac	kg/ha	lbs/ac-in	kg/m^3
1. Control--adequately watered	954	1070	26.7	0.118
2. Peak bloom stress, flowering days 8-34	598	670	24.5	0.108
3. Late bloom stress, flowering days 34-59	633	710	26.3	0.116
4. Peak and late bloom stress, at flowering days 8-59, except irrigated at flowering day 34	535	600	24.0	0.106

Table IV-6

Measured Evapotranspiration Rates for Crops in the Oklahoma Panhandle (Sternitzke and Elliott, 1986)

Crop	Maximum Measured ET, in./day		
	Well-Watered*	Normal Watering*	Stressed**
Alfalfa	0.47-0.55	0.43-0.55	--
Corn	0.35-0.47	0.31-0.43	0.28
Sorghum	0.39	0.35-0.39	0.24
Soybeans	0.39	0.35	0.28

* Data for 1984 and 1985 crop years.
** Data for 1985 crop year.

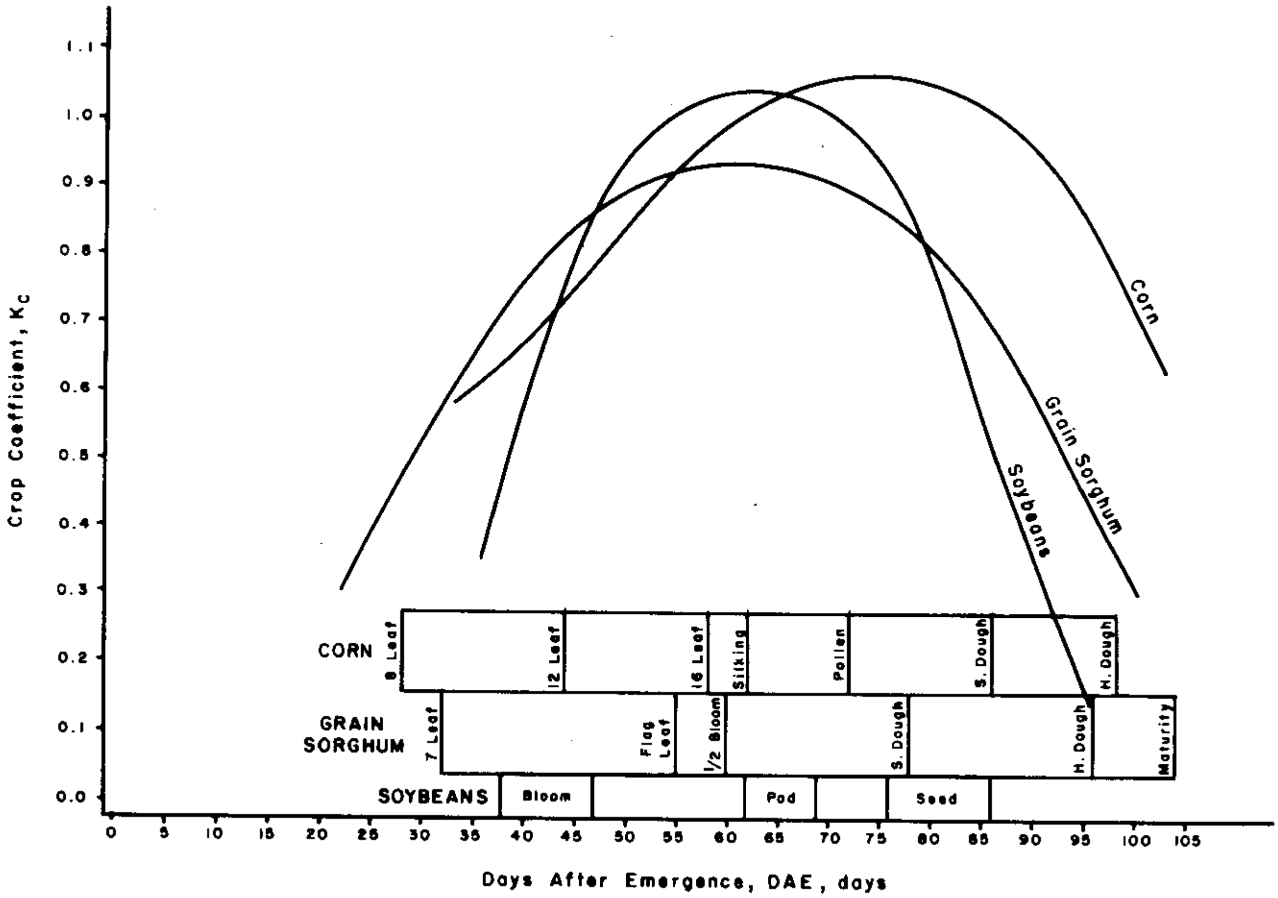

Figure IV-3. Calculated crop coefficients (K_c) for corn, grain sorghum, and soybeans versus days after emergence (DAE) for Oklahoma Panhandle, 1984-85 (Sternitzke and Elliot, 1986).

Summary

Scheduling irrigations to meet crop water needs both in time and quantity is one of the most promising areas of recent research and application to commercial farming in the High Plains. There are several available approaches, and new areas being developed include crop models and climatic monitoring for specific regions. Daily evapotranspiration (ET) rate is the key parameter in irrigation scheduling models, and it consists of all water transpired from plant surfaces and evaporation from the soil surface. The ET rate depends more heavily on climatic factors, crop physiology and soil moisture content than on management factors. Potential ET values represent an adequately watered grass crop of uniform height that is used as a reference crop. However, actual evapotranspiration for a given crop is usually less than potential ET and the difference is often expressed numerically by a crop coefficient term (ratio of actual to potential ET) that varies with stage of growth. Crop coefficient values have been defined for many crop and site situations in the U.S. but are lacking for the Texas High Plains. Another evapotranspiration term is maximum ET for a given crop, and it represents a full crop canopy and adequate water.

The water deficit experienced by a crop can be numerically defined as the difference between maximum and actual ET, with this difference usually expressed as a decimal fraction of the maximum ET. Yield reductions caused by water stress vary widely among crops and also among growth stages for a given crop. The magnitudes of yield reduction and water deficit are directly related for a given crop and growth stage.

Knowing the depth of water to add to a soil at the critical growth stages can save water, improve crop yields and boost irrigation water use efficiency. Soil moisture sensing devices are available to provide such information to all irrigation farmers. Data from yearly soil moisture surveys in winter can help farmers select crops and planting dates and decide whether and how much to irrigate before planting. All farmers should master and practice the art of soil moisture sensing by the feel method. Gypsum blocks and tensiometers are practical devices for soil moisture sensing. Gypsum blocks should be utilized especially for relatively fine-textured soils and relatively drought tolerant crops (cotton, sorghum, wheat) while tensiometers are most beneficial on coarser textured soils and crops that require frequent irrigation (corn and vegetables). Neutron probes are accurate but impractical for most farmers.

Several mathematical models have been developed for irrigation scheduling based on evapotranspiration, climate, soil moisture, and crop growth stage. The most widely used method is the water balance model, which basically provides a day-to-day summation of water depletion in inches (mm) within the root zone using daily values for ET, soil drainage loss (deep percolation), net irrigation amount, and net precipitation. The estimated number of days before the next irrigation and the desired amount of irrigation water are then calculated. Use of the water balance approach to schedule irrigations has increased yields in some experiments.

A stress-day index (SDI) concept was developed to quantify the relative effects of water stress on a crop at different growth stages. The stress day index is calculated as the product of a crop susceptibility factor (i.e. relative plant sensitivity to water deficit at various growth stages) times a stress day factor (relative measure of plant water deficit, e.g. leaf water potential or soil water potential). The SDI concept has produced improved yields and irrigation water use efficiencies in research plots.

Some progress has been made toward determining whether sequences of moisture stress will actually condition a crop to additional or prolonged stress during a period of normally high moisture use. Optimal sequences of stress were identified by one researcher for corn but have not been corroborated by High Plains researchers.

The difference in leaf and air temperatures offers another promising method for scheduling irrigations in some crops with a large differential temperature denoting high ET and soil moisture availability, or vice versa. However this method needs further development.

The success of any soil or plant monitoring method or crop/irrigation model must rest with the ability of a farmer, perhaps aided by sources of technical assistance, to increase yields and irrigation water use efficiency when it is used as a decision aid. Irrigation scheduling methods are continually being refined and placed in practice on commercial farms, as they offer considerable potential.

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CHAPTER V

PRECIPITATION MANAGEMENT FOR CROP PRODUCTION

In 1982, the acreage of dryland cropland was 54 percent of the 15.6 million acres (6.3 million ha) of cultivated land in the Southern High Plains (Jones et al., 1985). Precipitation is now considered a primary water resource for crop production even among irrigation farmers. Water management practices for dryland agriculture have gained renewed importance because of increasing costs and decreasing profits from irrigation (Stewart and Burnett, 1985).

Dryland agriculture includes farming systems without irrigation in regions of limited rainfall, typically less than 30 inches per year (750 mm/yr) (Stewart and Burnett, 1987). Dryland farming is a high risk undertaking, and the key to success in semi-arid regions is to take advantage of rainfall that can be stored in the soil. Past research has shown that 1 inch (25 mm) of stored soil water produces 350 pounds (160 kg) of sorghum grain or 2½ bushels (68 kg) of wheat at Bushland (Petr et al., 1984).

Components of Dryland Water Management

Three components of a successful dryland water management system are: (1) precipitation retention by increased infiltration rate or rainwater capture to allow infiltration; (2) reduced evaporation with crop residues or mulches that maximize soil cover; and (3) utilizing crops that are drought tolerant and have growing seasons that best fit the rainfall patterns (Stewart and Burnett, 1987). The most important component is rainfall conservation. In the High Plains, it would be desirable to eliminate runoff from cropland in favor of soil moisture storage. Furrow diking, conservation bench terracing, and land leveling have proven effective in both rainfall conservation and soil erosion control.

Evaporation from the soil surface outside the crop growing season is a major loss of water that is counterproductive. For example, precipitation lost as evaporation during the non-growing season ranges from 36 percent for continuous wheat (3-4 month fallow) to 61 percent for a wheat-fallow system (16 month fallow period) (Stewart and Burnett, 1987). The 16 month fallow period for a wheat-fallow system normally does not increase soil water storage over the 11-month fallow in a wheat-sorghum-fallow rotation (Musick, 1987). The most effective practice for reducing soil evaporation is a mulch, and crop residues are about the only practical source of mulching material in dryland areas of the Southern High Plains (Stewart and Burnett, 1987). Unfortunately, limited amounts of crop residues are produced under dryland farming.

Unger (1978) determined that rainwater storage efficiency and grain sorghum yields increased sharply with increasing amounts of straw mulch on Pullman clay loam soils. Data for 38 years at 7 locations in the Great Plains indicated that soil water storage during fallow averaged 4.6 inches (117 mm) with straw mulches versus 3.5 inches (89 mm) for bare soil (Greb et al., 1979). At four Great Plains locations, the net soil water gain at the end of the fallow period increased with mulch application rate (Greb, 1983). The net increase in soil moisture was 0.8, 1.5 and 2.0 inches (20, 38 and 50 mm) for straw mulch rates of 2,000, 4,000 and 6,000 pounds per acre (2,200, 4,400 and 6,600 kg/ha).

Dryland cropping depends on matching the cropping system with the climate to increase the probability of harvestable yield (Stewart and

Burnett, 1987). Dryland crops should be grown during periods of high rainfall probabilities to allow more of the rainfall to be used for evapotranspiration, which will increase yields and water use efficiency. Average rainfall data can be very misleading, and probability levels set at any desired rainfall amount are a better way of assessing risk. Crop growth models can be used to estimate crop yields under various climatic conditions. It is also important to increase the drought tolerance of crops through improved germplasm.

Precipitation Probabilities

Heerman et al. (1971) determined probabilities that a given day or sequence of days will be wet or dry for selected Texas weather stations. Dugas (1983) developed precipitation probabilities for locations near research and extension centers in Texas for periods of 1 week, 2 weeks, 3-weeks and one month to determine the probability of receiving more than nine selected precipitation amounts ranging from 0.01 to 10 inches (0.25-254 mm). He also determined the number of consecutive days without daily precipitation above 0.0, 0.1 and 0.4 inches (0.0, 2.5, and 10 mm) at probability levels of 90, 50 and 10 percent. For example, the data for Lubbock (Table V-1) shows that there is a 50 percent chance that a dry spell will be ended by precipitation of 0.4 inches (10 mm) or more within 6 to 13 days between April 26 and September 19 based on 68 years of record. Similar data for Amarillo is also shown in Table V-1. Both data sets show that consecutive periods of more than one or two months without 0.4 inches (10 mm) or more of daily precipitation should be expected at least 50% of the time between mid-October and mid-March. In using the data in Table

Table V-1

Number of Days Until One-Day Precipitation Event Greater Than 0.1 or 0.40 Inches (2.5-10.0 mm) for Amarillo and Lubbock (Dugas, 1983)

	Amarillo (32 years data)						Lubbock (68 years data)					
	Probability of Precipitation > 0.10 inch			Probability of Precipitation > 0.40 inch			Probability of Precipitation > 0.10 inch			Probability of Precipitation > 0.40 inch		
Date	90%	50%	10%	90%	50%	10%	90%	50%	10%	90%	50%	10%
MAR 1	48	14	2	77	41	18	51	19	5	68	29	9
MAR 8	46	14	2	65	33	14	42	16	4	61	26	8
MAR 15	40	15	4	62	33	15	33	13	3	64	30	11
MAR 22	34	10	2	56	26	10	33	13	3	56	24	8
MAR 29	29	9	1	50	25	10	29	12	4	51	24	9
APR 5	25	8	1	47	22	8	28	10	3	44	19	6
APR 12	32	12	3	39	17	5	31	12	3	43	20	8
APR 19	31	12	3	38	17	5	26	10	3	42	16	4
APR 26	26	10	2	35	17	7	20	6	1	40	12	2
MAY 3	23	9	2	29	14	5	15	5	1	39	12	2
MAY 10	14	4	1	24	9	2	14	4	1	43	13	2
MAY 17	16	3	0	28	8	1	17	5	1	37	11	2
MAY 24	19	3	0	29	9	1	16	5	1	40	12	2
MAY 31	16	3	0	26	8	1	19	6	1	38	12	2
JUN 7	14	2	0	30	5	0	24	7	1	35	6	0
JUN 14	23	7	1	40	12	2	21	6	1	47	8	0
JUN 21	16	5	1	33	10	2	19	6	1	46	8	0
JUN 28	17	5	1	28	9	1	21	8	2	41	7	0
JUL 5	14	4	1	23	7	1	17	3	0	46	8	0
JUL 12	13	4	1	27	8	1	29	9	1	51	9	0
JUL 19	12	4	1	45	8	0	19	3	0	52	9	0
JUL 26	14	5	1	42	7	0	25	4	0	79	13	1
AUG 2	10	4	1	36	6	0	33	10	2	71	12	1
AUG 9	11	4	1	38	7	0	32	10	2	75	13	1
AUG 16	13	2	0	35	6	0	30	9	1	79	13	1
AUG 23	24	7	1	50	15	2	31	9	1	72	12	1
AUG 30	23	7	1	59	10	0	21	4	0	65	11	1
SEP 6	31	9	1	63	11	1	28	5	0	66	11	1
SEP 13	25	7	1	61	10	0	38	12	2	70	12	1
SEP 20	32	10	2	102	17	1	51	9	0	86	15	1
SEP 27	63	19	3	97	17	1	52	9	0	89	15	1
OCT 4	42	7	0	111	19	1	57	10	0	99	17	1
OCT 11	44	8	0	181	55	8	56	9	0	91	16	1
OCT 18	42	7	0	176	67	16	57	10	0	152	46	7

TABLE 1, CONTINUED

	Amarillo (32 years data)						Lubbock (68 years data)					
	Probability of Precipitation > 0.10 inch			Probability of Precipitation > 0.40 inch			Probability of Precipitation > 0.10 inch			Probability of Precipitation > 0.40 inch		
Date	90%	50%	10%	90%	50%	10%	90%	50%	10%	90%	50%	10%
OCT 25	45	8	0	168	64	16	55	9	0	130	39	6
NOV 1	63	19	3	178	84	31	76	23	4	155	59	14
NOV 8	52	16	2	156	73	27	83	25	4	142	54	13
NOV 15	54	16	3	170	80	30	89	27	4	164	71	22
NOV 22	61	23	6	157	79	33	87	26	4	156	67	21
NOV 29	62	23	6	153	77	32	76	23	4	135	58	18
DEC 5	55	21	5	153	84	40	74	22	3	153	72	27
DEC 12	61	26	8	141	77	37	66	20	3	146	69	25
DEC 19	49	21	7	129	69	31	60	18	3	132	62	23
DEC 26	50	19	5	126	63	26	74	28	7	127	64	26
JAN 3	50	19	5	121	57	21	50	15	2	119	60	25
JAN 10	50	19	5	113	57	23	64	24	6	121	66	31
JAN 17	49	15	2	110	56	23	50	15	2	111	59	26
JAN 24	54	21	5	103	56	27	54	21	5	105	53	22
JAN 31	42	13	2	103	55	24	57	22	5	93	44	16
FEB 7	41	7	0	101	53	24	41	12	2	89	42	16
FEB 14	57	17	3	87	44	18	43	13	2	81	35	11
FEB 21	56	17	3	84	40	15	42	13	2	84	39	15

V-1, keep in mind that a large number of days denotes a dry season and vice versa.

Soil Moisture Storage

Soil moisture storage and efficient utilization of stored soil water through evapotranspiration are the essential keys to productive dryland agriculture. Water that plants extract from the soil can exceed total rainfall during the growing season thus allowing a sorghum crop to produce respectable dryland yields (Unger, 1984).

Following harvest, farmers should measure the residual soil moisture and then decide on the use of the land for the following year (Stewart, 1984). If the soil is dry, the probability is small that a succeeding crop can be grown without a fallow period to collect soil moisture. On the other hand, if the soil profile at harvest is more than 50 percent charged with moisture, (e.g. contains over 3.5 inches (89 mm) of available water for a Pullman clay loam), a farmer could hope to capture only 3 to 3.5 inches (76-89 mm) of additional soil water in an extended fallow period, or about 16 to 18 percent of annual rainfall. Beginning with about 3.5 inches (89 mm) of stored soil water plus the expected rainfall of 9 inches (230 mm) from June to September (50 percent probability level), a farmer could expect a dryland sorghum grain yield of 1,900 pounds per acre (2,130 kg/ha). Stewart (1984) suggested that crop models be developed to project yields to be expected in 25, 50 or 75 percent of the years given the residual soil moisture at harvest, crop yield/water use relationships and rainfall probabilities.

Precipitation Storage Methods

Studies of soil moisture storage efficiencies in northeastern Colorado indicated that the efficiency of precipitation storage has increased as the number of field tillage operations has been decreased in the period 1915 to 1977 (Stewart, 1984). The efficiency of retaining precipitation as stored soil water during fallow has increased to the 33 to 55 percent range with minimum tillage and no-tillage (0 to 3 tillage operations annually) as compared to 16 to 24 percent with conventional or maximum tillage (5 to 10 annual tillage operations). The most desirable soil management from the standpoint of water infiltration is no-till although necessities of weed control and seed bed preparation will dictate that some tillage be performed (Jones, 1984).

Systems for rainfall capture and soil moisture storage should be designed to collect runoff from small to medium-sized storms (Jones, 1984). Rains of 0.25 to 2.00 inches (6.4-51 mm) accounted for 84 percent of the precipitation at Bushland from 1960 to 1979. Average annual runoff loss from dryland watersheds at Bushland with wheat-sorghum-fallow rotation with stubble mulch tillage averaged 1.4 inches (36 mm) per year for 26 years, as compared to 18.2 inch (462 mm) average rainfall. Twice as much runoff was lost from sorghum and fallow as from wheat in the 3-year rotation. Most runoff occurred during June, July and August during sorghum and fallow (Figure V-1).

Methods of conserving both precipitation and soil erosion can be classified as follows (Jones et al., 1985):

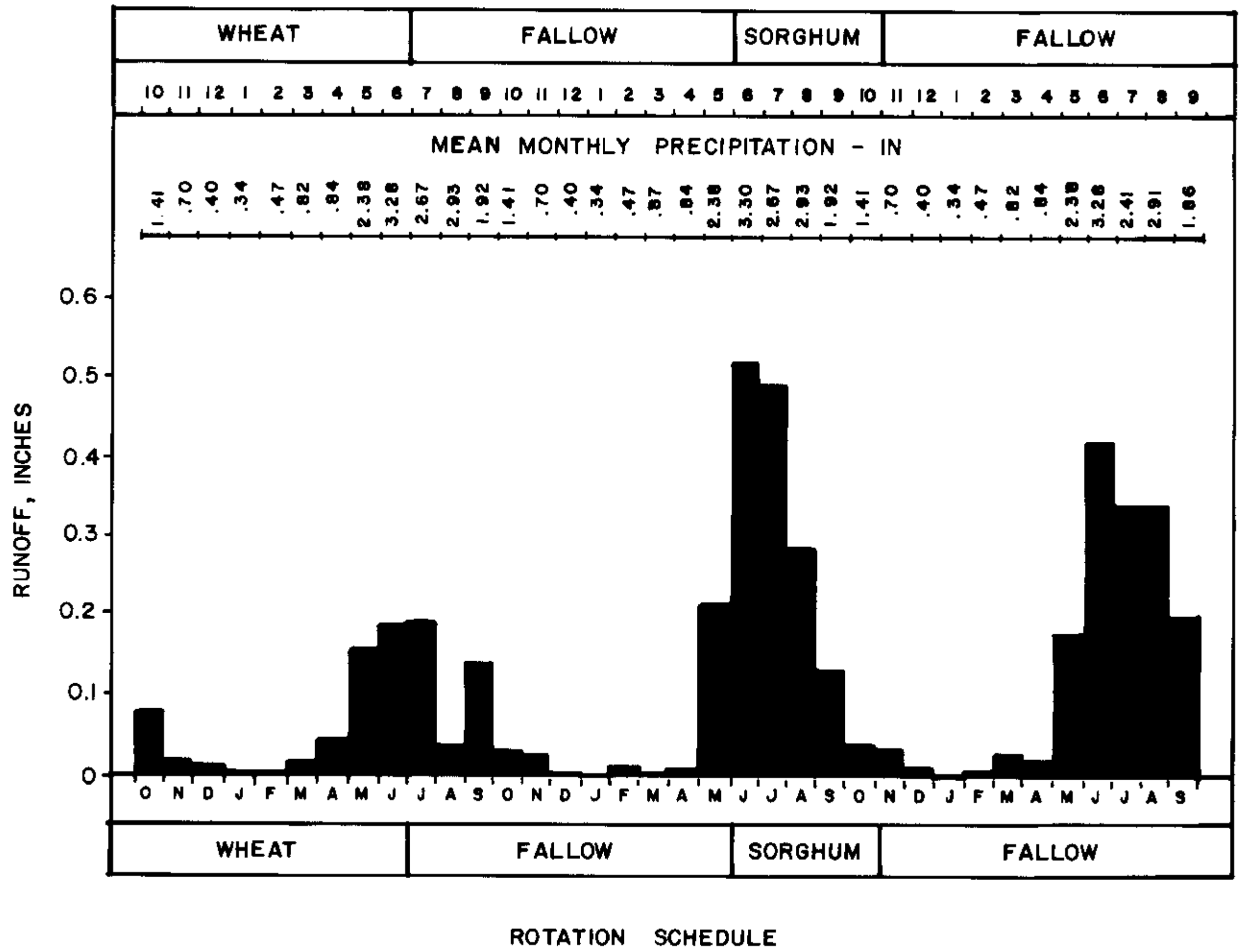

Figure V-1. Twenty-five year (1959-83) mean monthly precipitation and runoff from three graded terraces cropped in a 3-year wheat-sorghum- fallow sequence. One terrace was in each phase of the sequence every year (Jones, 1984).

Traditional	Recent Technology
Stubble mulch tillage	Land leveling
Contour tillage	Narrow bench terraces (mini-benches)
Broad base terraces	Conservation bench terraces
	Furrow diking (basin tillage)
	Conservation tillage

Some of the history of tillage, terracing, and furrow diking in the Great Plains was reviewed by Musick (1981).

Terracing and Land Leveling

Level or graded terracing with irregular horizontal distances between terraces (i.e. terrace intervals) was initiated in the 1930's and has essentially been abandoned in the Southern Great Plains because of the difficulty it imposes on field machinery operations (Musick, 1981). Conservation bench terracing was developed in the 1950's, and it involves bench leveling of a part of the crop interval above each terrace ridge with the remaining upslope interval contributing runoff to the bench. The contributing area typically has twice the area of the leveled bench. Parallel terraces involve some land leveling above the terrace ridges to maintain a constant terrace interval. Parallel terracing evolved and was adopted in the 1970's as a new practice for runoff retention and increased water storage.

The following discussion of crop research on terrace systems was provided by Musick (1981). Hauser et al. (1962) compared level closed-end terraces with graded terraces at Bushland, Texas, for the period 1949-60. In a wheat-sorghum-fallow system, the prevention of runoff in the level terraces did not affect wheat yields, but increased sorghum yields by 11 percent. During 9 of 12 years, level terraces impounded runoff on sorghum.

The first conservation bench terrace system installed at Bushland in 1955 included a sloping runoff contributing area that was twice the bench area (Zingg and Hauser, 1959). Jones (1975) summarized 14 years of results with continuous grain sorghum grown on the benches and a dryland wheat-sorghum-fallow rotation grown on the runoff contributing slopes. Sorghum yields on the benches averaged 1,990 pounds per acre (2,230 kg/ha). The slopes that had an 11-month fallow period and about twice the rainfall between harvest and planting as the benches averaged 1,790 pounds per acre (2,010 kg/ha). Hence, runoff retention on the benches permitted successful annual cropping, and increased average water use efficiencies for grain production by 35 percent. Runoff retention on the level benches averaged 15 percent of precipitation onto the terrace interval.

Armbrust and Welch (1966) indicated that the conservation bench terrace system did not increase cotton and grain sorghum yields on a sandy soil at Big Spring, Texas. Runoff in May to June adversely affected cotton establishment, while September runoff was too late to benefit the crop. Runoff retention may have contributed to deep profile drainage but apparently resulted in little additional soil profile water storage. On a clay soil at Hays, Kansas, bench terracing did not increase sorghum production during a 6-year study, primarily because of frequent wet soil conditions from water ponding that delayed planting (Cox, 1968).

The most recent development in level terraces are the mini-bench (completely leveled between small terraces) and the conservation mini-bench (having a watershed to bench ratio of 1:1) designed and tested by Jones (1981) at Bushland. The level mini-benches were designed as low cost installations with minimum earth moving and topsoil removal. The benches and slopes were both designed for one pass of 13.3 feet (4.1 m) wide field equipment but could be designed for wider equipment. Over a 4-year test (1975 to 1978), sorghum yields on mini-bench terraces averaged 2,150 pounds per acre (2410 kg/ha), compared with 1,830 pounds per acre (2,050 kg/ha) for conservation mini-bench terraces and 1,070 pounds per acre (1,200 kg/ha) for graded furrows. The graded furrows lost 2.6 inches (66 mm) of storm runoff per year.

A disadvantage of conservation bench terraces is the occasional need for surface drainage of collected runoff through grass waterways on clay soils during periods of major runoff (Musick, 1981). Reducing the ratio of slope:level bench area can reduce the surface drainage problem. Also, on Pullman clay loam, results from an 11-year test indicate that one-time mold-board plowing to the 2-foot (0.6 m) depth increased intake rates for several years and largely eliminated the need for surface drainage. Terraces also require periodic maintenance.

Furrow Dikes (Basin Tillage)

Furrow diking, also called furrow damming or basin tillage, has gained wide acceptance by farmers in the Southern High Plains and the Rolling Plains. Lyle and Dixon (1977) described the early history of furrow diking, which began in the 1930's using a lister attachment in which soil blocks were placed in listed furrows for storm runoff retention. Research with furrow diking was conducted for more than a decade at several Great Plains locations beginning in the late 1930's (Clark and Hudspeth, 1976; Musick, 1981). Furrow dike treatments had little or no effect on yields of continuous winter wheat as compared to conventional lister tillage because the dikes were usually in place only during a short fallow season when runoff was small (Lyle and Dixon, 1977; Clark and Jones, 1980).

Favorable yield response to furrow diking (basin tillage) has primarily been with summer row crops when runoff is otherwise expected and the crops can use the extra soil moisture almost immediately. For instance, corn yields with furrow diking were increased 12.4 percent at Lincoln, Nebraska as compared to moldboard plowing, and sorghum yields were increased by 16.6 percent at Garden City and 22.1 percent at Hays, Kansas (Musick, 1981). The 12 to 22 percent yield increases were consistent with the quantity of water conserved--typically 1 to 2 inches (25-51 mm) of storm water runoff.

Clark and Hudspeth (1976) initiated research in the High Plains with furrow dikes on dryland grain sorghum at Bushland and dryland cotton at Lubbock in 1975. The storage capacity of furrow dikes at alternate furrow spacings was observed to be 2.0, 2.4, and 4.7 inches (50, 60, and 120 mm), respectively, for furrow spacings of 30, 40, and 60 inches (0.76, 1.0, and 1.5 mm).

Lyle and Dixon (1977) developed two furrow diking implements: (a) raising shovel, and (b) tripping shovel. The tripping shovel was found to be superior and was made to be hydraulically operated. Sweeps were placed in front of the tractor tires to plow out existing furrow dikes during field operations. Furrow diking used on an alternate furrow basis eliminated the need for plow-out sweeps. However, diking of every furrow is the most desirable for maximum rainfall utilization.

Sorghum Grain: Effects of Furrow Diking

Clark and Hudspeth (1976) found that grain sorghum yields at Bushland were 13 percent higher with the furrow dams (2,607 pounds per acre, or 2,922 kg/ha) than with open furrows (2,305 pounds per acre or 2,583 kg/ha). The furrow dikes prevented approximately 0.8 inch (20 mm) of runoff. Clark and Jones (1980) summarized research with furrow diking at Bushland in which dryland grain sorghum yields for 4 years averaged 1,838 ± 879 pounds per acre (2,060 ± 985 kg/ha) for furrow diked plots and 1,579 1,014 pounds per acre (1,770 ± 1137 kg/ha) for open graded furrow plots, a 16 percent increase in mean yields due to furrow diking. Furrow dikes produced little difference in 2 years but prevented a crop failure in one year. Each year where runoff was caught in diked furrows before August 15, grain yields were increased. The effect of furrow diking on soil moisture is illustrated in Figure V-2, in which soil moisture content increased 2.2 inches (56 m) following rainfall of 3.3 inches (85 mm) in mid-August, 1977. With sorghum in the High Plains, furrow dikes should be established before June (Clark and Jones, 1980) to take advantage of late spring and early summer rains. On relatively steep slopes, furrow dikes should be used in conjunction with terracing to prevent soil erosion that may occur when furrow dikes overtop, but on gentle slopes of 2 percent or less furrow dikes can control runoff from large storms without severe erosion (Clark & Jones, 1980).

In a 2-year test (1980-81) at Etter, Texas with continuous sorghum, furrow dikes resulted in average yields of 2,210 pounds per acre (2,477 kg/ha) as compared with 910 pounds per acre (1,012 kg/ha) for open furrows that averaged 3.1 inches (79 mm) of runoff, a yield increase of 143 percent (Musick, 1981). A yield increase of 1,510 pounds per acre (1,690 kg/ha) in

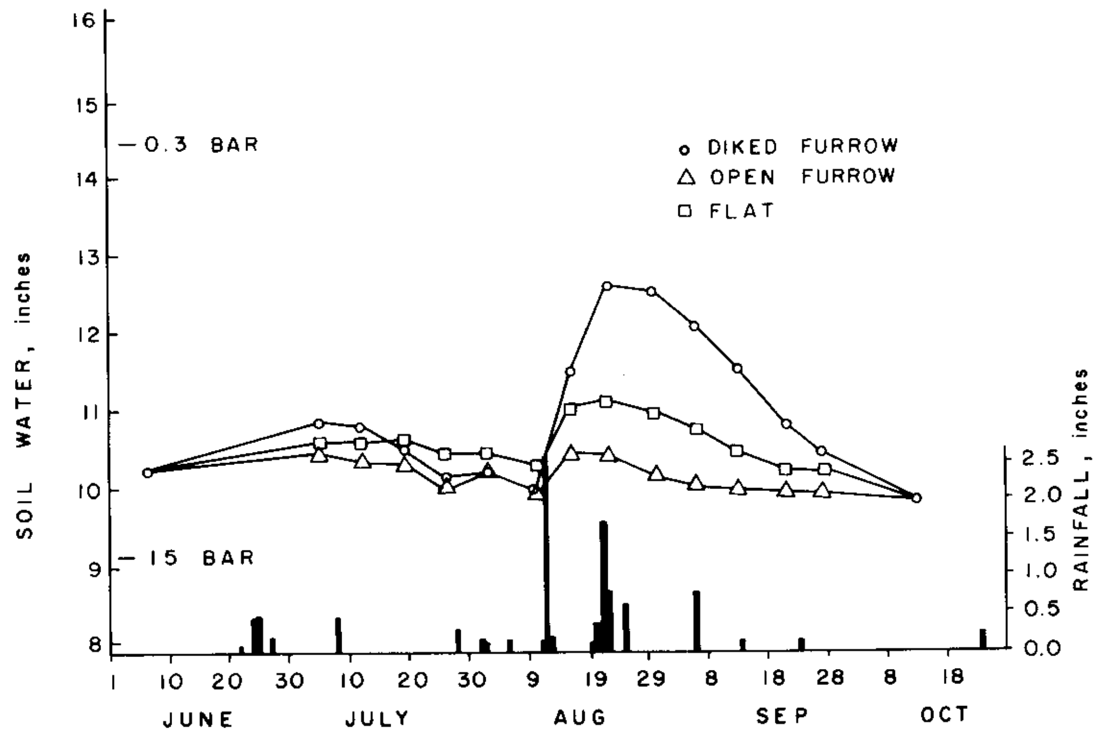

Figure V-2. Soil water content in the top 3.9 feet (1.2 m) of soil depth and seasonal precipitation for grain sorghum grown on furrow diked, open furrow, and flat tillage treatments at Bushland, Texas, 1977 (Clark and Jones, 1980).

1980 was the highest sorghum yield response to furrow dikes measured in the High Plains.

Gerard (1982) obtained an average sorghum grain yield increase of 20 percent during 2 years (1979-80) of tests at Chillicothe in the Rolling Plains. In the 1979 test, furrow dikes increased sorghum yields on the upper part of the sloping area from 2,700 to 4,400 pounds per acre (3,030-4,930 kg/ha). Gerard (1982) concluded that furrow dikes could help develop sorghum as an alternative dryland crop to cotton in the Rolling Plains.

Cotton: Effects of Furrow Diking

Dryland cotton at Lubbock yielded 249 pounds per acre (279 kg/ha) for diked furrows versus 200 pounds per acre (244 kg/ha) for open furrows, a 25 percent yield difference (Clark and Hudspeth, 1976). Also at Lubbock, Bilbro and Hudspeth (1977) obtained dryland cotton yield increases of 5 to 25 percent (Table V-2) using furrow diking on 10 feet (3.0 m) spacings in furrows with 0.2 and 0.9 percent slope. All plots received 11.7 inches (297 mm) precipitation in the growing season without runoff from the diked furrows.

Gerard et al. (1983) reported experiments conducted near Vernon on Miles fine sandy loam during 1980 and 1981 to determine the effect of furrow diking and subsoiling on cotton yields. These practices had no effect on cotton yield in 1980 because of low rainfall and extremely high temperatures. In 1981, furrow diking prevented runoff and boosted yields from an average of 326 pounds per acre (365 kg/ha) for non-diked furrows to 430 pounds per acre (482 kg/ha) for diked furrows, an increase of 32 percent. Cotton yields for half-diked and diked/subsoiled treatments were

Table V-2

Increases in Lint Yield of Dryland Cotton
From Furrow Diking, Lubbock, 1975
(Bilbro and Hudspeth, 1977)

Test No.	Average Cotton Lint Yield Diked lbs/ac	 Undiked lbs/ac	 Difference, %
A--40 inch rows, 0.9% slope	300	271	10.7
B--40 inch rows, 0.2% slope	342	303	14.7
C--(a) 40 inch rows, 0.2% slope	249	200	24.5
(b) 10 inch rows on 40 inch beds, 0.2% slope	236	225	4.9
Average	282	250	12.9
Standard Deviation	49	46	--

* Furrow dikes in place March-October and received 11.7 inches rainfall.

15 and 38 percent higher than for the undiked furrows. Water use efficiency was estimated at 31 to 34 pounds lint per acre-inch of water for all treatments. Cotton fiber quality was improved, and the value of cotton per acre was significantly higher (5 percent level of probability) for the furrow diking treatments. The cotton value was $146 per acre ($360/ha) for undiked furrows versus $175, $205, and $218 per acre ($432, $506, and $538/ha) for half-diked, diked, and diked/subsoiled plots.

At Chillicothe, Clark (1983) installed furrow diking on Abilene clay loam to capture spring rains prior to planting, which resulted in significant increases in cotton yield. Furrow dikes 6 inches (0.15 m) tall were installed in March, 1981 at 6 feet (1.8 m) intervals along the furrows. Substantial rainfall of 12.63 inches (321 mm) was received between the time that dikes were established until planting in late June. Diking all furrows produced 36 percent average cotton yield increase, while diking alternate furrows resulted in a 16 percent average yield increase (Table V-3). Furrow diked plots had significantly greater boll count than undiked furrows. The combination of subsoiling with reduced tillage did not provide a significant yield advantage over conventional tillage. Following tillage operations, furrow dikes that were re-established in late July on half of each plot did not produce a significant yield response due to the low rainfall of 2.19 inches (56 mm) that was subsequently received. Diking all furrows resulted in a $31.62 per acre ($78.10/ha) increase over not diking. Diking alternate furrows resulted in an increase of $15.20 per acre ($37.54/ha).

Results on Miles fine sandy loam at Munday in 1981 (Bordovsky, 1983) showed 6 to 17 percent average increase in cotton yield from furrow diking

Table V-3

Yield Response of Cotton to Furrow Diking Treatments at Chillicothe, Texas, 1981 (Clark, 1983)

		Yield, pounds lint per acre			
		Furrow Dike Treatment			
Tillage System	Sub-Soil Treatment	None	Alternate Furrows	All Furrows	Average
Conventional	None	191	262	280	244 a
Reduced tillage	40 in. spacing	227	233	280	247 a
Reduced tillage	20 in. spacing	N.A.	231	294	263 a
Average		209c*	242b	285a	

* Means within a row or column followed by the same letter are not significantly different at the 5 percent probability level.

of alternate rows as compared to non-diked furrows. Yield differences were not significant.

Dikes were installed in early March and were re-established twice during the growing season. A total of 10.4 inches (264 mm) of rainfall was received while dikes were in place, with most of this occurring before the cotton was planted. Water use ranged from 7.2 to 7.4 inches (183-188 mm) for all treatments. Water use efficiency was 41 pounds per acre-inch (0.18 kg/m^3) for the non-diked check plots and 42 to 47 pounds lint per acre-inch (0.19-0.21 kg/m^3) for the alternate-furrow diked plots. These differences were not significant.

Management Considerations and Costs

The cost of furrow diking is very low, particularly in relation to the sizable crop yield increases usually obtained. Wistrand (1984) estimated total cost at less than one dollar per acre per year on a cash basis (Table V-4). If equipment is financed, total costs will be about 13 percent higher than in Table V-4. With annual yield increases of $12.50 to $72.00 per acre ($30.90-$177.80/ha) being reported, an extremely high benefit:cost ratio is indicated.

Furrow diking must be correlated with the time of greatest runoff potential and crop water use (Clark and Hudspeth, 1976). Furrow dikes should be established for sorghum and cotton by early May (Musick, 1987), and as shown by the Rolling Plains research, as early as mid-March. However, diking after mid-June will have less benefit due to lower probability for runoff producing rains. The use of furrow diking for wheat has little potential (Clark and Hudspeth, 1976).

Table V-4

Estimated Total Annual Cost per Acre of Furrow Diking with 9-Row Tool Bar Unit (Wistrand, 1984)

	Cost of Furrow Diking			
	Every Furrow		7-diked and 2 undiked wheel-track furrows	
	$/acre	$/ha	$/acre	$/ha
Fixed costs, total*	$0.44	$1.09	$0.28	$0.69
Operating Costs, total	0.43	1.06	0.29	0.72
Total Annual Cost*	0.87	2.15	0.57	1.41

* Cash Basis

Alternatives to diking every furrow include diking of alternate furrows, or in the case of wide multi-row equipment, omitting dikes in wheel traffic furrows (Bordovsky, 1983). With four-row equipment, diking alternate furrows or all furrows are the only practical options (Clark, 1983), but six or eight row equipment allows diking 2/3 or 3/4 of the furrows, respectively, while leaving wheel furrows open for tillage operations.

A grain sorghum simulation model (SORGF) was combined with surface runoff hydrology algorithms from the Erosion-Productivity Impact Calculator (EPIC) to evaluate the effect of furrow diking on sorghum yields at Lubbock and two other locations (Krishna et al., 1987). Simulation results indicated that furrow diking during the growing season only will likely increase dryland sorghum grain yields at Lubbock by 180 pounds per acre (202 kg/ha) in 7 out of 20 years. In 9 out of 20 years, diking all year around will likely increase sorghum yields by 270 pounds per acre (303 kg/ha) or more. Average yield increases of 400 pounds per acre (450 kg/ha) were estimated over the long term for dryland sorghum grain at Lubbock.

Furrow diking is now well established for precipitation management to prevent runoff in cotton production systems in the Southern Plains, and it has major potential for successful use in other row crops. The modern day success of furrow diking relates to (1) its use as a precipitation management practice in summer row crop production systems, (2) the development of improved simple and reliable equipment, and (3) the use of residual-type herbicides that minimize the need for subsequent tillage operations (Musick, 1981).

Conservation Tillage

Limited and no-tillage management systems can be very effective in reducing water losses from evapotranspiration and storm runoff on either dry farmed or irrigated land (Musick, 1981). The term "conservation tillage" includes all tillage methods that leave at least 20 percent of the soil surface covered with residues after planting (Dickey et al., 1984). Crop residues limit soil particle detachment from raindrop impact, create debris basins that slow the runoff rate and increase opportunity time for infiltration, and reduce sediment transport capacity of runoff.

Soil loss and sediment concentrations were highly correlated with percent of soil surface covered with residue from continuous dryland corn, in Eastern Nebraska research (Dickey et al., 1984). The measured fraction of soil surface covered by dryland continuous corn residues varied widely with tillage practice (Table V-5). For 5 and 10 percent slopes, tillage systems leaving 20 percent or more of the soil surface covered with residues reduced soil loss by 50 percent or more as compared to clean-tillage.

Successful minimum tillage and no-tillage methods have been developed through research at Bushland, Texas on tillage methods and planting equipment for fourteen dryland and irrigated cropping sequences (Wiese et al, 1986). Relatively high levels of wheat residue resulted in soil profiles being consistently wet almost to field capacity when planting the next sorghum crop (Musick, 1981). On the other hand, with conventional disk or sweep tillage, soil profiles in the Southern High Plains are not usually filled to field capacity after fallow because of relatively low efficiencies of soil moisture storage.

Table V-5

Percent of Soil Surface Covered with Dryland Corn Residues vs. Tillage Treatments (Dickey et al., 1984)

Tillage Treatment	Corn Residue Cover	
	Average %	Range %
1. Moldboard Plow	4.3	1.1-6.3
2. Chisel Plow	16.5	7.6-34.6
3. Disk	16.2	14.4-20.6
4. Till-plant	21.0	7.2-33.6
5. No-till	50.8	38.9-75.7

* Data are averages of treatment means for two farms for 1980 and 1981 crop years.

Residue levels that remain after harvesting most dryland crops are relatively low, usually below 1,800 pounds per acre (2,020 kg/ha). Low residue levels provide limited efficiency for soil water storage (Jones et al., 1985) and in some cases insufficient residue on the surface to prevent wind erosion (Wiese et al., 1986). Under low residue conditions, as little as 15-20 percent of the precipitation during fallow for dryland crop production is stored as soil moisture (Unger et al., 1981; Jones et al., 1985).

By contrast, irrigated wheat may produce large amounts of residue per acre (Unger et al., 1971). A limited tillage system that consists of irrigated wheat/fallow/ dryland grain sorghum has shown considerable promise at Bushland (Unger, 1982). During 9 years of research with this cropping system, water storage during the 11-month fallow after irrigated wheat was increased an average of 2.1 inches (53 mm) with no-tillage as compared to disk tillage. This additional water is about equal to that stored in the soil from one irrigation. Non-irrigated sorghum yields increased about 1,000 pounds per acre (1,100 kg/ha) with no tillage as compared to disk tillage. In the irrigated wheat/fallow/dryland sorghum system, dryland sorghum yields from the 1972-78 crop years averaged 2,800, 2,230, and 1,720 pounds per acre (3,140, 2,500, and 1,930 kg/ha) for no-tillage, sweep tillage, and disk tillage methods used during the 11 months fallow (Unger and Wiese, 1979). Moisture stored as soil water during the 11 months of fallow averaged 35, 23, and 15 percent of precipitation, and available soil water contents to the 5.9 foot (1.8 m) depth at sorghum planting averaged 8.5, 6.7, and 6.0 inches (217, 170, and 152 mm). Water use efficiencies (WUE) for the sorghum grain averaged 202, 175, and 150 pounds per acre-inch (0.89, 0.77, and 0.66 kg/m^3) for no-till, sweep tillage and disk tillage, respectively. No-tillage also lowered the production costs. By using herbicides, tillage operations can be reduced and crop production economics can be improved if the herbicides cost less than tillage (Unger, 1982).

Harman (1982) determined that limited tillage, in comparison with conventional tillage, is profitable for these three cropping rotations:

Rotation	Projected Profit	
	$/acre/year	$/ha/yr
a. Irrigated Wheat/Fallow/Dryland Sorghum	47	116
b. Irrigated Wheat/Fallow/Irrigated Sorghum	52	128
c. Continuous Irrigated Wheat	9	22

The main cost differences were due to increased sorghum production from additional stored soil moisture and to reduced machinery depreciation with limited tillage.

Harman and Wiese (1984) evaluated no-tillage versus conventional tillage for dryland cotton following irrigated barley or wheat production at the Etter Research Field in 1983. At planting time, no-tillage plots contained 1.5 inches (38 mm) more moisture in the top 6 feet (1.8 m) of soil and 1.1 inches (28 mm) in top 3 feet (0.9 m). As a result, no-tillage dryland cotton yields were 10 percent higher (173 pounds per acre, or 194 kg/ha) than for conventional tillage (157 pounds per acre, or 176 kg/ha) for a short, very dry growing season.

Unger et al. (1971) determined that maintaining wheat residues on the soil surface has tremendous potential for storing precipitation for the succeeding crop. They determined the effectiveness of various tillage, herbicide and no-tillage treatments for storing soil water, maintaining surface residues, and controlling weeds between irrigated wheat and irrigated sorghum crops (10½ months fallow). Surface residues were 10,000 pounds per acre (11,200 kg/ha) immediately after July wheat harvest and the following spring had decreased to 200-4,100 pounds per acre (224-4,600 kg/ha) depending on tillage/residue treatment. As shown in Table V-6, no-tillage with herbicide for weed control and sweep tillage with herbicide treatment maintained the largest amount of surface residue, provided the most effective weed control, and retained the highest percentage of the 14.2 inches (361 mm) total precipitation than the other mechanical tillage treatments.

These significant increases in available soil moisture and precipitation storage (Figure V-3) were attributed to three factors: increased infiltration, reduced soil evaporation, and reduced evapotranspiration (weed and volunteer wheat control). Unger et al. (1971) contended that the 2.5-3.6 inch (64-91 mm) net gain in stored soil water should eliminate the customary preplant irrigation of 6 inches (150 mm) which accounts for 25 to 33 percent of the total water applied each year to the succeeding grain sorghum crop.

On sprinkler-irrigated or dryland fields where limited tillage is practiced, chiseling or other tillage will be necessary only if the soil is compacted from livestock grazing or other practices (Wiese et al., 1986).

Precipitation Management on Irrigated Land

Precipitation losses on irrigated land occur primarily from spring rains following preplant irrigation before summer row crops are established to use water (Musick, 1981). Most rainfall on wet soil is lost to evaporation, runoff, and deep percolation. Storage efficiencies are much higher on dry soil that has not received preplant irrigation. In general, the drier the soil profile after harvest, the higher the precipitation

Table V-6

Increased Surface Residue Retention, Weed Control, and Soil Moisture Storage Resulting From No-Tillage (Herbicides Only) and Sweep Tillage with Herbicides, 10½ Month Fallow Between Irrigated Wheat and Grain Sorghum, Bushland, Texas (Unger et al., 1971)

Tillage Treatment	Surface Residues lbs/acre Initial July 1968	Final April 1969	Weed Control, %	Precipitation Stored in Soil, %	Available Soil Water Increase, inches
1. Tandem Disk Tillage	10,000	200	76	22	3.1
2. Tandem Disk & Sweep Tillage	10,000	1,000	52	14	2.0
3. Sweep Tillage	10,000	3,200	44	24	3.4
4. Sweep Tillage & Herbicides	10,000	4,000	100	39	5.6
5. No-Tillage--Herbicides	10,000	4,100	100	39	5.6

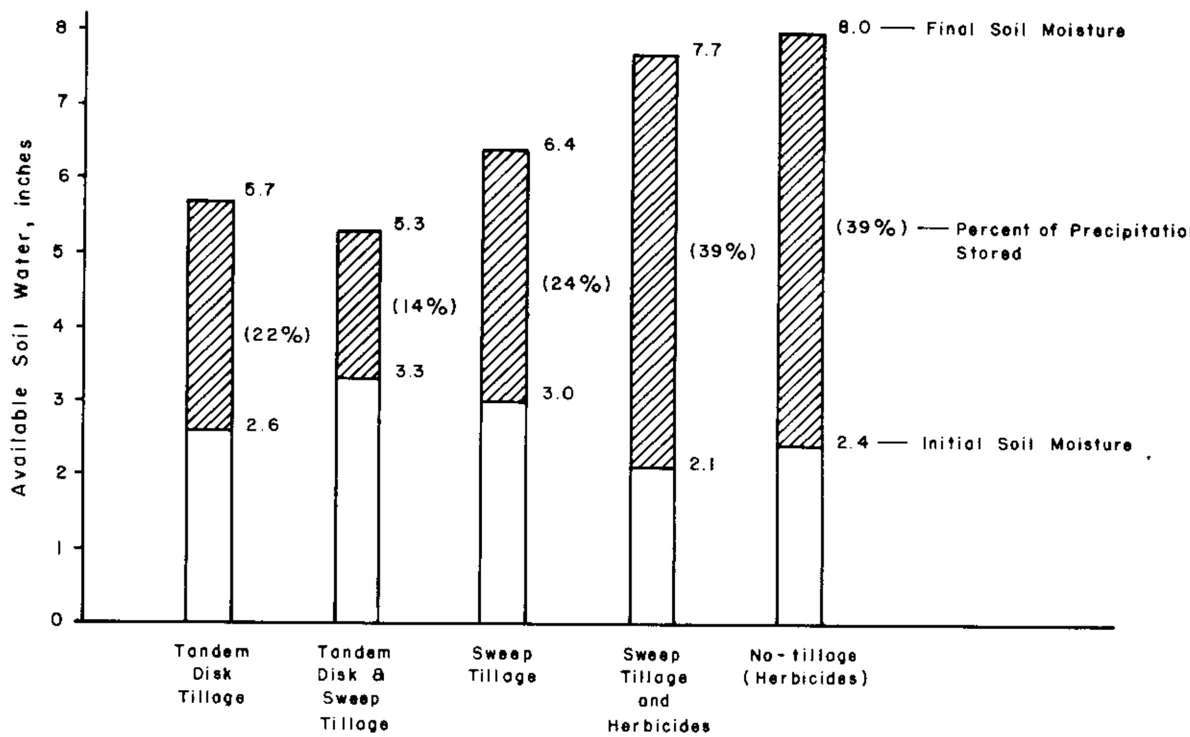

Figure V-3. Increase in water content of Pullman clay loam soil during 10½ months fallow between irrigated wheat and irrigated sorghum with various residue treatments (tillage vs. herbicide vs. no-till), July 9, 1968–May 21, 1969 (Unger et al., 1971) storage efficiency between harvest and planting. Efficient soil storage of precipitation also involves using an early irrigation cutoff date to better utilize late season soil water and provide capacity for precipitation storage before the next crop.

Water management practices that can result in more efficient management and use of precipitation with limited irrigation include: (1) furrow dams to retain potential runoff on the field; (2) no-tillage management following wheat for increased fallow season storage and reliability of eliminating a preplant irrigation for sorghum establishment; and (3) wide furrow and skip-row irrigation that allows for some rainfall storage capacity in the soil profile following graded furrow irrigation.

In a 4-year study, no-tillage of irrigated wheat residues at Bushland, Texas increased soil water storage during an 11-month fallow period to sorghum seeding from 0.9 to 4.0 inches (23 to 102 mm) as compared with disk tillage (through fall and winter) followed by bed-furrow management until sorghum seeding (Musick et al., 1977). No-tillage resulted in good profile wetting and sorghum establishment without preplant irrigation and saved 4 to 6 inches (100-150 mm) of irrigation water. No-tillage prevented spring runoff from intense storms in contrast with disk tillage plots having bed-furrows during the runoff events.

Wiese and Regier (1984) studied three tillage systems with short-set irrigation in a wheat/fallow/sorghum/fallow cropping sequence. Each crop received approximately 8 inches (200 mm) of irrigation water, with the short irrigation sets allowing irrigation water to advance about 2/3 of the furrow length. In the irrigated section of furrows, no-tillage produced lower yields of sorghum grain in 1983 and wheat in 1984 than either conventional tillage alone or conventional tillage with furrow diking, as shown in Table V-7. However, in the dryland section of furrows, no-tillage produced similar yields to the other two tillage methods.

Undersander (1984) determined that corn and sorghum grain yields under center pivots were higher for minimum tillage than for conventional tillage with furrow diking. The yield differences, averaged for two center pivot speeds, were 12 percent for corn as follows: 153 bushels (8,570 pounds) per acre (9,590 kg/ha) for minimum tillage vs. 137 bushels (7,670 pounds) per acre (8,590 kg/ha) for conventional tillage with furrow diking. For sorghum grain yields were 5,120 vs. 4,165 pounds per acre (5,740 vs. 4,668 kg/ha) for minimum tillage and conventional tillage with furrow diking, respectively, a 23 percent difference.

Allen et al. (1975) determined that crop residues from 1 year of wheat and 2 years of sorghum in the furrow with no-till slowed irrigation water advance, caused deeper water penetration, and increased soil moisture storage as compared to clean tillage (tilled twice with rotary tiller and bed-furrow shaper, followed by sweep-rod weeder operation). Before preplant irrigation, no-till plots contained 1.1 inches (28 mm) more water to 4 feet (1.2 m). In addition, water intake was increased by no-tillage during each irrigation, with the greatest effect observed during the early-June preplant irrigation. Water intake increased during the first four irrigations and totaled 12.7 inches (323 mm) on no-till versus 10.5 inches (267 mm) on clean-tilled plots, an increase of 21 percent in favor of no-till. The additional 2.2 inches (56 mm) of increased water intake represents over 15 percent of the total irrigation water applied to the crop and a reduction in tailwater runoff of 58 percent. Several problems were noted however: (a) inadequate control of volunteer plants before

Table V-7

Comparison of Soil Moisture and Grain Yields With No-Tillage and Furrow Diking for "Short-Set" Irrigation of Sorghum and Wheat, Etter, Texas (Wiese and Regier, 1984)

Tillage System	Sorghum Grain			Wheat		
	Initial Soil Water,[1] Inches	Yield, lbs/acre		Initial Soil Water,[1] Inches	Yield, bu/acre	
		Irrigated (0-800 ft)	Non-Irrigated (800-1,200 ft)		Irrigated (0-800 ft)	Non-irrigated (800-1,200 ft)
1. Conventional	6.2	3,108	2,225	6.4	63.5	37.0
2. Conventional with furrow-dikes	7.3	3,293	1,935	6.2	64.8	36.5
3. No-tillage	6.2	2,910	2,130	6.7	57.8	36.5

[1] Prior to planting; in top 6 feet of soil.

seeding; (b) difficulty of seeding into undisturbed soil; and (c) partial blockage of old irrigation furrows with residues.

Summary

Precipitation is an important resource for both dryland and irrigated crop production in the High Plains. Dryland crops should be grown during periods of highest rainfall probabilities. Rains of 0.25 to 2.0 inches (6-51 mm) have accounted for 84 percent of the precipitation at Bushland. Rainfall probability data have been tabulated for Lubbock and Amarillo, and they show a 50 percent chance of more than 0.4 inches (10 mm) of rainfall within 5 to 15 days between May 3 and August 30. However, winter precipitation of similar magnitude may occur at one or two month intervals.

To eliminate runoff from cropland and enhance infiltration rate, furrow diking, conservation tillage, land leveling and level (bench) terracing are some of the methods that have been developed and utilized. Conservation bench terraces, mini-bench terraces, and conservation mini-bench terraces have increased sorghum grain yields at Bushland by as much as 100 percent as compared to graded furrows. However, cotton yields at Lubbock were not increased by terracing due to drainage problems. Surface drainage needs to be provided for major rainfall events, and terraces require maintenance.

Furrow diking, or basin tillage, is being widely adopted to limit runoff from graded furrows and increase infiltration. Furrow dikes can store 2.2 to 2.4 inches (50-60 mm) of rainwater at furrow spacings of 30-40 inches (0.76-1.0 m). Commercial devices have been developed to install furrow dikes for less than one dollar per acre. Dryland grain sorghum yields with furrow dikes as opposed to open furrows have been increased by

13-16 percent at Bushland, 143 percent at Etter, and 20 percent at Chillicothe. Runoff reductions have reportedly amounted to 0.8-3.1 inches (20-80 mm) with furrow dikes. Dryland cotton yield increases of 5-25 percent have been recorded at Lubbock and 32 percent at Vernon with furrow dikes as compared to undiked furrows. Diking alternate furrows increased cotton yields by 6-17 percent at two Experiment Stations in the Rolling Plains. Furrow dikes should be installed by late spring to take advantage of expected peak rainfall prior to crop establishment. Extremely high benefit/cost ratios have been registered with furrow diking.

Limited tillage and no-tillage systems leave crop residue on the surface and are usually effective in reducing runoff and evaporation from dryland or irrigated crops. Crop residue levels following dryland crops are usually low and provided limited soil protection or soil water storage (e.g. 15-20 percent of fallow-season precipitation stored as soil moisture). However, irrigated wheat may leave 5 times greater residue than dryland wheat and has been used in several crop rotations (including dryland or irrigated sorghum) to realize good soil moisture benefits from limited tillage or no-till. For example, no-till fallow with irrigated wheat residue for 11 months increased stored soil moisture by 1.8-3.6 inches (46-91 mm), which represented up to 35-40 percent of precipitation, and substantially increased yields of the subsequent dryland sorghum crop by 63 and 26 percent as compared to disk tillage and sweep tillage of the wheat residues, respectively. And, no-till likewise improved water use efficiencies for the dryland sorghum crop by 15-35 percent. Sweep tillage was somewhat superior to disk tillage for soil moisture storage. Herbicides should be used to control weeds and preserve the extra soil moisture stored from no-till or limited tillage, which may be sufficient to eliminate preplant irrigation of sorghum or corn. Economics have been shown to be favorable.

No-till or minimum tillage with corn or sorghum residues have also substantially increased yields and soil moisture storage by 1.1 to 2.2 inches (28-56 mm) during fallow periods and from seasonal irrigations, respectively. In fact, minimum tillage improved corn and sorghum yields in one High Plains experiment by 12 and 23 percent more than the combination of conventional tillage plus furrow diking.

It is apparent that precipitation harvesting and utilization methods are available and enjoying expanding use on commercial farms as a way to improve yields and likely eliminate preplant irrigation in many years.

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CHAPTER VI

FURROW IRRIGATION SYSTEMS

Surface irrigation is usually less energy intensive than sprinkler irrigation, but has gained a reputation for inefficiency and wastefulness due to tailwater and deep percolation losses (Stringham and Keller, 1979). However, with proper design and management, high efficiencies can be obtained with surface irrigation, but often with relatively high labor inputs. Adoption of water- and energy-efficient surface irrigation practices on a widespread basis requires systems that are non-labor intensive, reliable, flexible with respect to soil moisture and furrow stream requirements.

Recent advancements and research results in furrow irrigation for the Texas High Plains are discussed in this chapter. Some of the recurrent terms used to describe furrow irrigation are as follows (SCS, 1986):

a. Application time--the time water is actually applied to a furrow.

b. Advance time--the time required for water to travel a specified distance down the furrow (usually from upstream to downstream ends).

c. Infiltration time--the time required for the desired water application to infiltrate the soil.

d. Recession time--the time that water remains on the soil surface after the furrow stream is stopped.

e. Opportunity time--the time that water flows or stands on the surface enabling infiltration; difference between the elapsed water advance time and elapsed time of recession for a given station.

Numerous other terms are defined as they appear.

Graded Furrow Irrigation Systems

Graded furrow irrigation is practiced on about 2.82 million acres (1.14 million ha) or 63 percent of the irrigated acreage on the Texas High Plains (Musick et al., 1987) as compared to 5 million acres (2 million ha) more than a decade ago (Musick et al., 1973). Sixty percent of the acreage is on slowly permeable Pullman or Sherm clay-loams (Musick et al., 1983). The most common furrow spacings are 30-40 inches (0.76-1.0 m) and typical grades are 0.2 to 0.6 percent. The use of 60 inch (1.5 m) spacing is increasing. The low hydraulic conductivity of slowly permeable soils permits irrigation of long furrows, with normal field lengths of 0.25-0.5 miles (400-800 m). Because of a clay B2 restrictive horizon at 12-16 inches (0.3-0.4 m) depth, there is little deep percolation. In Pullman soils, it appears that deep percolation occurs under graded furrows only when the surface soil has a high intake capacity, such as following primary tillage and when the subsoil is relatively wet and has limited storage capacity. Farmers have frequently used small furrow streams, long irrigation sets (12-24 hours), and tailwater return systems (Musick et al., 1973). Usually, 3-6 hours of flow are required for lateral movement to wet the beds. Growers may allow tailwater to run for about 4 to 8 hours for efficient application to limit runoff, but longer times may be required to fully wet the soil on the lower part of the field.

Effects of graded furrow lengths of 900 and 1,800 feet (275 and 550 m) on water intake, soil water distribution, grain sorghum yields and irrigation water use efficiencies were evaluated on Pullman clay loam at Bushland in 1961-1966 (Musick et al., 1973). Following a practice of limiting the tailwater runoff to less than about 10 percent of water applied, the lower end of furrows were always drier than the upper end, and this difference persisted throughout the growing season. Irrigation water intake decreased with length of run (Figure VI-1) and grain yield declined 8 percent in the lower 300-600 foot (90-180 m) furrow segment. The reduced water intake down the field was efficiently used by the crop, and irrigation water use efficiencies (IWUE) were substantially higher on the lower 600 feet (180 m) segments. Specifically, values of IWUE were 306, 373 and 479 lbs sorghum grain per acre-inch of water (1.35, 1.65, and 2.11 kg/m^3) on the upper, middle, and lower 600 feet (180 m) of furrow, respectively. Musick et al. (1973) hypothesised that flow duration and intake can be safely reduced so that tailwater runoff can be limited to less than 10 percent of total application on long furrows. If so, with minimal deep percolation in Pullman clay loam soil, it would appear possible to attain 90 percent application efficiency of these soils.

Reducing Tailwater Loss

A major objective in furrow irrigation system design and management is to obtain uniform yields along the furrow by minimizing crop yield reduction at the downstream end of the field while causing minimum tailwater loss (Schneider et al., 1976). Irrigation of graded furrows in Pullman soils normally wets the soil 1 to 3 feet (0.3-0.9 m) in depth, and deep percolation seldom occurs below the 4 foot (1.2 m) zone (Musick and Dusek, 1974). Depending upon the type of soil and furrow slope, methods of reducing tailwater include reducing the furrow stream application time, use of a cutback furrow stream, or installing a tailwater recovery and reuse system (Schneider et al., 1976). Many farmers use tailwater collection

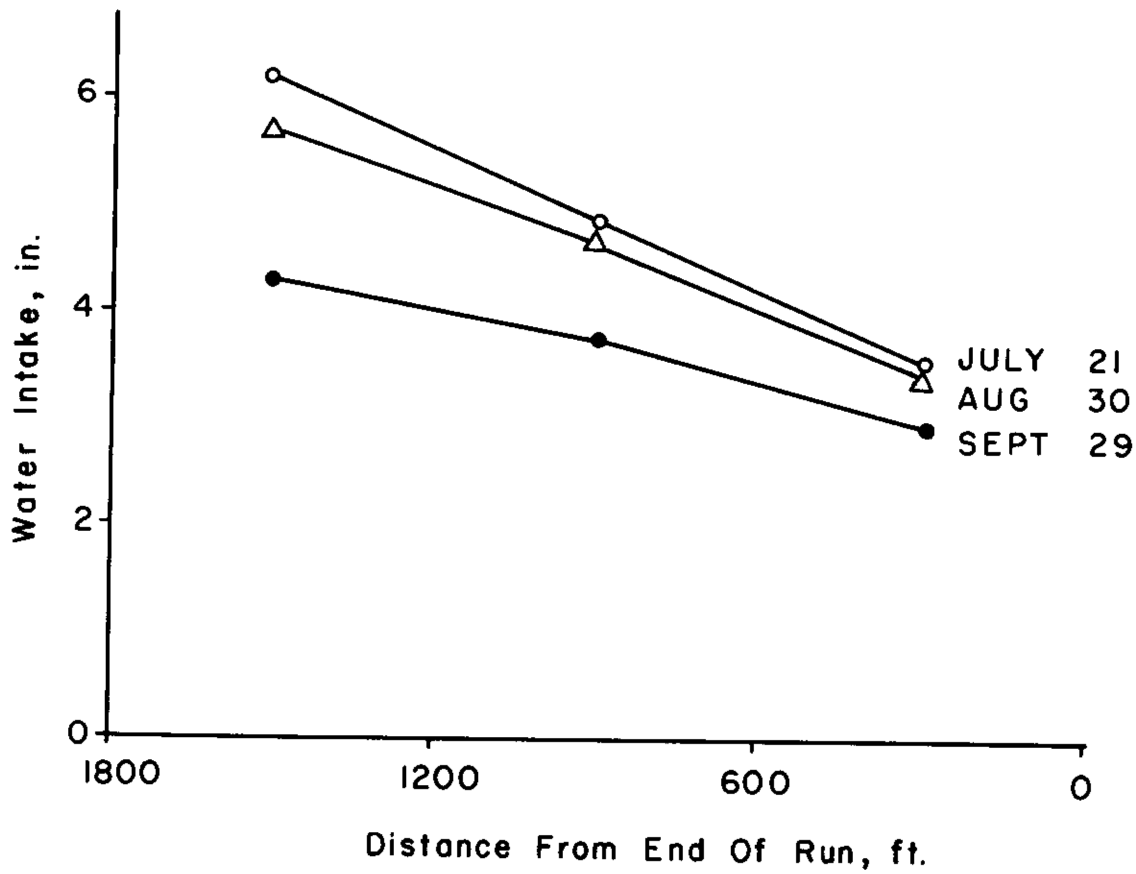

Figure VI-1. Effect of furrow length on water intake during three seasonal irrigations of grain sorghum on Pullman clay loam (Musick et al., 1973).

and reuse systems. However, these systems require additional energy for pumping, and approximately one-third of the tailwater runoff may be lost (Stewart et al., 1981). Schneider et al. (1976) estimated that as much as 40% of the runoff in tailwater recovery/ reuse systems may be lost to evaporation and seepage.

In a Pullman clay loam soil, which attains a slow steady-state infiltration rate of less than 0.1 inch per hour (2.5 mm/hr) after 4-6 hours, a field study showed the feasibility of limited or no-tailwater irrigation on grain sorghum (Schneider et al., 1976). Tailwater runoff from 1870 feet (570 m) graded furrows was varied from 0 to 8 hours duration with an average reduction in grain yield of only 0-11 percent. Irrigation water use efficiency for the no-tailwater treatments was 28 percent higher than for 8 hours of tailwater runoff and was 13-22% higher than with the 6 hour tailwater runoff system. Available soil water decreased nearly 50 percent from upstream to downstream ends of the furrow with 5.1 vs. 2.8 inch (130 vs 70 mm) of soil water, respectively, but varied little between tailwater runoff treatments. Very long periods of tailwater would have been required to fully wet the Pullman soil profile at the lower end of the field.

Hence, Schneider et al. (1976) showed that irrigating to achieve a minimum acceptable soil water level at the lower end of the graded furrows resulted in high sorghum grain yields and small tailwater losses. Reducing or eliminating tailwater runoff substantially increased the irrigation water use efficiency and slightly increased the seasonal water use efficiency. More acres could be irrigated with the limited groundwater supply by reducing the duration of tailwater runoff. Reduced water intake in the lower furrow segment also leaves greater potential for storing rainfall should it occur following irrigation. Results should be applicable to other drought resistant crops on similar soils with high water storage in areas where seasonal rainfall contributes substantially to crop water requirements.

Skip-Row Planting and Irrigation

Skip-row planting provides one or more unplanted rows between planted strips and can be used where water is inadequate for the irrigated land available. The plant can use some of the soil water stored in the unplanted rows, but some is also lost to evaporation directly from the soil. According to Musick and Dusek (1982), skip-row planting of cotton has been widely used and evaluated for 30 years or longer. In most tests, rows adjacent to skip-row produced increased cotton yield per row, but yield increases did not fully compensate for leaving out rows. As a result, yield on a total area basis (i.e. pounds lint per acre) were decreased. Skipping one row and planting two (2 in/1 out) has given the best yields for cotton as compared to skipping two or more rows. Skip row systems with either a 2 in/1 out pattern or 2 in/2 out pattern on rows spaced at 40 inches (1 m) increased irrigation water use efficiency by 51 and 21 percent, respectively, as compared to solid planting and every furrow irrigation (Newman, 1967). However, solid planted cotton significantly out-yielded skip-row cotton at Lubbock.

Musick and Dusek (1982) used the skip-row system with two 30-inch (0.8 m) rows planted and one skipped on irrigated grain sorghum (1979) and corn (1976-1977) on a Pullman clay loam soil. The site had been deep-tilled to 16-24 inches (0.4-0.6 m) with a large moldboard plow in 1966 to mix the slowly permeable B2t horizon. Furrow streams were 8-16 gallons/minute

(0.5-1.0 L/s), and tailwater runoff was allowed for 3-8 hours. Total water intake (application minus runoff) was much less for skip-row irrigation (Table VI-1). As compared to every-furrow irrigation, the average reduction in water intake by skip-row irrigation ranged from 59 percent for corn (1977) to 51 percent for sorghum (1979), and averaged 54 percent over all treatments (Table VI-1). The reduction in water intake was slightly lower for the residual deep tillage treatment than for conventional tillage. The average water intake per surface acre would have been only one-third that for every-furrow irrigation had it not been for lateral wetting into the skipped (dry) row. The widest lateral wetting zone occurred in the upper part of the furrows.

For pre-emergence irrigation, the depth of prior deep tillage had a major effect on water intake with every-row irrigation (Musick and Dusek, 1982). For instance, water intake was about twice as high for 24-32 inches (0.6-0.8 m) tillage depth which resulted in 9.4-10.2 inches (240-260 mm) water intake than for 8 inch (0.2 m) tillage depth that provided 5.1 inch (130 mm) water intake. But tillage depth had little effect on the skip-row treatment, in which intake was only 2.8-3.9 inches (70-100 mm) for 8-32 inches (0.2-0.8 m) tillage depth.

For skip-row cropping to be successful, a farmer needs to experience increased yield per planted row to compensate for the yield loss from unplanted rows. For corn, grain yields per surface acre were 23 percent lower for 2 in/1 out planting than for every-row planting. Average yields were 4,980 vs. 6,495 pounds per acre (5,583 vs. 7,280 kg/ha), respectively. However, the irrigation water use efficiency was 35 percent greater at 617 vs. 456 pounds per acre-inch (2.72 vs. 2.01 kg/m^3) for the skip row treatment (2 in/1 out) for one year. But the following year reduced corn

Table VI-1

Reduction in Water Intake With Skip-Row Irrigation
(Musick and Dusek, 1982)

Furrow Irrigation Method	Water Intake[1] in.	Water Intake[1] mm	Reduced Water Intake, %
a. Every-row irrigation	5.1	130	--
b. Skip-row irrigation	2.4	60	54

[1] Averages for 3 crops, 2 irrigation levels (2 and 4 per season) and 4 residual-effect tillage treatments with tillage depths of 8, 16, 24 and 32 inches (0.2, 0.4, 0.6, and 0.8m).

yield due to stress from only 2 seasonal irrigations suggested that while the size of each irrigation could be reduced with skip-row irrigation, the number of irrigations cannot safely be reduced simultaneously without risking plant stress.

For sorghum grain, furrow yields from skip-row irrigation (2 in/1 out) were 16 percent higher than for every-row irrigation for both 2 and 4 in-season irrigations. However, on a surface area basis, yields averged 6,260 vs. 8,060 pounds per acre (7,020 vs. 9,035 kg/ha) for skip-row and every-row irrigation, respectively. The IWUE for grain yield was significantly higher for skip-row irrigation at 458 pounds per acre-inch (2.02 kg/m^3) as compared to every-row irrigation which resulted in 340 pounds per acre-inch (1.50 kg/m^3). However, the IWUE for skip-row irrigation was not significantly higher than the IWUE for alternate-row irrigation of 485 pounds per acre-inch (2.14 kg/m^3).

In summary, results by Musick and Dusek (1982) from skip-row irrigation tests in 1976-1977 with corn and in 1979 with grain sorghum indicate that this method can be used to reduce water application and increase irrigation water use efficiency. The favorable effect on irrigation water use efficiency should be even greater on more permeable soils than on the Pullman clay soil. However, good management is necessary so that the remaining planted rows can yield enough to compensate for the skipped rows.

Alternate-Furrow Irrigation

Alternate furrow irrigation involves irrigating one furrow for every two normally-spaced planted rows (Musick and Dusek, 1982). Alternate-furrow irrigation is a practical system of wide furrow irrigation and offers another alternative to reducing the amount of irrigation water applied, since it permits irrigating a field in a shorter time with a given water supply (Musick and Dusek, 1974). The reduced size of irrigation may more than offset the reduced yields and thus increase irrigation water use efficiency. New (1971) reported that alternate-furrow irrigation of grain sorghum on Olton loam with 40-inch (1 m) row-spacing reduced the average size of 5 irrigations by one-third, while grain yields were reduced by 12 percent or 960 pounds per acre (1,076 kg/ha) due to reduced water intake.

Alternate-furrow irrigation from gated pipe on 12-24 hour application sets for 600-1,800 feet furrow lengths (183-550 m) decreased irrigation water intake on Pullman clay loam and silty clay loam (Musick and Dusek, 1974). The reduction in water intake averaged 26-33 percent for sorghum on 40-inch (1 m) row spacing; 17-27 percent for sugarbeets on 30-inch (0.75 m) spacing; and 13 percent for potatoes on a 36-inch (0.9 m) spacing (Table VI-2). Alternate furrow irrigation affected the shape of the water intake curve as water moved laterally from irrigated furrows into adjacent beds. Lateral movement continued for a longer period of time from the wider spaced furrows which resulted in a more gradual decline in intake rate. In the upper part of the field, water moved completely through the beds and fully wet the nonirrigated furrows, but lateral wetting was more limited in the lower part of furrows where most of the reduction in water intake occurred.

Alternate-furrow irrigation with 30 and 40 inch (0.75 and 1.0 m) bed spacing (i.e. 60 and 80 inches (1.5 and 2 m) between irrigated furrows) reduced average yields (Table VI-2) of all crops by 2 to 11 percent. The low soil moisture near the downstream end apparently did not affect yields of potatoes because of frequent irrigation, but caused significant yield

Table VI-2

Alternate Furrow Irrigation in the High Plains: Effect on Water Intake and Crop Yield (Musick and Dusek, 1982)

Crop	Water Intake Reduction %	Yield Reduction %	Yield lb/ac	Yield kg/ha
Grain Sorghum--30 inch (0.75 m) beds	17	3.3	230	260
Grain Sorghum--40 inch (1.0 m) beds	26-33	11.2	770	860
Sugar Beets--30 inch (0.75 m) beds	27	9.7	540	605
Potatoes--36 inch (1.0 m)beds	13	1.5	340	380

reductions in both sugarbeets and grain sorghum in the last 600 feet (180 m) for 30-inch (0.75 m) bed spacing and 900 feet (275 m) for 40-inch (1.0 m) bed spacing. Eliminating some yield reduction on the lower part of the field would require excessive tailwater runoff time. Deeper preseason tillage on the lower part of the field could increase water intake and yield in that sector. Because of these reduced yields alternate furrow irrigation on slowly permeable soils is not recommended at row spacings exceeding 30 inches, i.e. 60-inch spacing between irrigated furrows (Musick and Dusek, 1974). However, alternate furrow irrigation has been satisfactory with 40-inch row spacings (i.e. 80-inch irrigated spacings) on moderately permeable soils, such as the Richfield series near Goodwell in the South Central Oklahoma Panhandle (Stone et al., 1979 and 1982). This soil is similar to Olton clay loam.

Furrow Compaction for Controlling Water Intake

Furrow compaction by tractor wheel traffic is a good method of increasing furrow stream advance rates, reducing excessive water intake and reducing profile drainage losses in moderately permeable soils. Graded furrow applications of 6-8 inches (150-200 mm) are common for the first irrigation after major tillage on Pullman soils while late season applications are about 3.1-4.7 inches (80-120 mm) (Allen and Musick, 1985). Field experiments were conducted both on Pullman clay loam and Olton clay loam to determine the effects of furrow compaction on irrigation water intake.

Furrow compaction research (Musick et al., 1985) with irrigated corn production on moderately permeable Olton clay loam in Parmer County, Texas utilized 1,300 feet (400 m) long furrows on 30 inches (0.75 m) spacing and

0.25 percent grade. Irrigation treatments were every-furrow irrigation (EF), irrigation of "soft" or non-wheel track furrows at 60 inches (1.5 m) spacing, and irrigation of "hard" or wheel track furrows 60 inches (1.5 m spacing) after one tractor pass. Corn stalks from the previous crop had been shredded, and the land was disked and chiseled twice. Soil bulk densities were higher for the tractor wheel furrows at 101 pounds per $foot^3$ as compared to the bulk density for soft furrows of 77 pounds per $foot^3$ (1,620 vs. 1,240 kg/m^3).

For four seasonal irrigations, the average water intake on the "hard" furrows averaged 3.2 inches (82 mm) per irrigation, which was 63 percent of water intake for the EF (every furrow) control and 67 percent of the "soft" furrow treatment (Table VI-3) excluding the preplant irrigation.

Irrigation water advance time was reduced to only 5.7 hours on the "hard" alternating furrows versus 13.0 hours on the "soft" furrows. The every-furrow irrigation treatment which had alternating soft and hard furrows encountered advance times of 10.3 and 3.8 hours, respectively. Treatment differences were much greater early in the season.

Profile drainage losses for the hard-furrow treatment were greatly reduced (Musick et al., 1985). Estimated drainage below the 4.6 feet (1.4 m) depth was only 9.1 percent for the hard (compacted) furrow treatment, which was less than one third the profile drainage (29-31 percent) for the soft furrow and control (EF) treatments. Irrigation runoff was slightly greater for the "hard" furrow treatment and was recycled through a tailwater return system. Taking into account losses due to tailwater runoff and estimated profile drainage, field application efficiencies were somewhat greater for the hard-furrow treatments. Corn yields were also greater for the hard furrow treatments, but differences were not

Table VI-3

Average Effects of Wheel Traffic Compaction on Water Application and Corn Grain Yields, Olton Clay Loam (Musick et al., 1985)

	Control, Every Furrow	Soft Furrow, No Wheel Traffic	Hard Furrow, Wheel Traffic
	Irrigated Furrow Spacing, in. (m)		
	30 (0.75)	60 (1.5)	60 (1.5)
1. Water Applied, in.	5.98	5.59	4.45
2. Tailwater Runoff, in.	0.87	0.75	1.18
3. Water Intake, in.	5.12	4.84	3.23
4. Water Advance Time, hrs.	3.8H/10.3S	13.0	5.7
5. Estimated Drainage below 4.6 feet (1.4 m)			
a. Depth, in.	1.85	1.65	0.39
b. % of Application	30.8	29.4	9.1
6. Field Application Efficiency, %	54.5	58.5	63.7
7. Grain Yields, lbs/acre			
a. Hand Harvested	11,550	11,670	11,900
b. Combine Harvested	11,690	11,160	11,140

H = hard compacted furrow.
S = soft (uncompacted) furrow.

significant. Hence, wheel-traffic compaction increased yields per unit of net water intake.

Practical management techniques can be applied to take advantage of alternating compacted furrows for irrigation. The early-season irrigation that is more susceptible to excessive drainage losses can be managed more efficiently in the compacted furrows. On the other hand, irrigation of soft-furrows can be used to catch up during periods of higher plant water use during the growing season (Musick et al., 1985).

Allen and Musick (1985) determined the effect of furrow compaction by controlled wheel traffic on irrigation water intake during the first irrigation of grain sorghum after clean tillage 60 inches (1.5 m beds). They also determined the effects of both wheel traffic and standing wheat residue after no-till fallow. The wheat stubble treatment area had been previously moldboard plowed in 1966 to depths of 8, 16, 24 and 32 inches (0.2, 0.4, 0.6, and 0.8 m) (Schneider and Mathers, 1970). Furrow treatments for irrigation were traffic, traffic plus residue clearing by cultivation, and no-traffic. Alternate furrows that were 980 feet (300 m) long on 0.8 percent slope received 3 passes of wheel traffic with a 11,000 pound (5,000 kg) tractor with 79 inches (2.0 m) wheel spacing. Grain sorghum was no-till planted on 40 inches (1.0 m) furrow spacing before the first irrigation with four succeeding irrigations.

During the first irrigation, furrow traffic alone reduced intake 15 to 30 percent, as compared to the control (no-traffic) treatment. Traffic furrows with residue cleared had irrigation intake reduced up to 75 percent. Advance times were only 3 hours for the traffic/residue-cleared treatment, versus about 24 hours for the other treatments. For the second irrigation, traffic had less effect on intake reduction, but traffic/

residue clearing again reduced intake by 37-75 percent below that of the controls. Over all irrigations, furrow water intake was reduced by 60 percent for the traffic/residue-cleared treatment and 16 percent for the traffic-alone treatment (Table VI-4). Depth of prior plowing increased water intake by 9-25 percent with increased plowing depths of 8-24 inches (0.2 - 0.6 m).

Reduced water intake from the furrow compaction treatments translated into much lower soil moisture, below the 3.3 feet (one meter) soil depth, following the first irrigation. In fact, lack of profile wetting caused crop stress in the traffic/residue-cleared furrows so that for the third irrigation during rapid sorghum development water was switched to the adjacent non-traffic furrows.

Soil bulk density measurements showed no difference attributable to plowing depth (Allen and Musick, 1985). The compacting effect of the traffic and traffic/residue clearing treatments extended only to the 8 inch (0.2 m) depth as compared to the control.

The second study of wheel traffic compaction on Pullman clay loam soil involved clean tillage on 60 inch (1.5 m) bed spacing with sorghum grain (Allen and Musick, 1985). Furrow traffic (one tractor pass) reduced water intake by only 18.5 percent for the first irrigation. There was no difference in intake during the second and third irrigations, probably because of soil consolidation following the first irrigation. Similiarly, ripping the furrows to 10 inches (0.25 m) soil depth before the second irrigation increased intake by 22 percent, but the effect did not continue for later irrigations. Soil bulk density increased from 77.4 to 84.3 pounds per cubic foot (1,240-1,350 kg/m^3) for the top 2 inches (0.05 m),

Table VI-4

Effect of Furrow Traffic Compaction and Wheat Residue Clearing on Total Irrigation Water Intake for Pullman Clay Loam with 4-5 Irrigations (Allen and Musick, 1985)

Plow Depth		Furrow Compaction Treatments		
		No Traffic	Tractor Traffic	Tractor Traffic and Residue Clearing
in.	m	Total Water Intake, inches		
8	0.2	18.1	16.2	7.6
16	0.4	21.3	18.3	8.9
24	0.6	22.6	17.8	8.3
Average		20.7	17.5	8.2
Reduction, %		--	16	60

but did not increase at greater depths where normal bulk densities of 87-94 pounds per cubic foot (1,400-1,500 kg/m^3) prevailed.

Together, these studies of irrigated furrows compacted by tractor wheel traffic have shown that excess water intake and potential deep percolation losses can be controlled by applying at least the first irrigation in the compacted furrow. Greater water intake, if needed during rapid crop development, can be managed by irrigating the alternate uncompacted furrow. On the other hand, a light, late season irrigation might be applied to the compacted furrow.

Limited Tillage with Furrow Irrigation

Limited tillage, in which a portion of residue from the previous crop is left on the soil surface, can influence furrow irrigation in several ways. On the one hand, the crop residue can enhance soil storage of precipitation by lessening soil compaction due to raindrop impact and wheel traffic while lowering the evaporation rate. The increased soil moisture may reduce irrigation water intake. On the contrary, residue can retard furrow stream advance and increase water intake. Research in the Texas High Plains has attempted to balance these factors for improved irrigation water management and for optimizing crop production under a variety of crop rotations and reduced tillage methods.

For continuous wheat irrigated with 40 inch (1 m) furrow spacing, which typically leaves 4,500-8,900 pounds per acre (5,000-10,000 kg/ha) of wheat stubble, three tillage treatments were evaluated (Allen et al., 1976):

1. No-tillage--herbicide; NH_3-chiseled before seeding;

2. Limited tillage--herbicide; NH_3-chiseled and cultivated with sweep-rod weeder cultivated before seeding; and
3. Clean-tillage (control)--tandem disk, chisel (20cm), disk, disk bed, NH_3-chiseled, and sweep-rod weeder cultivation before seeding.

Irrigation water inflow and outflow were measured. As compared to clean tillage, no tillage and limited tillage treatments both produced greater wheat yields, lower water intake, and higher irrigation water use efficiency (Table VI-5). The yield increases were the results of more soil moisture available in storage (Allen et al., 1976). No problems were experienced in irrigating the no-till furrows. Limited tillage averaged significantly higher water use efficiency than clean tillage for the low irrigation levels, while no-till was significantly higher for both irrigation levels. Considering cost, limited tillage was a more practical alternative than no-till.

Musick et al. (1977) reported the results of 7 years of field research on a variety of limited and no-till management systems for furrow irrigated crops (primarily wheat and grain-sorghum). The 40 inch (1.0 m) wide furrows were 690-980 feet (210-300 m)long on Pullman clay loam with 0.15-0.8 percent grade. With continuous grain sorghum, the no-tillage plots increased the irrigation water intake by 19% for one of two crop years studied because residue in the furrows retarded flow and increased the wetted perimeter of furrow streams. Irrigation water use efficiency was only 4 percent lower on no-till than on normal tillage.

Allen et al. (1980) also found that limited tillage of sorghum residue increased irrigation water intake but also improved seasonal water use

Table VI-5

Effects of Limited Tillage of Furrow Irrigated Wheat on Average Irrigation Water Intake, Water Use Efficiency, and Yield, 1972-1974 (Allen et al., 1976)

Treatment	Wheat Yield lbs/ac/yr Mean	Std. Dev.	Irrigation Intake in/yr	Irrigation Water Use Efficiency lbs/ac-in.
1. Dryland*	1,136	821	--	--
2. Adequate Irrigation (3-5 irrig./year)				
- No-tillage	2,950a	970	14.0b	130a
- Limited Tillage	2,730ab	770	13.9b	115b
- Clean Tillage	2,690ab	670	15.4a	102bc
3. Limited Irrigation (2-3 irrig./year)				
- No-tillage	2,600b	1,040	10.5d	140a
- Limited Tillage	2,480bc	950	10.4d	136a
- Clean Tillage	2,330c	820	11.6c	105bc

* Average precipitation was 13.2 ± 4.0 inch per year (33.5 ± 10.1 mm/yr).
** Treatment Means ± one standard deviation.

efficiency as compared to clean tillage (disking to incorporate crop residue).

In continuous winter wheat, irrigation water intake was 9-10 percent less both with no-till and limited tillage as compared to the normal-tillage treatment (Musick et al., 1977). Irrigation water use efficiency was calculated to be 18 percent higher for no-till and 7 percent higher for limited tillage in relation to normal tillage (disking/disk bedding/cultivating).

Musick et al. (1977) found that no-tillage chemical fallow for 11 months after the wheat harvest increased soil moisture storage in the 5.9 feet (1.8 m) soil profile by 0.87-4.0 inches (22-101 mm) as compared to disk tillage of residue. The no-till treatment resulted in good to excellent soil moisture for sorghum germination in the old wheat beds. Good sorghum stands were obtained on the no-tillage plots without an emergence irrigation, but normal disk tillage plots were dry and required an emergence irrigation. The additional soil moisture for no-till chemical fallow plots (Figure VI-2) increased sorghum grain yields. Irrigation water use efficiency was increased with no-till by an average of 14 percent for sorghum grain on level borders from 451-512 pounds per acre-inch (1.99 to 2.26 kg/m^3) and by 37% from 562-769 pounds per acre-inch (2.48-3.39 kg/m^3) on graded furrows. No-tillage management of irrigated wheat residue consistently improved soil moisture storage during the fallow period and resulted in sorghum stand establishment without preplant or emergence irrigation. Graded furrow irrigation in permanent beds and furrows was successful in no-tillage and limited tillage systems.

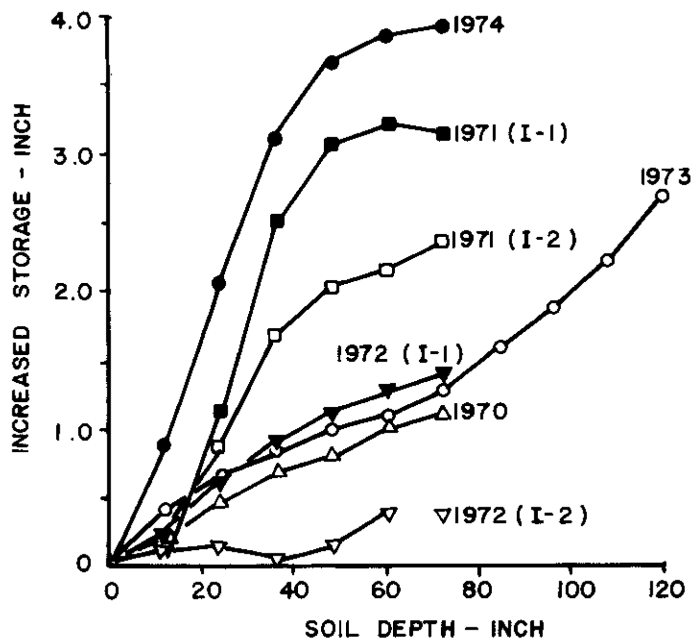

Figure VI-2. Effect of no-tillage treatment (irrigated wheat residues on the surface during 11 months chemical fallow) on increased soil water storage with depth at sorghum seeding compared with disk tillage. Treatments were limited irrigation (I-1) and adequate irrigation (I-2) of the preceding wheat crop (Musick et al., 1977).

Limited Irrigation-Dryland (LID) System

Irrigation systems in the southern High Plains are generally designed for average rainfall conditions which often leads to stressed crop conditions during hot, dry seasons or to runoff during above-normal rainfall years (Stewart et al., 1981). An ideal water management system for the region would meet these requirements:

a. full use of rainfall by eliminating or minimizing crop rainfall runoff;

b. application of irrigation water without runoff; and

c. efficient use of applied water in crop production.

To meet these requirements, Stewart et al. (1981) designed and evaluated a Limited Irrigation-Dryland (LID) system for grain sorghum at Bushland on Pullman clay loam soil. The LID system utilizes limited amounts of irrigation water in conjunction with rainfall. The system was designed to supply irrigation water for 75 percent of the crop years, wherein 6.0-13.8 inches (153-351 mm) of rainfall is received during June-September, as compared to 9.9 inches (251 mm) seasonal average. The concept was to supplement rainfall with a fixed amount of irrigation water so that the area that receives irrigation water will be determined by the rainfall amount.

With the LID system, the upper half of the field is essentially fully irrigated. The next 25 percent is a tailwater runoff section that receives limited irrigation, and the lower one-fourth is a dryland section which may receive runoff from the upstream sections.

Alternate furrows are irrigated, and furrow dams are placed in all furrows on 13 feet (4 m) spacing. In irrigated furrows, the soil dams are lower and slightly cupped so that they are over topped and washed out with irrigation to the extent of water advance. Beyond the irrigated section, furrow dams remain until washed out by subsequent irrigations or rainfall, while the dryland portion of the row provides a "sink" for runoff from the upstream 3/4 of the furrow. The furrow distance that irrigation water advances depends on rainfall and soil moisture, and will vary among irrigations and years.

The LID system automatically adjusts the amount of land irrigated during the crop growing season in response to rainfall (Stewart et al., 1983). More land is irrigated during above-average rainfall years with the same amount of irrigation water than with below-normal rainfall. With the original LID concept, the seeding rate was varied also reflecting lower expectations for moisture in the dryland portion. A reduced number of plants in areas expected to receive less water is essential to alleviate water stress.

Stewart et al. (1981) conducted research to compare the LID system with dryland and full irrigation treatments in terms of sorghum grain yields and water use efficiencies for three LID variations. The six treatments were:

1. Dryland
2. Dryland with furrow dams;
3. Full irrigation, every furrow;
4. LID, partial irrigation in every furrow;
5. LID, partial irrigation in every second furrow; and
6. LID, partial irrigation in every third furrow.

The LID treatments retained 100 percent of the applied irrigation water and all seasonal rainfall as the plots received near-normal precipitation during the growing season. For the fully irrigated plots

(Treatment 3), 61-68 percent of the 23.3 in (593 mm) of applied irrigation water was retained and the remainder (about 35 percent) was lost as runoff. Substantial rainfall runoff occurred both on the dryland plots (0.5 in.) and the every-furrow fully irrigated plots (0.9 in.), i.e. Treatments 1 and 3, respectively. By comparison, Treatment 5 (LID/every second furrow partially irrigated) received 7.3 inches (185 mm) irrigation water which was distributed satisfactorily according to the theoretical concept. Treatment 4 came close to producing irrigation water runoff from one of the five irrigations that totaled 9.7 inches (246 mm).

Mean grain yields and water use efficiencies are shown in Table VI-6 (Stewart et al., 1981). Sorghum grain yields ranged from 2,877 pounds per acre (3,225 kg/ha) for dryland open furrows (Treatment 1) to 8,010 pounds per acre (8,980 kg/ha) for full irrigation (Treatment 3). Decreased grain yield with furrow distance for the LID treatments is strikingly shown in Figure VI-3. The 3 LID treatments produced significantly lower grain yields overall but had twice the irrigation water use efficiency of about 450 pounds per acre-inch (2.0 kg/m^3) as compared to 226 pounds per acre-inch (1.0 kg/m^3) for the fully irrigated treatments. However, seasonal water use efficiencies (SWUE) based on evapotranspiration were similar for all four irrigation treatments at 279-308 pounds per acre-inch (1.23-1.36 kg/m^3). The lower values of SWUE for Treatment 6 (LID every third row irrigated) and for both dryland treatments were indicative of plant water stress. This research showed that Treatment 5 (alternate furrow irrigation) was the most attractive variation of the LID system.

Disadvantages of the LID concept consist primarily of the economic need to change both seeding and fertilization rates in two or three steps down the furrow length. The seeding rate change would require a change in

Table VI-6

Limited Irrigation-Dryland (LID) System: Effects on Sorghum Grain Yield and Water Use Efficiency, 1979 (Stewart et al., 1981)

	Grain Yield[1]		Water Use Efficiency[1]			
			IWUE Applied (Irrigation Water)		SWUE (Evapotranspiration)	
Treatment	lbs/ac	kg/ha	lbs/ac-in	kg/m^3	lbs/ac-in	kg/m^3
1. Dryland	2,880	3,225	--	--	202	0.89
2. Dryland, furrow diked	2,930	3,285	--	--	199	0.88
3. Full irrigation, every furrow 23.3 in (593 mm)	8,010	8,980	222	0.98	295	1.30
4. LID, every furrow 9.7 in (246 mm)	7,170	8,035	444	1.96	306	1.35
5. LID, alternate furrows 7.3 in (185 mm)	6,410	7,190	485	2.14	308	1.36
6. LID, every third furrow 4.9 in (124 mm)	5,100	5,720	458	2.02	279	1.23

[1] Mean values for North and South fields, based on weighted means for the entire 2000 feet (600 m) field length.

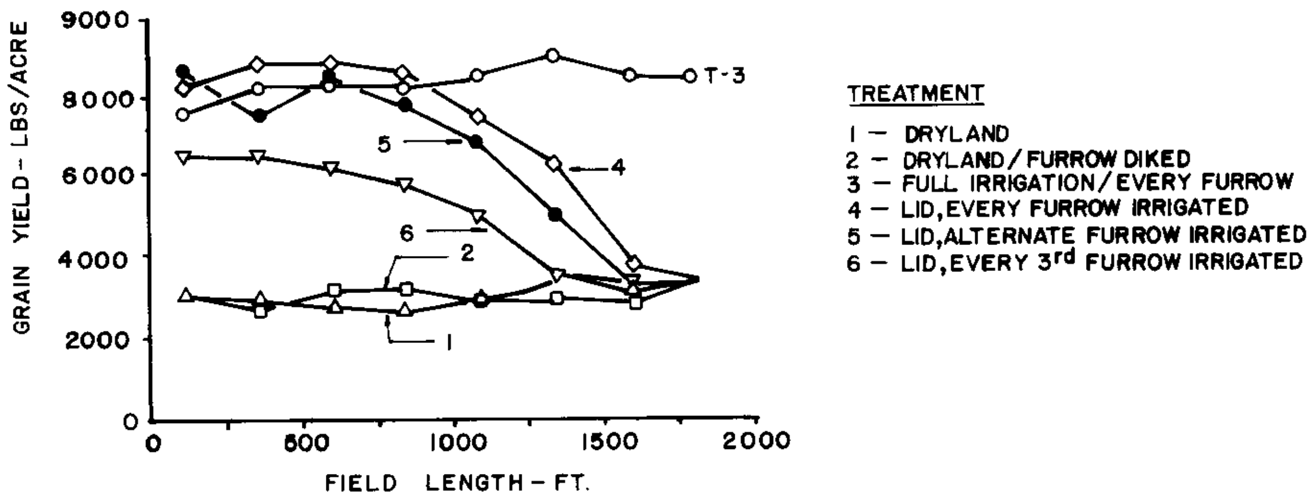

Figure VI-3. LID treatment effect on sorghum grain yield at eight sampling points down the north field area (Stewart et al., 1981).

mechanical equipment or procedure. A clutch mechanism has been developed to change seeding rates at the predetermined row distance by rotating planter plates on a seeder simply by controls in the tractor cab (Lindemann, 1987). Variable rates of fertilization could be handled by (a) fertilizing the entire field with a base rate, and (b) application of additional nitrogen in the irrigation water to achieve parallel rates.

After 3 years of data, Stewart et al. (1983) reported that the LID system reduced all water losses other than transpiration and increased irrigation water use efficiency. For the 3-year study (1979-81), rainfall during the growing season averaged 10 inches (250 mm), exactly matching the 42-year average, but the rainfall varied 4-fold among the three years from extreme drought to surplus moisture. The treatments are listed in Table VI-7 together with the average amounts of irrigation water applied, runoff, and soil water change. Runoff from the fully irrigated and dryland treatments was higher than for all LID treatments.

Grain yields and evapotranspiration were greatest for the fully irrigated sorghum and least for dryland. Above the zero-yield threshold of 5.6 inches (143 mm) ET, sorghum grain yields increased linearly with seasonal evapotranspiration (Figure VI-4) in a ratio of 863 pounds grain per inch of ET (15.4 kg/mm ET). With the LID system, ET varied directly with applied irrigation water. Grain yields decreased with distance down the furrow for the LID treatments as exemplified in Figure VI-5.

Water use efficiency (SWUE) based on seasonal ET was slightly higher for the fully irrigated treatment at 265 pounds per acre-inch (1.17 kg/m^3) than for the LID treatments that resulted in a SWUE value of 245 pounds per acre-inch (1.08 kg/m^3). Dryland/furrow diked treatments had by far the lowest SWUE. Conversely, irrigation water use efficiency (IWUE)

TABLE VI-7

Summary of Treatments and Water Balances
For Limited Irrigation - Dryland (LID) System, 1979-81[1,2] (Stewart et al., 1983)

Treatment	Applied Irrigation Water, in.		Runoff, in.		Soil Water Change, in.		Sorghum Grain Yield, lbs/ac		Evapo-transpiration (ET), in.		Seasonal Water Use Efficiency (SWUE), lbs/ac-in.		Irrigation Water Use Efficiency, lbs/ac-in.	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1. Dryland	0	0	1.18	1.42	2.91	3.90	2260	870	11.61	2.44	188	48	--	--
2. Dryland, dammed	0	0	0.28	0.43	2.52	5.08	2160	700	12.13	2.32	172	29	--	--
3. Fully irrigated, every furrow	20.31	2.80	6.97	2.44	1.18	3.03	6460	1220	24.37	3.11	265	34	209	23
4. LID-9.8 in.; every furrow 1979, alternate furrows 1980-81	9.17	0.94	0.35	0.55	1.73	3.94	5080	1620	20.47	2.72	245	52	308	118
5. LID-7.3 in. alternate furrow	6.85	0.71	0.16	0.28	1.81	4.25	4580	1460	18.35	2.36	247	52	340	134
6. LID-4.9 in.	4.69	0.51	0.39	0.67	2.05	4.61	3990	1030	16.18	1.93	245	45	385	109

1/ Average of North and South research fields.

2/ Seasonal rainfall was the same for all plots: average = 9.84 inches (250 mm); range = 4.06-16.69 inches (103-424 mm).

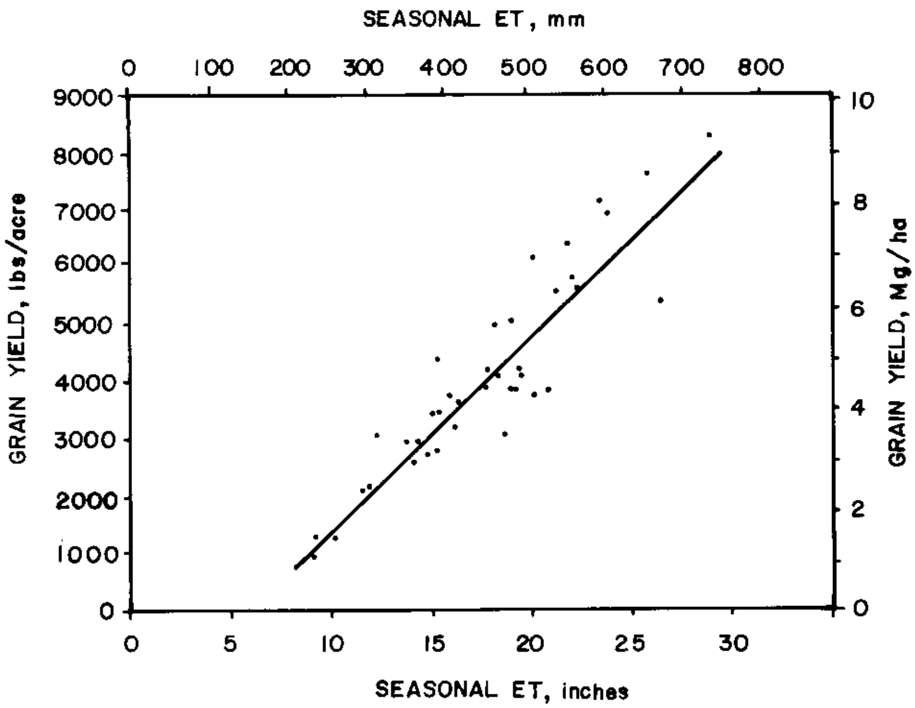

Figure VI-4. The relationship between grain yield of sorghum and seasonal evapotranspiration, LID system, 1979-81 (Stewart et al., 1983).

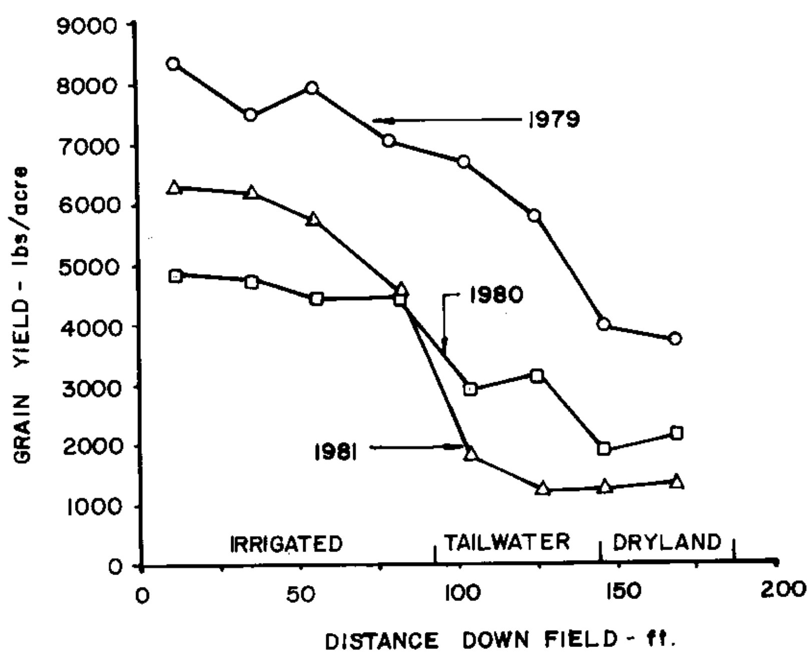

Figure VI-5. Grain yield of sorghum at various distances down the field for the LID-7.3 inch (185 mm) per year irrigation treatment (Stewart et al., 1983).

was much higher for the LID treatments that produced 308-385 pounds per acre-inch (1.36-1.70 kg/m^3) than for the fully irrigated plots at 209 pounds per acre-inch (0.92 kg/m^3), which produced tailwater runoff.

The favorable results from the LID system are partly related to two unique features of the study region (Stewart et al., 1983):

a. Pullman clay loam soil where percolation is negligible; and

b. Good quality irrigation water that minimizes the need for leaching for salinity control.

Research with the LID system was conducted for 4 years at Etter (Moore County) by the Texas Agricultural Experiment Station from 1979-82 to compare different variations of the limited irrigation - dryland system (Undersander, 1986). The research was conducted on a Sherm silty clay loam soil (fine, mixed mesic Torrertic Paleustoll) with graded furrows on a 0.3% slope. The Sherm series is a slowly permeable soil. Irrigation treatments were 0, 1, 1.5, 2, and 4 inches (0, 25, 38, 51, and 101 mm) per irrigation, with the latter level representing full irrigation. All furrows were dammed at 10 feet (3 m) intervals. The 1-inch (25 mm) irrigation treatment was planted and irrigated in a skip-row fashion (every third row watered). The 1.5 inch (38 mm) irrigation treatment was irrigated in alternate furrows, while the 2 and 4 inch (51 and 101 mm) treatments were applied in all furrows. One of the chief limitations of the original LID concept--variable seeding rate--was compared with uniform seeding for the 1.5 inch (38 mm) irrigation treatment. A 4-year summary of results is presented in Table VI-8 (Undersander, 1986). Seasonal rainfall averaged 7.3 ± 6.3 inches (186 ± 160 mm) for all treatments. Runoff was measured in the last three years only.

Table VI-8

Summary of LID Treatments, Sorghum Yields, and Irrigation Water Use Efficiencies at Etter Experiment Station, 1979-82 (Undersander, 1986)

Irrigation System, Amount (mm), and Duration[a]	Distance Between Irrigated Furrows, ft	Irrigation Water (Ave.), in/yr	Runoff, in/yr	Sorghum Grain Yield, lbs/ac	Irrigation Water Use Efficiency, lbs/ac-in
1. Dryland, UR	--	0	0	1,550	--
2. LID-1 in. VR, Skip-Row (2 yrs)	10	5.5	0[b]	3,030	297
3. LID-1.5 in. UR (2 yrs)	6.6	6.3	0.7[c]	4,750	449
4. LID-1.5 in. VR	6.6	7.3	0.4[d]	4,100	363
5. LID-2 in. VR (3 yrs)	3.3	10.3	0.1[c]	3,740	222
6. Full Irrigation, UR	3.3	20.7	2.6[d]	5,070	181

a Data were from 4 years except as otherwise noted. Seasonal rainfall averaged 10.3 ± 4.2 inches (262 ± 107 mm/yr).

b,c,d Runoff data from one, two and three years, respectively.

VR= Variable seeding rate of 4.5, 3.0 and 1.5 pounds per acre (5.0, 3.4, and 1.7 kg/ha) for 50%, 25%, and 25% increments of furrow distance.

UR= Uniform seeding rates of 1.5, 2.0 and 4.5 pounds per acre (1.7, 2.2, and 5.0 kg/ha) for dryland, LID-1.5 inch, and full irrigation, respectively.

In general, water advanced farther down the field with each successive irrigation, with the increase in advance depending on the amount of intervening precipitation (Undersander, 1986). Irrigation water advance was always greater for the LID-1.5 inch (38 mm) treatments (alternate furrows) than for the LID-2 inch (51 mm) treatments (every furrow). Furrow diking eliminated all runoff from the dryland treatment. Runoff from both rainfall and irrigation were reduced from all limited irrigation treatments as compared to full irrigation.

Yields from the limited irrigation treatments decreased with distance down the furrow (Undersander, 1986). These decreases were slight for the wettest year but very pronounced for the driest years due to lack of sufficient water. The variable and uniform seeding rates in the LID-1.5 inch (38 mm) treatments produced essentially the same yield and irrigation water use efficiency for the two years they were both tested, so the 2.0 pound per acre (2.2 kg/ha) uniform seeding rate appeared sufficient.

Irrigation water use efficiencies were significantly higher for all LID treatments than for the full irrigation treatments (Undersander, 1986). The highest irrigation water use efficiency was attained with the intermediate irrigation treatment (LID-1.5 inch VR). This was expected because fewer furrows were watered and there was less evaporative surface. Skip row planting with the LID system was found unacceptable because yields were reduced and irrigation water use efficiencies were not improved. Since soil moisture data were not reported, seasonal water use efficiency (ET-based) could not be assessed.

Short Irrigation Sets

A simplified form of limited irrigation-dryland was evaluated by Wiese and Regier (1985) for 3 years at the TAES Research Field at Etter on a Sherm silty clay loam with wheat-sorghum-fallow rotation. This method was termed "short irrigation sets", which indicated that only the upper 2/3 of the 1400 feet (425 m) furrows was irrigated, while the non-irrigated part of the field received rainfall runoff from the irrigated portion. Furrow dams were not used, in contrast to the LID system. Furrows were watered for 11 hours at 8 gpm (0.5 L/s). A pre-irrigation of 6 inches (150 mm) was applied to only the first wheat crop and otherwise the crops received 4 or 5 irrigations of 2 inches (50 mm) each. Yields were generally highest on the upper end of the field as expected. Wheat and sorghum grain yields both varied widely due to seasonal rainfall differences. Over the 3 years, wheat yields averaged 66 bushels per acre (4,440 kg/ha) with 10.0 inches (25 mm) irrigation water per year. Sorghum grain yields averaged 4,400 pounds per acre (4,930 kg/ha) with an averge of 8.6 inches (218 mm) of irrigation water annually. Values of IWUE and WUE could not be calculated for this experiment. Thus, short irrigation sets produced good yields without tailwater and with zero capital outlay or increased operating cost.

Surge Flow Irrigation

Irrigators have frequently experienced difficulty in getting furrows to "water through" (i.e. complete the advance phase) due to high water intake rate following major cultivation. Some irrigators discovered that the advance phase could be completed by interrupting furrow flow and then reapplying it hours or days later, a practice sometimes called "bumping" (Walker, 1984). From this concept, surge flow irrigation has evolved.

Surge flow irrigation is intermittent application of irrigation water to furrows or borders through a series of on-off watering periods of constant or variable time span (Stringham and Keller, 1979; Schneider, 1984). The primary benefit of surge flow irrigation is a faster rate of water advance down the furrow for a given size furrow stream, which reduces deep percolation losses and provides flexibility in the amount of water applied (Schneider, 1984). After the water has advanced to the end of the furrows, the on/off times can be adjusted to minimize runoff.

The practical application of surge flow irrigation utilizes a surge valve and flow controller in a tee placed in an irrigation water supply pipeline. Downstream from each side of the tee is a setting of gated pipe at the upstream end of furrows. The surge valve diverts flow alternately from one side of the tee to the other. The frequency and duration of flow diversion into furrows is specified in terms of cycle time and cycle ratio. The cycle time for surge flow is the period of time required for a complete on/off cycle, i.e. the sum of the water on-time and off-time for each furrow (Bishop et al., 1981). Cycle time may be varied from several minutes to a few hours and typically is 10-60 minutes. The cycle ratio (or duty cycle) is defined as the ratio of surge on-time to the total cycle time.

Surge Flow Irrigation: Early Research

Surge flow has been defined as "an automated gated pipe irrigation system concept which utilizes a microprocessor control unit that includes cutback capability which is accomplished by cutting back the time instead of the instantaneous flow rate into the furrow" (Stringham and Keller, 1979). The pilot system tested at Utah State University in 1978 had surge control valves on each furrow stream that cycled on and off at 8 or 16 second intervals. The frequent pulses or surges eventually merged before the end of the furrow. A patent was issued in March, 1986 for the method and system of surge flow (Stringham, 1986).

Stringham and Keller (1979) found that the cycled flows had a significant impact on furrow stream advance rates and soil intake. The advance time for the 16-second surge-on and 8-second surge-off furrows, which had an average stream flow of about 8.6 gpm (0.54 L/s), was less than the advance time for the steady flow furrows that had an average flow rate of 13 gpm (0.82 L/s). Using the same apparatus, Bishop et al. (1981) later determined that, when applied to non-wheel traffic furrows that were newly formed (first irrigation), surge flow reduced the advance time in 600 feet (180 m) by at least 10-fold as compared to continuous furrow irrigation (Figure VI-6). Advance times were also decreased, but to a lesser extent, for wheel-compacted furrows and for the second irrigation. Furthermore, the variability in advance rates among compactive treatments, irrigations, and individual furrows was greatly reduced with surge flow as compared to continuous irrigation, which suggested opportunities for more precise irrigation. Bishop et al. (1981) concluded that surge flow alters the basic intake characteristics of the furrow, and the advance phase was accomplished with less irrigation water.

In Utah, Bishop and Walker (1981) reduced the advance time by 23 percent and the total water requirement to reach the end of 330 feet (100 m) furrows by 60 percent with surge flow (20 minute cycle time and 0.5 cycle ratio) as compared to continuous flow irrigation. However, surge flow produced runoff sooner and with higher peak amounts. In other Utah studies with 1,180 foot (360 m) furrows in sandy loam soil, surge flow

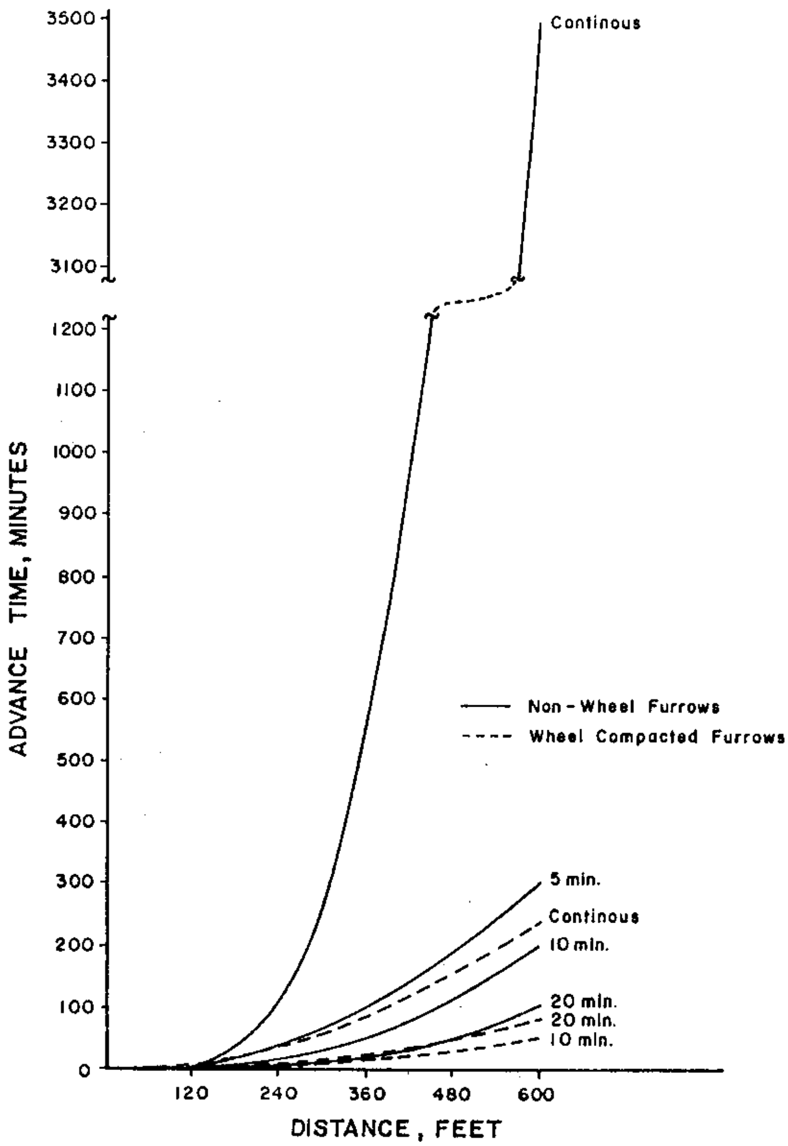

Figure VI-6. Advance rates for first irrigation in wheel and non-wheel compacted furrows under continuous and variable surge flow cycle times (Bishop et al., 1981).

(with 40 minute cycle time and 0.5 cycle ratio) applied 2 inches (51 mm) to the entire field, whereas with continuous flow irrigation 6 inches (152 mm) was applied without reaching the lower 400 feet (120 m) of furrows. Surge flow reduced furrow intake rates by 20-50 percent as compared to continuous flow irrigation. Data presented by Walker (1984) from these experiments indicated that surge flow was more beneficial in completing the advance phase in non-wheel traffic furrows on two kinds of soil than in wheel compacted furrows.

Coolidge et al. (1982) presented data from surge flow experiments with 12 combinations of surge on-times (5, 10, 20 minutes) and off-times (5, 10, 20, 40 minutes) replicated 5 times. With surge flow, there was a statistically significant reduction in the net advance time to reach 100-meters on a silt loam soil in wheel traffic furrows as shown in Table VI-9. Reduced furrow intake occurred during the first five minutes after drainage between surge pulses. Surge irrigation from the 10 and 20-minute on-times used only 38 to 56 percent as much water used by continuous irrigation to advance the same distance.

Weckler et al. (1984) achieved a condition of cutback furrow irrigation using surge flow by switching to short cycle times (1-2 minutes) and varying the cycle ratio (25-50 percent) after the advance phase was completed. The 1-minute surges produced a continuous furrow stream with half the instantaneous furrow inflow. The time-averaged inflow rate was reduced to slightly above the soil intake rate and runoff was reduced. Runoff was less with 25 and 33 percent cycle ratios than with the 50 percent cycle ratio for the 1 minute surges.

Table VI-9

Reduced Furrow-Stream Advance Time to 328 feet (100 m) Furrow Distance With Surge Flow Irrigation, Average of 4 Off-Times (Coolidge et al., 1982)

Treatment	Advance Time, (Minutes)	
	Mean	Std. Dev.
Continuous furrow irrigation	228	168
Surge Flow		
a. 5-minute on-time	143	66
b. 10-minute on-time	82	29
c. 20-minute on-time	70	19

Reduced Soil Intake with Surge

Higher advance rates with surge flow irrigation are caused by changes in soils during the off-time which reduces soil intake rate during the following on-time. Two phenomena affecting infiltration rate occur: (a) redistribution of infiltrated water, and (b) partial sealing of the wetted soil surface (Samani et al., 1985). The infiltration rate reduction is likely due to a combination of several of the following mechanisms (SCS, 1986):

a. hydration or swelling of clay particles

b. reduced soil water potential

c. consolidation of top soil layer after initial wetting

d. sediment deposition and downward migration to block large pores

e. air re-entry and entrapment in pore space of top soil layer.

Samani et al. (1985) determined with laboratory experiments that, between surge cycles, the soil drainage creates soil tension (negative pressure) that increases bulk density (i.e. soil consolidation) which in turn reduces the saturated hydraulic conductivity. Subsequent surges cause soil reswelling but not enough to regain the original soil volume, bulk density, or conductivity. The effect of soil consolidation more than offsets any increase in hydraulic gradient (i.e. soil water potential) that occurs through soil drainage. However, it was projected that on previously irrigated (consolidated) soils, the intake rate could possibly increase due to increased soil water potential during the off-times.

Field experiments in 20 feet (6 m) segments of non-wheel track furrows, for the first irrigation after cultivation, determined sharp reductions in intake rate after the first 15-minute off-time as compared to continuous irrigation (Samani et al., 1985). Intake rates were reduced by 55 percent by the first surge cycle. In the same experiment, there was less reduction in intake rate from second and third irrigations (Malano, 1983).

Surge Equipment

Since its inception, surge flow irrigation methods and equipment have undergone significant development and refinement. Today, the water is delivered typically to a single in-line control valve and electronic controller stationed between two sets of multiple irrigation furrow streams discharging from gated pipe. Water is discharged alternately between the two sets for 4 to 6 on-off cycles per irrigation. The watering cycle times can be constant or variable (SCS, 1986). A surge control system consists of two components (Blair, 1984):

a. actuating valve (pneumatic, solenoid, hydraulic, etc.)

b. valve controller or timer, programmed to follow a predetermined valve sequencing pattern.

Types of automated surge control valves and electronic controllers are discussed in other publications (SCS, 1986; Schneider, 1984; HPUWCD, 1986; Ebeling and Marek, 1984).

Management Implications

Cycling the furrow stream gives a time-averaged flow rate that is less than the instantaneous flow rate (Weckler et al., 1984) so that more furrows can be watered to the end of the field within a given time period and with a given water supply than using continuous irrigation (SCS, 1986). The main appeal of surge flow irrigation has been a potential for reduced deep percolation loss due to several factors:

a. reduced infiltration rate between succeeding on-periods;

b. more rapid furrow stream advance over the previously-wetted furrow sections;

c. more nearly equal opportunity time for infiltration between the upstream and downstream ends of the field; and

d. less variation in furrow stream advance times.

Because of reduced infiltration rate, surge flow irrigation allows light irrigation to be applied with less deep percolation loss. By enabling farmers to uniformly apply 2 to 3 inches (50-75 mm) of water rather than 5 inches (127 mm) or more per irrigation, surge gives some of the management flexibility afforded by center pivot systems (Walker and Schlegel, 1984). However, if managed improperly, irrigation applications may be too light during critical periods of crop growth. Surge irrigation can become a liability if the farmer plants extra acres to compensate for reduced irrigation time, and then cannot water adequately to meet peak crop needs (Walker and Schlegel, 1984). Heavier applications might take longer and result in greater tailwater loss than with continuous flow unless cycle time or cycle ratio is appropriately altered after the initial advance phase (SCS, 1986). For plow-pan soils such as the Pullman and Sherm series, the potential benefits of surge flow are reduced because infiltration rates are already low (Musick, 1986). The method requires greater operator skill, record keeping, and adjustments between irrigations to realize the potential for increased efficiency.

In managing surge flow irrigation, parameters that can be varied include flow rates, furrow length, cycle time, and cycle ratio (Bishop and Walker, 1981). Cycle time for a given field should be largely determined by soil infiltration characteristics. Excessive on-time will approximate continuous furrow irrigation with possibly excess deep percolation. The off-time for each cycle must be great enough to allow the furrow to become dewatered before the next surge, so that the desired infiltration rate reduction will occur (SCS, 1986). Generally, a cycle ratio of 0.5 is chosen and water is applied equally to irrigation sets on both sides of the tee. This is partly due to limitations of most current systems.

The controlling variable in efficient surge flow irrigation appears to be the depth of application needed to replenish root zone moisture (Walker, 1984). The two major variables that can be managed with surge irrigation are (a) furrow stream flow, and (b) on-time. Values of these two parameters are dependent upon field length, furrow size and shape, soil infiltration characteristics including the effect of surging, and surface debris (Walker, 1984). Inflow rates and cycle times should be relatively large for: light-textured soils, long furrows, large furrows, and abundant crop residues. On the contrary, smaller flows and cycle times are appropriate for heavy-textured soils, and short, small, clean furrows.

Managing Surge Flow Irrigation

An initial estimate of furrow stream size for surge irrigation can be computed as follows (Walker and Schlegel, 1984):

Furrow stream, gpm = 0.02 x Furrow length, feet.

For example, for a furrow length of 1,000 feet (305 m), choose a 20 gpm (1.26 L/s) furrow stream.

There are three basic alternative methods for choosing the best on-time for a surge flow systems (SCS, 1986):

1. Variable time/constant distance method--Calibrate and set the time needed for an advance of 300-500 feet (91-152 m) of dry furrow per

surge cycle until water has advanced to the end of the field, after which a reduced on-time should be selected to allow a 75 percent furrow advance distance for the final on-time.

2. Constant time/variable distance method--Set a constant time to allow wetting about 35-45 percent of the furrow length with the first surge cycle, and on succeeding cycles, try to wet about 75 percent of the dry furrow length wetted on the preceding cycle. With this guideline, the furrows will water out in 3-5 surge cycles as illustrated in Table VI-10. After the rows are watered out, reduce the on-time for the last surge to that required to achieve 75 percent of furrow advance (as in method 1).

3. Flow increase method--Using a reduced number of rows per set (1/2 or 3/4 the furrows normally watered per set), follow either method 1 or 2 until the rows are watered out. Then increase the furrow stream and use a very short on-time for the final surge, switching when 75 percent furrow advance distance is reached.

Method 1 is generally regarded as the easiest method to follow. Once surge times are established for the first field setup, surge on-times can be maintained for subsequent setups in the same field (assuming similar soil and site characteristics).

After water has reached the end of the field, total irrigation time (on plus off times) with surge irrigation may need to be longer than would be the case with continuous flow irrigation in order to obtain adequate moisture penetration and crop yield. Specific management procedures will depend on soils, their moisture status, and changing soil infiltration characteristics through the growing season.

Table VI-10

Cumulative of Furrow Length Wetted by Surge Flow Cycles Using the Constant Time/Variable Distance Method of Adjustment (SCS, 1986)

Surge Cycle	Percent of Furrow Length Wetted on Initial Surge					
	35		40		45	
	Cumulative Furrow Distance Wetted After Constant-time Surges in 1,000 ft Furrows					
	%	feet	%	feet	%	feet
1	35	350	40	400	45	450
2	61	610	70	700	79	790
3	81	810	93	930	104	1,040*
4	96	960	109	1,090*	--	--
5	107	1,070*	--	--	--	--

* Watered out

When the irrigation advance reaches the end of the field, one of four alternate water management alternatives can be followed (Walker, 1984):

a. maintain constant furrow stream rate and cycle time;

b. prolong the last surge of the advance phase until the root zone at the downstream end has been filled;

c. reduce cycle time to the point where furrow infiltration rate matches application rate; or

d. further reduce cycle time until individual surges combine, creating steady flow at a reduced (cutback) rate.

On low intake soils, getting sufficient water into the soil at the downstream end may be a problem with the surge flow system. In that case, several alternate management strategies can be attempted when the furrows have essentially watered out (Walker and Schlegel, 1984):

a. Apply continuous flow (i.e. cycle ratio of 1.0 to one side of the set until the desired intake has been achieved, then divert flow to the other side of the irrigation set.

b. Open both sides of the surge valve and irrigate both sides at a reduced (cutback) rate.

c. Reduce the surge cycle time drastically to achieve essentially continuous flow at a cutback rate.

Tailwater management is an important component of surge flow systems. To reduce tailwater on long furrows on heavy-textured soil, it may be necessary to reduce the cycle ratio to 1/3 or 1/4 by irrigating multiple irrigation sets (Walker, 1984). The optimal cycle time may vary during the irrigation (Blair, 1984). According to Lindemann (1987) a manufacturer now supplies a solar battery powered controller equipped with three rotary dials. By dialing one of the off times, the program runs automatically with a set number of surge cycles in a series of lengthening surge times to get water out and a recommended cut-back time. Another manufacturer is marketing a controller which automatically calculates watering schedules. It is operated with a single hand-held programmer for an unlimited nubmer of valves. The remote programmer can store two different automatic watering programs, or one four-step manual program.

Field Tests with Surge Irrigation in Texas High Plains

The best results with surge flow irrigation in the Texas High Plains have been on the moderately permeable soils such as Olton clay loam and Acuff and Amarillo fine sandy loams, which have about 0.3-0.5 inch per hour (7.6-12.7 mm/hr) water intake rate (Musick et al., 1987; Schneider, 1984). The greatest decline in use of furrow irrigation has occurred on these soils. Water savings are also possible on slowly permeable fine-textured soils such as Sherm and Pullman clay loams (0.1 inches per hour (2.5 mm/hr) intake), especially during preplant irrigation when water intake is high following primary tillage.

According to Schneider (1984), the best results with surge flow have been achieved with furrow streams that are 25 to 50 percent larger than used for continuous irrigation. On sandy soils, on-cycle times of 30 to 60 minutes have worked best, versus 1 to 2 hours on fine textured soils. The on-cycle time can be reduced to 15 to 30 minutes after water reaches the end of the field. Surge flow irrigation works best with smooth, clean furrows so that water can advance and recede rapidly. Advance rates over previously-wetted furrow sections are greatly reduced when furrows contain standing residue or growing wheat.

Musick et al. (1987) evaluated surge flow on a moderately permeable soil (Olton clay loam) for corn production. Field scale tests were conducted using 1,300 feet (400 m) long furrows with 0.25 percent slope, spaced at 30 inches (0.75 m), and irrigated as follows for 7 irrigations including preplant:

a. Surge flow treatment--30 gpm (1.9 L/s) for 23.3 hours, 45-minute on-time

b. Steady-flow treatment--38 gpm (2.4 L/s) for 12.3 hours

Water was applied in alternate rows (1.5 m spacings) that were (a) compacted by tractor wheel for the preplant irrigation, and (b) non-wheel track furrows for the 6 suceeding irrigations. Surge flow reduced the cumulative seasonal water application by 31 percent (Table VI-11) due to reduced water intake, deep percolation and tailwater runoff (Musick et al., 1987). Cumulative water intake was reduced by surge flow by 28 percent (Table VI-11), with the greatest reduction early in the season (Figure VI-7). The water intake with surge was reduced 32 percent for the first irrigation in non-compacted furrows and by a total of 17 percent during the next four seasonal irrigations. The bulk density of the surface soil increased as a result of surge flow. Cumulative tailwater runoff for the seven irrigations (shown in Table VI-11) totaled 16 percent of applied water using steady-flow irrigation and 12 percent for surge flow. By reducing excessive intake, surge flow reduced excessive wetting of the deep soil profile below the root zone by 64 percent. Surge flow resulted in more uniform soil water contents down the furrow as compared to continuously decreasing soil water content toward the lower end of the furrow with steady flow irrigation.

Table VI-11

Comparison of Surge Flow vs. Steady Flow For Furrow Irrigation of Corn, Olton Clay Loam, Parmer County, Texas (Musick et al., 1987)

Irrigation System	Cumulative Seasonal Totals				
	Application, in.	Runoff, in.	Intake, in.	Deep Profile Drainage, in.	Storage, in.
Steady Flow	46.5	7.4	39.1	4.0	35.1
Surge Flow	32.0	4.0	28.1	1.4	26.7
Reduction, %	31	46	28	64	24

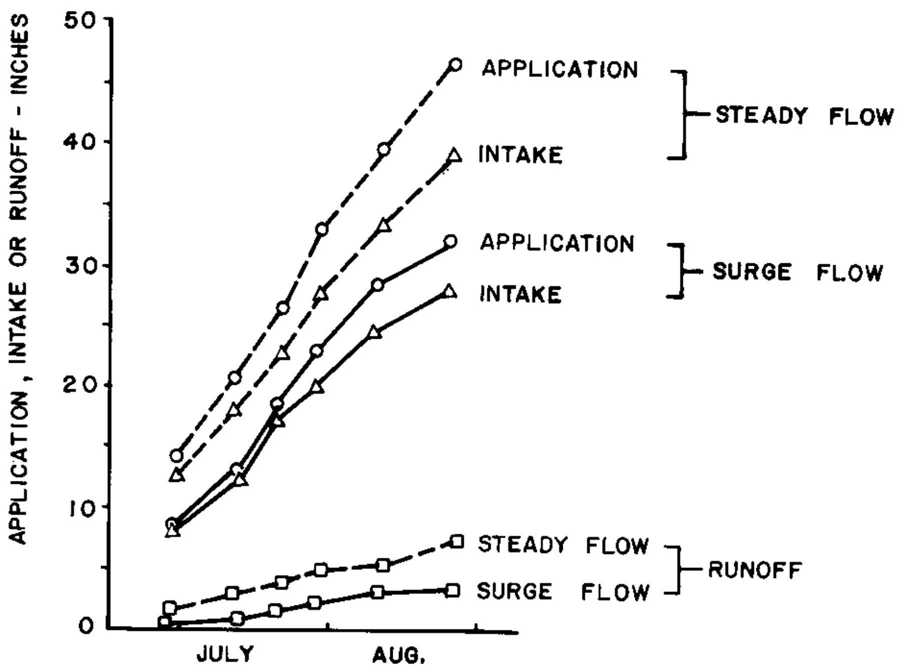

Figure VI-7. Cumulative water application, intake and runoff for successive seasonal irrigations by surge and steady flow methods in uncompacted furrows on Olton clay loam (Musick et al., 1986).

Musick et al. (1987) measured 6 percent lower corn yields with surge irrigation treatments, in which less water was applied, than with steady flow furrow irrigation. The authors reported that surge flow reduced calculated seasonal water use from 34.7 inch (881 mm) to 32.4 inch (823 mm), and that seasonal water use efficiencies were essentially the same for both systems at 363 pounds per acre-inch (1.6 kg corn/m^3). Therefore, the advantage of surge flow irrigation was more efficient application resulting in reduced water application rather than increased yields.

Walker and Schlegel (1984) ran field tests of surge irrigation systems in comparison with continuous or steady flow furrow irrigation on High Plains farms. Flowrate, rate of advance and recession, soil moisture, and runoff were measured at five stations along selected furrows. Intake, distribution (pattern) efficiency, and application efficiency were calculated. Two such field tests on Olton clay loam soil gave radically different results (Table VI-12), attributed mainly to differences in soil preparation, compaction and management. In Field Test I, distribution efficiency was higher with conventional irrigation, but application efficiency was higher with surge flow. Tailwater runoff was lower with surge. The distribution efficiency could have been improved with surge but at the expense of increased tailwater runoff. The lack of significant benefit from surge irrigation was believed due to prior extensive tillage and soil compaction on the test site that limited water intake and prevented deep percolation for either system.

In Field Test II, however, surge resulted in a very large reduction in water intake from 15.2 to 5.8 inches (386 to 147 mm) (Walker and Schlegel, 1984). By greatly reducing deep percolation, surge flow increased application efficiency from 34 to 83 percent. However, the runoff rate was

Table VI-12

Results of Surge Irrigation Field Tests in Texas High Plains, Olton Clay Loam Soil (Walker and Schlegel, 1984)

	Test I		Test II	
	Conventional	Surge	Conventional	Surge
A. Test Conditions				
Well discharge, gpm	870	870	736	736
Pumping Time, min	600	634	1,595	1,422
Run Length, ft	1,600	1,600	1,275	1,275
Number of Rows	31	58	19	42
Row Spacing, in.	40	40	60	60
Irrigation Set, acres	3.8	7.1	2.8	6.1
Average Slope, %	0.3	0.3	0.1	0.1
B. Results				
Average Intake, in.	3.6	2.7	15.2	5.8
Deep Percolation, in.	0	0	10.0	0.6
Distribution Efficiency[1], %	93	74	100	100
Application Efficiency[2], %	71	82	34	83
Tailwater, % of Water Pumped	29	15	4	9

[1]Distribution Efficiency =

$$\frac{\text{Water added to root zone in 25\% area with lowest intake, in.}}{\text{Water added to root zone, in.}} \times 100$$

[2]Application Efficiency = $\frac{\text{Water added to root zone, in.}}{\text{Gross water applied, in.}}$ 100

slightly higher with surge. Total water applied with the surge system was 6.3 inches (160 mm) as compared to 15.4 inches (391 mm) with the continuous system, a savings of 9.1 inches (230 mm). In this case, surge flow was very successful in reducing the excessively large aplication and still provided adequate application to prewater corn. This capability was not available with continuous furrow irrigation. Watering time with surge was reduced by 59 percent at an energy savings of 570 kWh per acre (1,400 kWh/ha).

Risinger (1984) compared irrigation distribution efficiencies and application efficiencies for surge flow and continuous furrow irrigation on 6 farms in Lubbock, Floyd, Lamb and Castro Counties (Table VI-13). Details such as cycle times, cycle ratios, and furrow streams were not reported. Results indicated that in most cases surge increased application efficiency but reduced distribution efficiency. Tailwater runoff was reduced in most of these field studied, but amounts were not specified. Efficiencies were computed as shown in Table IV-12. Risinger (1984) concluded that surge flow does not significantly improve efficiency in short, level fields where water management efficiency is already quite high.

Manges and Hooker (1984) compared surge irrigation of corn with continuous and cutback furrow irrigation in research at Garden City, Kansas on Ulysses and Richfield silt loams with silty clay loam surface. Stream advance time in tractor wheel-track furrows was significantly greater during the first irrigation for all three types of irrigation treatments. Surge flow with 60 and 120 minute cycle times failed to reduce the advance time, perhaps due to the influence of deep soil cracks on water intake. Treatments did not cause significant differences in soil moisture.

Table VI-13

Comparison of Distribution and Application Efficiencies for Surge Flow Irrigation, Southern High Plains (Risinger, 1984)

	Distribution (Pattern) Efficiency[1], %		Application Efficiency, %		System Efficiency, %	
Farm No.	Surge	Continuous	Surge	Continuous	Surge	Continuous
A	71	95	92	95	65	90
B	66	58	64	52	42	30
C	78	82	84	86	66	71
D	84	94	90	80	76	75
E	91	94	82	82	75	77
F	88	77	67	65	59	50
Mean	80	83	80	77	64	66
Std. Dev.	10	14	12	16	12	22

[1] Distribution efficiency calculated from soil water contents obtained with neutron probe at 5 to 6 intervals along furrow.

Manges et al. (1985) also studied the effect of surge cycle times on advance rates for Ulysses and Richfield soil planted to soybeans. Advance times for each of two flow rates in wheel-compacted and non-wheel compacted rows were determined from 2 irrigations. Advance rates were faster for all treatments during the second irrigation as compared to the first irrigation. However, surge flow with either constant or fixed cycle times was ineffective in increasing the advance rates over continuous irrigations on these soils.

Modeling of Surge Flow

Mathematical modeling of surge flow irrigation is desirable to evaluate the effects of variables on flow advance time, infiltration, deep percolation and runoff for a wide range of conditions based on limited experimental data. Accurate models could greatly assist the development of surge management guidelines for situations where actual field data do not yet exist.

Mathematical models of surge flow have been or are being developed by numerous researchers. These models can be broadly classified as: volume balance, kinematic-wave, zero inertia, and full hydrodynamic wave (Wallender and Rayej, 1985).

Walker and Humphreys (1983) evaluated a kinematic-wave furrow irrigation model based on the continuity equation. There was good correlation between measured and predicted surge advance fronts. It was concluded that kinematic-wave analysis is a satisfactory tool for predicting water advance, intake, and runoff for sloped furrows in comparison with continuous flow irrigation. Spatial variability in soil intake properties affects accuracy of the model more for surge flow than for continuous flow.

Blair (1985) utilized a kinematic-wave model to predict surge flow hydraulics and infiltration. Irrigation simulations with the model indicated that the effectiveness of surge flow is highly dependent on the soil infiltration characteristics. Wetted perimeter of furrows was also identified as an important variable. For some soils with high intake rates, surge flow has potential for markedly improving distribution efficiency. However, an improperly operated surge flow system can reduce irrigation efficiency below that of continuous flow irrigation, and little improvement can be expected on low intake rate soils.

A zero-inertia model for surge irrigation was developed from a non-linear furrow model. It provided adequate simulation of surge advance and recession when compared to field data (Wallender and Rayej, 1985).

Summary of Surge Flow Research

Surge flow irrigation reduces deep percolation losses in many soils through a large decrease in infiltration rate during the off-time of the first surge cycle. Therefore, surge gives farmers an opportunity to apply lighter applications than is possible with continuous flow irrigation. However, tailwater losses may not be reduced and with improper management could be increased with surge. Lower crop yields due to lighter applications during the high crop water use periods may be a problem as well if surge is not managed properly. The beneficial effects of surge are most dramatic on the first irrigation of the season, especially in non-wheel compacted furrows (Musick, 1986). It may be best to use surge as the preplant or first seasonal irrigation and then in some instances use continuous irrigation for later seasonal irrigations (Walker and Schlegel, 1984). Surge irrigation offers the promise of more efficient furrow irrigation in terms of water use and reduction in water and energy requirement. However, more careful management is required to realize these benefits, and there are indications that surge irrigation is not advantageous in every situation.

Advance Rate Feedback Irrigation System (ARFIS)

One of the major problems in managing surface irrigation systems is the variability in soil infiltration rates across a field. The variability in infiltration rate with respect to space and time is a major reason that surface irrigation systems are less efficient than sprinkler and trickle systems. A significant amount of tailwater may occur from some rows while little or none may occur from others. However, rows with no tailwater may have greater deep percolation losses.

The most desirable surface irrigation system would involve the determination of infiltration rates for each furrow during irrigation (Reddell, 1984). The infiltration rates could then be used to calculate the furrow flow rate and time of application. A computer with the assistance of several sensors located in the field could easily do this calculation. A research program is underway in the Texas Agricultural Experiment Station to develop an advance rate feedback irrigation system (ARFIS), previously termed automatic furrow irrigation system (AFIS), with the objective of providing a water management system for furrow irrigation that is equivalent to trickle or sprinkler irrigation, but which costs less (Reddell, 1984). ARFIS can be thought of as a "feed-back" computer-controlled surge system. The hardware and software are still in the development stage.

A basic feature of ARFIS is sensors placed in the field to calculate infiltration rates for each furrow during each irrigation (Reddell, 1984). From these infiltration rates, the desired average furrow flow rate and time of application will be calculated. The computer will then control valves on each furrow using a pulsing or surging action to achieve the desired average flow rate.

According to Reddell (1984) and Reddell and Latimer (1986), ARFIS is comprised of four components: (1) two water advance sensors for each furrow, (2) a telemetry system (radio or infrared) to communicate advance data between the sensors and microcomputer, (3) a microcomputer to process and control the irrigation system, and (4) a solenoid flow-control valve for each furrow. Two inexpensive water advance sensors are placed at approximately 50 percent and 90 percent of the furrow length (L). When water is detected, a radio or infrared signal transmitter is automatically turned on and a message is sent to the computer. The computer identifies the transmitter and the time the message was received. From this information, the time for water to advance the distances of 0.5L and 0.9L for each furrow are determined and soil infiltration rates are calculated from theoretical irrigation hydraulics. Then the computer goes into a design mode and calculates the furrow flow rate and time of application necessary to achieve a prescribed level of application efficiency and uniformity coefficient for the desired irrigation application depth. A message is then sent by microcomputer to individual furrow flow control valves to adjust the flow rate to the desired level.

This is where ARFIS becomes similar to surge irrigation. It is easier to adjust the flow rate to a prescribed level by pulsing or surging the flow rate in an "on-off" mode. For example, if a solenoid flow control valve is calibrated to deliver 40 gpm (2.5 L/s) and the computer calculates a desired delivery rate of 20 gpm (1.25 L/s), then the desired flow rate could be achieved by turning the valve on for 30 seconds and off for 30 seconds. Other time increments could also be used, such as 1 minute on and 1 minute off, or 10 minutes on and 10 minutes off. The best "on-off" cycle time and cycle ratio must be determined by research.

The first ARFIS system was field tested in 1983 using five initial furrow flow rates (Reddell, 1984). The application efficiency (E_a) and uniformity coefficient (E_d) as predicted by the computer and as measured in the field are shown in Table VI-14. The computer-calculated uniformity coefficients averaged 93 percent and were in close agreement with measured values. Measured application efficiencies (78 percent) tended to be better than those predicted by the computer (70 percent). Measured system efficiencies (E_a X E_d) ranged from 64 to 75 percent.

Subsequent field evaluations were conducted with ARFIS in 1986 on MIller clay near College Station using 600-800 feet (180-240 m) furrows on 40-inch (1 m) spacing planted to grain sorghum (Reddell and Latimer, 1986). Furrow flow rates ranged from 14-25 gpm (0.88-1.58 L/s). Actual and ARFIS-predicted furrow stream advance times differed by an average of 6%. Measured irrigation water application efficiencies varied from 90 to 100% and water distribution efficiencies ranged from 85-92 percent on five irrigation dates. These results are encouraging and warrant continuing research and development of the ARFIS system.

Table VI-14

Comparison of Computer-Predicted and Measured Application Efficiencies (E_a) and Uniformity Coefficients (E_d) for ARFIS System, Five Initial Furrow Flowrates (Reddell, 1984)

Initial Furrow Flow Rate, Q (gal/min)	Application Efficiency		Uniformity Coefficient	
	Computer Predicted %	Measured %	Computer Predicted %	Measured %
4	76	92	87	82
5	69	81	94	93
6	74	77	93	94
8	63	75	95	95
10	68	67	94	96
Mean	70	78	93	92
Std. Dev.	5	9	3	6

Summary

Furrow irrigation accounted for 63 percent of the irrigated acreage in the Texas High Plains, in 1984. Nevertheless, the acreage has decreased by almost 40 percent in a decade. Graded furrow irrigation is often inefficient due to tailwater and deep percolation losses. Preplant irrigations are usually regarded as the most inefficient due to deep percolation losses on some soils in the region early in the season. Several methods are being or have been developed by researchers to improve water use efficiency while realizing the capital-cost economy of furrow irrigation.

Tailwater can be reduced by shortening the application time or installing tailwater recovery systems. However, tailwater recovery systems may be only 60 percent efficient due to seepage and evaporation losses. Reduced application time to restrict or eliminate tailwater may leave soils at the downstream end of the furrow at less than field capacity throughout the root zone and thereby lower yields. However, the research has shown this practice to be a good tradeoff as reflected in 13 to 28 percent increases in irrigation water use efficiency.

Skip-row planting with irrigation has generally increased cotton yields in the planted rows but not enough to compensate for the area left unplanted (i.e. yields per acre declined). Nevertheless, irrigation water use efficiencies in cotton were higher with skip-row systems (plant 2/skip 1, or plant 2/skip 2). Irrigation water intake on an area basis was reduced by 54 percent with skip-row plantings of corn and sorghum. Corn yields were reduced but sorghum yields were increased and irrigation water use efficiencies were 35 percent higher for both corn and sorghum grain with the skip row pattern as compared to every-row plantings.

Alternate furrow irrigation has given higher irrigation water use efficiencies for corn and sorghum than either skip-row production or every-furrow irrigation. Alternate furrow irrigation lowered the water intake by an average of 30 percent for sorghum and 20 percent for vegetables, which lowered yields by 2-11 percent. Alternate furrow irrigation is satisfactory with narrow row spacings on slowly permeable soils or perhaps with conventional 40 inch (1 m) row spacings on moderately permeable soils.

Irrigation in furrows compacted by tractor wheel traffic, as opposed to non-wheel traffic furows, speeded up furrow stream advance time and reduced water intake by 16-33 percent and deep percolation by one-third on a moderately permeable soil. The combination of furrow compaction and residue clearing has reduced water intake by 60 percent due to greatly reduced furrow stream advance time. Reduced water intake caused crop stress in one experiment. Therefore irrigating in compacted furrows may be a desirable practice for the preplant and last irrigation on moderately permeable soils, while uncompacted furrows are used at other times.

No-till and limited tillage with graded furrow irrigation has increased irrigation water use efficiencies in wheat and sorghum by about one-third. Yields were increased by approximately 10 percent.

A so-called limited irrigation-dryland (LID) system was designed to fully irrigate the upstream half of the furrows, partially irrigated the next 25 percent of furrow, and leave the remainder as dryland to capture rainfall runoff or tailwater. The system includes furrow diking and alternate furrow irrigation. With the LID system, sorghum grain yields were reduced in the lower half of the field, but the overall average yield was high despite using less than 10 inches (250 mm) of irrigation water.

Correspondingly high values of both seasonal and irrigation water use efficiencies were obtained both as Bushland and Etter. Runoff was virtually eliminated. The economic need to adjust seeding and fertilization rates along the furrow to reflect soil moisture expectations is a disadvantage of the LID system.

Surge flow irrigation involves intermittent application of water to furrows or borders through a series of on/off watering periods. The primary benefit of surge flow is faster net furrow stream advance rate due to surface sealing of wetted soils during each off-period. This reduces deep percolation at the upstream end and may allow lighter application rates than is possible with continuous flow irrigation, especially on preplant irrigations or the first seasonal irrigation. However, in some instances, tailwater may be increased and/or reduced yields may occur due to inadequate water intake according to some research results. Surge flow irrigation appears more advantageous on moderately permeable soils than on slowly permeable soils. Careful management is apparently necessary to realize benefits of surge.

Another innovation being tested is an advance rate feedback irrigation system (ARFIS) that adjusts the furrow stream while irrigation is underway. This is a computer-controlled system that relies on sensors that detect furrow stream advance causing a solenoid valve for each furrow to be activated including entering a surge flow mode of intermittent flow. Irrigation system efficiencies of 72 to 92 percent have been measured in early tests with the ARFIS system, which is still under development.

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CHAPTER VII

SPRINKLER IRRIGATION SYSTEMS

Sprinkler systems consist of main pipe lines, lateral lines carrying the branched flow, sprinkler risers, and nozzles. The objective of sprinkler irrigation is to uniformly apply water over the field for crop use at a rate that is lower than the soil intake rate to prevent surface runoff (Heerman and Kohl, 1983). The application uniformity depends on sprinkler spacing, operating pressure, nozzle dynamics, travel speed and path, wind and evaporation.

Distribution Uniformity

The water-distribution pattern of a single sprinkler at zero wind velocity is a key element in designing a system. The distribution pattern from stationary sprinkler nozzles can be predicted more easily than distribution from continuously moving sprinklers. Heerman and Kohl (1983) presented equations for calibrating the application depth of a moving sprinkler at a given distance from the center of the application pattern.

The water distribution pattern of a sprinkler system can be evaluated by placing collection cans at the soil surface in a grid pattern, or for center pivots in a radial pattern (Heerman and Kohl, 1983). For evaluating and comparing sprinkler irrigation systems, the Christiansen Uniformity Coefficient (C_u) is most often used (Addink et al., 1983; Merriam et al., 1983), as was shown in equation III-6:

$$C_u = 100 \left[1 - \frac{\text{Average deviation from the average depth caught}}{\text{Average depth caught}} \right]$$

which is calculated as:

$$C_u = 100 \left[1 - \frac{\sum \left| X_i - \bar{X} \right|}{n \bar{X}} \right] \quad \text{(VII-1)}$$

where n is the number of measurements, X_i is the depth of water for can i, and $\bar{X}$ is the average depth caught.

For center pivot irrigation systems, each collector represents a different size segment of a circular field, so it becomes desirable to modify the Christiansen Uniformity Coefficient to a more complex form (Heerman and Kohl, 1983):

$$C_u = 100 \left[1.0 - \frac{\sum_s S_s \left| D_s - \frac{\sum_s D_s S_s}{\sum_s S_s} \right|}{\sum_s D_s S_s} \right] \quad \text{(VII-2)}$$

where S_s is the distance from the pivot to individual equally-spaced collectors and D_s is the depth applied at a collector s.

Uniformity coefficients are usually reported for only one irrigation from a few grid points under a given set of climatic conditions. Irrigation uniformity measured over a whole season will generally be higher than for a single irrigation (Heerman and Kohl, 1983). Uniformity coefficients for sprinklers are typically 75 percent for hand move sprinklers, 71-86 percent for center pivot, and 88-92 percent for linear-move laterals (Heerman and Kohl, 1983).

The sprinkler uniformity coefficient and irrigation efficiency are affected by droplet size. The droplet size is important because (a) wind drift and evaporation are higher for small droplets, and (b) soil surface compaction, crusting and erosion are greater for larger droplets. The drop size distribution is strongly influenced by sprinkler pressure (decreasing for higher pressure) and to a lesser extent by nozzle size.

The smaller droplet size from low-pressure spray nozzles, as compared to high pressure impact sprinklers, tends to increase evaporative losses but these losses are at least partially offset by the smaller distance to the crop canopy (Undersander et al., 1985).

Water distribution efficiency (E_d) has been defined in a manner similar to Christiansen's Uniformity Coefficient (C_u) above, except that E_d is based on the depth of water actually stored in the soil (D). It is calculated as follows (Lyle and Bordovsky, 1983):

$$E_d = 100 \left[1 - \frac{Y}{D}\right] \qquad \text{(VII-3)}$$

where Y is the average numerical deviation from the average depth D stored in the soil. If irrigation runoff occurs, E_d will be different from C_u. If no runoff occurs from the point of application such as with basin tillage (furrow diking), E_d and C_u can be assumed to be equal, and the water distribution efficiency can be obtained from water catch cans at the soil surface (Lyle and Bordovsky, 1983).

Sprinkler System Types

Sprinkler irrigation systems include the following categories (Addink et al., 1983):

(a) Stationary Sprinklers--Solid set and periodic lateral move;

(b) Moving Sprinkler or Spray Systems--center pivot, traveling gun and traveling lateral.

Stationary sprinkler systems are designed to meet water use requirements of crops while preventing ponding and surface runoff by designing for an application rate less than the soil infiltration rate and an application time that will not exceed the soil moisture storage capacity. These design criteria are more difficult to meet with moving sprinkler systems.

Most of the recent research on sprinkler systems has been with moving systems, particularly the center pivot systems and traveling lateral systems, owing in part to their popularity with growers, and this is especially true in the Southern High Plains. Numerous significant improvements have been made through research to improve the application uniformity and efficiency of these moving sprinkler systems.

Center Pivot Irrigation Systems

A center pivot irrigation system consists of a single continuously-moving lateral that rotates around a pivot structure to irrigate a large circular area using sprinkler nozzles, spray heads, or drop tubes (Addink et al., 1983). The lateral distribution pipe is up to 2600 feet long (800 m) and is supported on drive units mounted on wheels spaced 80-250 feet (24-76 m) apart. The outermost drive unit sets the speed of travel, and automatic alignment devices activate the advance of successive interior drive units to create a uniform rate of travel. Center pivot systems are powered by electric motors on each drive unit, by water pressure (i.e. hydraulic drive), or oil pressure pumps. Almost all systems installed in recent years have been electrically-driven.

Center pivot irrigation systems are machines that combine the advantage of labor reduction with uniform distribution and adjustable depth of application. Flow rates often range from 5 to 10 gpm per acre (0.8-1.6 L/s/ha) of area circumscribed by the center pivot. Application rates and uniformity are determined by type and size of nozzle, pressure, sprinkler spacing, pipe size, and length of lateral (Dillon et al., 1972). For a given point along a lateral, application rates are fixed. Varying the speed of lateral rotation changes the depth of water application (inches) but not the application rate (gpm).

As compared to stationary sprinkler systems, application rates for moving systems are generally much higher and vary both in time and space. Because the speed of travel increases with distance away from the pivot point, so must the application rate be directly proportional to the distance from the pivot to obtain uniform application depth. To achieve this spatial variation in application rate, sprinkler spacing and/or nozzle size are varied along the lateral. Common arrangements are (Addinks et al., 1983):

1. Small-to-large sprinklers
2. Medium sized sprinklers, increased nozzle size and spacing
3. Spray-type nozzles.

Center pivots have limited ability to apply sufficient water to satisfy peak ET rates (Hess and Hamon, 1985). Conversely, center pivot sprinkler systems designed to meet crop water use requirements often involve application rates that exceed soil intake rates (Heerman and Kohl, 1983), because the desired water depth is applied for a shorter period than for stationary sprinklers. At a fixed point, the application rate begins at zero, reaches a peak rate directly under the lateral, and then decreases to zero (so-called elliptical pattern). The peak application rate increases with distance from the pivot, but the time of application is shorter, so that the total amount applied is designed to be relatively constant along the lateral (Figure VII-1). Nevertheless, the peak application rate usually exceeds the soil intake rate even before the basic intake rate is reached. Potential runoff can be decreased by increasing the travel speed and hence reducing depth of application while increasing irrigation frequency. However, evaporation losses may be greater.

Because the spray nozzles direct the spray onto a much smaller wetted area, spray nozzles give instantaneous application rates as high as 10.0 inches per hour (250 mm/hr) which greatly exceeds application rates from either high-pressure or low-pressure impact sprinklers of 2 inches per hour (50 mm/hr), according to Heerman and Kohl (1983). However, spray-type nozzles and small impact sprinklers have smaller droplet sizes, which tend to reduce surface soil dispersion and maintain higher soil intake rates.

Design of Center Pivot Systems

In designing a center pivot system, an effort should be made to match three elements: soil intake characteristics, water requirements of the crop, and water delivery characteristics of the center pivot. In order to match these three elements, and to prevent or minimize runoff, Dillon et al. (1972) recommended a design procedure that consists of the following basic steps:

1. Determine the length of lateral pipeline.
2. Determine peak water use rate of crops, usually 0.2 to 0.3 inches per day (5.1-7.6 mm/day) to be met by continuous operation of the center pivot system.

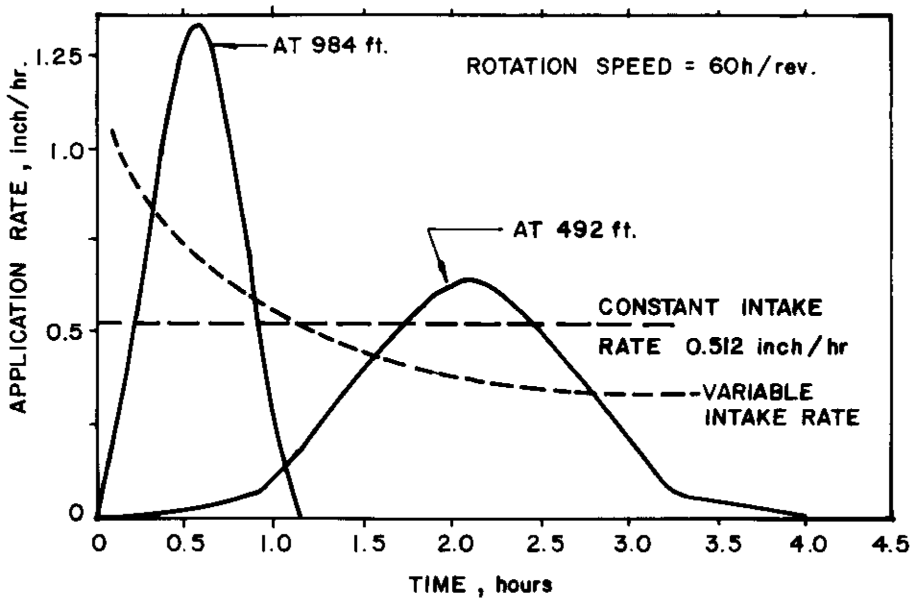

Figure VII-1. Potential runoff from two distances from the pivot of center pivot irrigation system with constant-spacing impact sprinklers (Heerman and Kohl, 1983).

3. Determine flow rate required at the pivot to service the area to be irrigated at the peak water use rate and expected irrigation efficiency.
4. Determine the minimum time (hours) needed to complete one revolution.
5. Calculate depth of water application per revolution.
6. Determine peak application rate (in./hr) directly below the moving lateral.
7. Determine the surface water storage available to limit surface runoff (e.g. 0.1 to 0.5 inches (2.5-12.7 mm) for surface slopes of 5 to 0%, respectively).
8. Determine time for the spray pattern to pass a given point, given the previously determined values of peak application rate and surface storage (Figure VII-2).
9. Calculate minimum design travel speed at the end tower.
10. Compute the maximum time to complete a pivot revolution.
11. Determine the maximum net depth of water application and if it exceeds the root zone storage capacity (rooting depth times inches of available water per foot of soil), a higher lateral speed is needed to prevent runoff.

Field testing of the design procedure was performed on three center pivot systems near Dalhart, Texas by the SCS-USDA (Dillon et al., 1972). Actual and predicted application rates and the elapsed times when surface ponding began were determined at distances of 30-90 feet (9-27 mm) just inside the end tower. Actual application rates and times that were tolerated before ponding occurred averaged 20% higher than predicted values

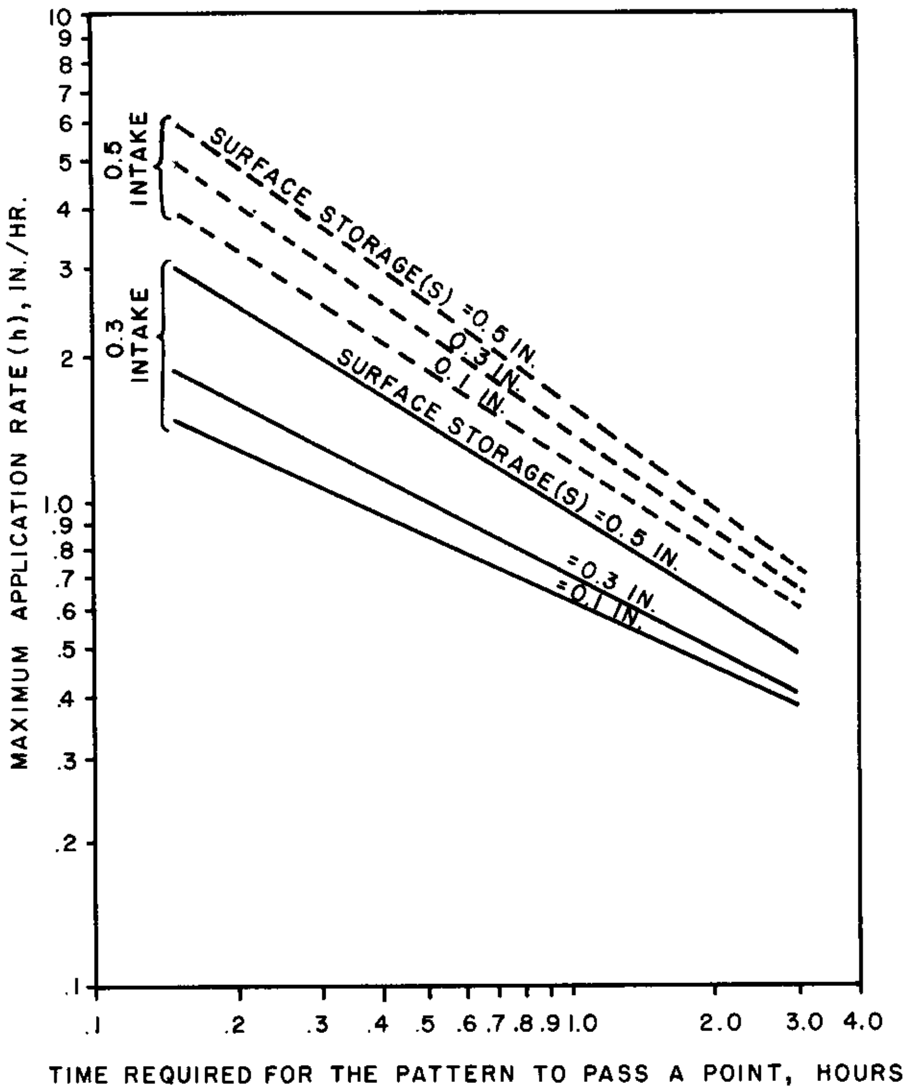

Figure VII-2. Surface storage curve for 0.3 and 0.5 intake family soils, used to determine combinations of application rate and required time for center pivot lateral to pass a given point (Dillon et al., 1972).

(Table VII-1). Consequently, the design procedure offered a conservative design basis.

Research Evaluation of Center Pivots

Marek and Ebeling (1982) evaluated center pivot systems, one each at Etter and Bushland, for 2 years comparing high and low pressure systems at each location. Flow rate was 6.5 gpm per acre (1.0 L/s/ha). Results (Table VII-2) indicated that higher water application efficiency (fraction of pumped water that reached the soil or plant surface) and uniformity were obtained from the high pressure system, although efficiencies were considered excellent in each case. Climatic factors, particularly low relative humidity, caused high application losses in some tests. The low pressure system, although less efficient in terms of water application, was more economical to operate because of reduced pressure. Other system modifications were necessary to accomodate the switch to low pressure. Runoff from the low pressure system was controllable with furrow diking and chiseling.

Corn and grain sorghum production were compared under impact and spray-nozzled center pivot sprinkler systems on clay loam soils at Etter and Bushland (Undersander et al., 1985). One center pivot at each location was equipped with high pressure impact sprinkler heads operated at 55-60 psi (379 - 414 kPa). The low pressure system at each location was equipped with spray nozzles at 25-30 psi (172 - 207 kPa). Half of each circle was planted to corn and half to grain sorghum. Four tillage treatments were included--conventional tillage, conventional tillage and deep ripping, conventional tillage plus furrow diking, and minimum tillage--in various growing seasons.

Table VII-1

Comparative Results of Center Pivot Design Procedure Versus Actual Field Measurements (Dillon et al., 1972)

System	Flowrate Q gpm	Radius R ft	Speed of last tower v ft/min	Distance From End Tower, ft	Application Rate for Ponding, inches/hour Predicted	Application Rate for Ponding, inches/hour Actual	Elapsed Application Time, min. Predicted	Elapsed Application Time, min. Actual
A	500	1310	2.6	30	0.675	1.025	24	25
				90	0.775	0.65	20	22
B	800	1335	2.0	80	1.15	1.15	17	23
C	1000	1330	3.0	50	1.00	1.44	17	26
				90	0.90	1.20	20	26
Mean				68	0.90	1.09	20	24
Standard Deviation				27	0.19	0.29	3	2

Table VII-2

Average Center Pivot Application Efficiency and Uniformity for Etter and Bushland, 1980-81 (from Marek and Ebeling, 1982)

Center Pivot Pressure	No. Systems	Application Efficiency %	Uniformity Coefficient %	System Efficiency %
High Pressure (55-60 psi)	2	94	76	71
Low Pressure (25-30 psi)	2	86	74	64

Application efficiency for 3 years at Etter and 2 years at Bushland averaged 81 ± 6 percent for the impact sprinklers and 74 ± 9 percent for the spray nozzles (Undersander et al., 1985). Runoff losses were slight (2% or less) for all except the conventional tillage treatment, in which case the low pressure spray nozzles produced 17-75 percent more runoff than the high pressure impact sprinklers (Table VII-3).

There were no significant differences between treatments or systems in terms of seasonal water use (Undersander et al., 1985). Corn yielded significantly more under the high pressure impact system with 5,350 pounds per acre (6,000 kg/ha) than for spray nozzles with 4520 pounds per acre (5,070 kg/ha). However, sorghum grain yields were not significantly different with 5,120 pounds per acre (5,740 kg/ha) for the high pressure system and 4,880 pounds per acre (5,470 kg/ha) for the low pressure system. Runoff from the center pivots was eliminated by furrow diking and reduced both by deep ripping and minimum tillage.

Harman (1982) evaluated a low-capacity center pivot system supplying only 5.85 gpm per acre (0.91 L/s/ha) for irrigating a dual crop of corn and grain sorghum, each on one-half circle. Peak water requirements for the two crops occurred at different times. Consequently, a repeat water application was made to early-planted corn at silking by reversing the center pivot while skipping the sorghum. Later, sorghum peak water use was met by a double application while corn was skipped during a lower water use period. Overall profits from the yields were increased and were equivalent to what would be expected from watering the full circle with corn.

New (1986) reported that center pivots in Texas High Plains field tests improved water application efficiency enough to allow irrigation of 20-25 percent more acreage than can be covered with the same water supply

Table VII-3

Runoff From Center Pivots With Impact Sprinkler and Spray Nozzles at Etter and Bushland, Texas (Undersander et al., 1985)

Sprinkler Type	Runoff			
	Etter		Bushland	
	inches	mm	inches	mm
High Pressure, Impact	0.79	20.0	1.47	37.3
Low Pressure, Spray	1.38	35.1	1.71	43.5

Table VII-4

Application Depth vs. Flowrate and Speed for 1290-foot Center Pivot, 120-acres (New, 1986)

Flowrate, gpm	Pivot Speed, Hours to Complete One Revolution					
	12	24	48	72	96	120
	Application Depth, inches					
400	0.09	0.18	0.36	0.53	0.71	0.89
500	0.11	0.22	0.44	0.67	0.89	1.11
600	0.13	0.27	0.53	0.80	1.06	1.33
700	0.16	0.31	0.62	0.93	1.24	1.55
800	0.18	0.36	0.71	1.07	1.42	1.78
900	0.20	0.40	0.80	1.20	1.60	2.00
1000	0.22	0.44	0.89	1.33	1.78	2.22
1100	0.24	0.49	0.98	1.47	1.95	2.44
Linear Speed at End Tower, ft/hr	667	334	167	111	83	67
Area Irrigated, ac/hr	10	5.0	2.5	1.7	1.3	1.0

by furrow irrigation. Irrigation time was reduced from 16-17 hours per acre per year (40-42 hrs/ha/yr) with furrow irrigation to only 12-13 hours per acre per year (30-32 hrs/ha/yr) with center pivots with similar crop yields.

Management

Runoff losses under center pivots can be reduced by farming in a circular pattern, furrow diking, deep chiseling of clay subsoils, adding organic matter to the soil, and other tillage practices (New, 1986). These methods can be used in conjunction with variations in travel speed to control application depth.

Water application depths for a nominal quarter-mile (0.4 km) center pivot system covering 120 acres (49 ha) are shown in Table VII-4 as a function of flow rate and speed of pivot rotation (New, 1986). The optimum irrigation depth is usually 1 to 1.5 inches (25-38 mm) per application to provide adequate water for the crop until the next revolution of the center pivot machine, to minimize runoff, and avoid depleting soil moisture before the peak crop growth stage.

Low Energy Precision Application (LEPA) Irrigation System

The application efficiency of sprinkler systems is adversely affected by high winds which cause non-uniform application and evaporation losses. Evaporation can be greater than 30% at wind speeds of 20 mph (9 m/sec) that are typical during spring irrigation (Lyle and Bordovsky, 1981A; Clark and Finley, 1975). Sprinkler systems usually provide higher irrigation application efficiency than furrow systems due to greater control over application rates, but this improved efficiency occurs at the expense of additional energy for distribution at higher pressures (Lyle and Bordovsky, 1981A).

Development of LEPA

To overcome these problems, Lyle and Bordovsky (1981A) invented a low energy precision application (LEPA) system which distributes water from overhead lateral pipelines directly into furrows at very low pressure through drop tubes and orifice-controlled emitters. The system is used with micro-basin tillage (furrow dikes) to minimize irrigation and rainfall runoff. The LEPA system has mimimized the effect of soil and climatic variables on irrigation efficiency and has resulted in significant energy and water savings.

The initial LEPA system design by Lyle and Bordovsky (1981A) utilized a linear-move overhead lateral pipeline to which water was transferred from underground pipe risers at less than 10 psi (or 69 kPa) through a flexible irrigation hose carried on a cart. Water was taken out of the LEPA mainline by manifold water-distribution pipes suspended below the mainline. Each furrow was served by a flexible drop tube and outlet at a height of 2-4 inches (50-100 mm)above the furrow. The outlets were operated at 1 to 5 psi (6.9-35 kPa) with discharge controlled by orifices of 5/32-1/4 inch (4-6.4 mm) diameter.

Evaluation of LEPA System

Christiansen's Coefficient of Uniformity (C_u) was determined with catch cans in 14 initial tests with nozzle flowrates of 1.07-2.5 gpm (0.067-0.16 L/s). Values of C_u ranged from 94.2 to 97.2%, and averaged 95.7 ± 2.1 %. On the 4-tower system, pressure regulation to the manifold did not enhance uniformity but was believed essential on a full-scale system.

Application efficiency (ratio of water stored in the root zone to water delivered to the field) was adversely affected only by evaporation of free-standing water in micro-basins following irrigation (30-40 minutes). This evaporation loss was measured to be less than 1 percent. Deep percolation losses were zero, as determined by soil moisture measurements with a neutron probe. Runoff was prevented by furrow dikes. Therefore, application efficiency exceeded 99 percent. Water application by LEPA could be precisely regulated by the linear speed of the system so as not to exceed the amount of water needed to fill the root zone. Without furrow diking, rainfall runoff from both the LEPA system and sprinkler-irrigated plots was 14 percent, which was higher than for furrow irrigated or dryland plots (8.5 percent runoff for each).

In the 1979 LEPA tests, seasonal runoff was greatly reduced with diked vs. undiked furrows (Lyle and Bordovsky, 1981B). Rainfall runoff was reduced from 1.12 inches to 0.22 inches (28.4 to 5.6 mm), while irrigation runoff was reduced from 2.99 inches to only 0.13 inches (75.9 to 3.3 mm). The total irrigation water savings represented a cost savings of $12.86 per acre ($31.76/ha) (Wistrand, 1984), assuming $5.00 per acre-inch cost ($0.049/m^3) of pumped water, less $1.00 per acre ($2.50/ha) for diking cost.

Extensive evaluation of LEPA irrigation between 1979 and 1981 proved that, in comparison with furrow and traveling overhead sprinkler systems, LEPA irrigation was superior in all areas evaluated including application efficiency, application uniformity, yield, water use efficiency, pumping energy requirement per acre, energy cost per unit yield, and net return over irrigation energy cost (Lyle and Bordovsky, 1983). Nearly equal amounts of water were applied through each system. A linear-move main pipeline was equipped alternately with impact sprinklers and LEPA emitters on drops in adjacent spans. Four furrow treatments with 1000 foot (305 m) furrow length were included alongside the sprinkler and LEPA treatments and used these four treatment combinations:

a. Furrow irrigation, with and without furrow diking;

b. Dryland furrows, with and without furrow diking.

Measured water distribution uniformity for the 14 tests in 1980 averaged 96.1 ± 1.2% for LEPA, 91.0 ± 7.5 percent for impact sprinkler, and 53.9 ± 16.2 percent for furrow irrigation (Lyle and Bordovsky, 1983). The wind velocity ranged from 2.5-22 mph (4.0-35.6 km/hr) and averaged 8.8 ± 5.3 mph (14.1 ± 8.6 km/hr). Comparable data was obtained only for the impact sprinklers in 1981, with distribution uniformity averaging 89.4 2.5 percent, over wind speeds of 2.1-13.8 mph (3.4 - 22.2 km/hr) with an average wind speed of 6.0 mph (9.6 km/hr).

Application efficiency for 24 comparative tests in 1980 and 1981 are summarized in Table VII-5. The LEPA system provided the highest application efficiency, with 99 percent application efficiency using furrow diking, which is an integral component of the system. Application efficiencies with sprinklers and furrow irrigation were acceptable but more variable than with the LEPA system.

Irrigation water use efficiency (IWUE) values on soybeans (equation III-1) were highest for the LEPA system (including furrow diking) at 165 pounds per acre-inch (0.729 kg/m^3), but was much lower at 144 pounds per acre-inch (0.634 kg/m^3) without the furrow diking component. Furrow diking likewise improved water use efficiency from sprinkler irrigation

Table VII-5

Water Application Efficiency of the LEPA System in Comparison with Linear-Move Impact Sprinklers and Furrow Irrigation (Lyle and Bordovsky, 1983)

Irrigation	1980		1981		Average %
	Average %	Range %	Average %	Range %	
A. With Furrow Diking					
1. LEPA	99	96-100	99	96-100	99
2. Sprinkler	77	7-97	90	79-100	84
3. Furrow	91	82-99	82	58-98	87
B. Conventional Tillage					
1. LEPA	91	80-100	84	69-99	88
2. Sprinkler	76	7-97	86	71-100	81
3. Furrow	89	71-99	83	66-99	86

(Table VII-5) but not from furrow irrigation. Pumping energy and irrigation energy cost were less with the LEPA system than with sprinkler irrigation and were similar to furrow irrigation.

New and Holloway (1984) equipped one span of a quarter-mile (0.4 km) center pivot system with LEPA drops and emitters to apply water 6-inches (150 mm) above the ground at lower pressure to corn and grain sorghum fields in Moore County, Texas. Treatments included LEPA drop spacings of 30 and 60 inches (0.75 and 1.5 m) and spray nozzles on drops or booms were used as controls. The quarter-mile center pivots were able to operate at 7 to 12 psi (48-83 kPa). Results for 1983 showed essentially no difference among treatments in yields or irrigation water use efficiency (Table VII-6). Corn yielded about 440 pounds per acre-inch (1.94 kg/m^3) from 27 inches (686 mm) of water, and sorghum grain produced about 470 pounds per acre-inch (2.07 kg/m^3) on 16 inches (406 mm) of water. These results did not include the preplant irrigation. In addition, the LEPA system added to the soil profile an extra inch of water that would not have to be pumped the next year.

LEPA vs. Drip Irrigation

Experiments were conducted to evaluate LEPA and drip irrigation systems on Pullman silty clay loam soil at Halfway, Texas (Lyle and Bordovsky, 1986). Various crops and irrigation methods were tested in 1983, 1984 and 1985. In 1983, irrigation water was applied to potatoes, onions and soybeans into every furrow using LEPA, buried drip, and surface-drip when the soil moisture tension in the buried-drip system reached 20-30 centibars (20-30 kPa). Potato yields were very similar (within 2%) for the three irrigation systems. Buried and surface drip

Table VII-6

Irrigation Water Use Efficiency and Grain Yield of Corn and Sorghum with LEPA System Versus Spray Irrigation on Center Pivots, Moore County, Texas (New and Holloway, 1984)

Irrigation System	Corn			Sorghum Grain			
	Water Applied, in.	Yield, bu/ac	IWUE, lbs/ac-in	Water Applied, in.	Yield, lbs/ac	IWUE, lbs/ac-in	Soil Moisture (4 ft) After Harvest, in. Water
LEPA, drops @ 60 in. spacing	27	213	442	16	7,530	470	3.0
LEPA, drops @ 30 in. spacing	27	212	439	16	7,555	472	3.2
Spray Nozzles, drops	27	214	444	16	7,505	469	2.0
Spray Nozzles, booms	--	--	--	16	7,640	478	2.0

system produced 1 and 8 percent more onions than LEPA irrigation, which yielded 30,120 pounds per acre (33,760 kg/ha). Soybean yields were 8 percent higher under LEPA than for buried drip, while surface drip was not tested on soybeans.

The 1984 LEPA vs. drip experiments were expanded to include cotton and corn as well as onions, potatoes, and soybeans. Average crop yields, irrigation amounts, number of irrigations, irrigation water use efficiencies, and soil moisture tension (in growing season) are summarized in Table VII-7 (Lyle and Bordovsky, 1986). The five irrigation treatments were two LEPA treatments (every furrow vs. alternate furrow) and three drip irrigation treatments (subsurface/every furrow, surface/every furrow, and surface/alternate furrow).

Cotton, corn and soybean yields and irrigation water use efficiencies were greatest for alternate furrow irrigation, both for LEPA and surface drip methods, than for every-furrow application. Generally, higher irrigation water use efficiencies (IWUE) were obtained from LEPA as compared to drip for corn and soybeans, but yields were similar.

Drip irrigated cotton out-yielded LEPA-irrigated cotton but received greater water application. Therefore, IWUE's were similar for LEPA (83.6-92.3 pounds per acre-inch, or 0.37-0.41 kg/m^3) and drip systems (81.7-92.9 pounds per acre-inch, or 0.36-0.41 kg/m^3). Subsurface drip was slightly superior to surface drip in each furrow for soybeans and cotton but not for corn.

For onions and potatoes, irrigation water use efficiencies were 12 to 20 percent lower for LEPA than for all drip systems (every furrow, surface and subsurface). The method of irrigation had little effect on total yield or size distribution of onions. But in potatoes, both subsurface and

Table VII-7

LEPA vs. Drip Irrigation Test Results at the Texas Agricltural Experiment Station, Halfway, Texas (Lyle and Bordovsky, 1986)

Crop	LEPA Irrigation Every Row	LEPA Irrigation Alt. Row	Drip Irrigation Surface Every Row	Drip Irrigation Surface Alt. Row	Drip Irrigation Subsurface, Every Furrow
1. Corn					
Yield, bu/ac[1]	219	239	221	247	220
Irr. Amt., ac-in/ac	25.1	24.7	27.2	26.1	29.1
No. of Irrigations	12	14	15	13	15
IWUE, bu/ac-in	8.7	9.7	8.1	9.4	7.6
2. Soybeans					
Yield, bu/ac[2]	52.6	54.2	51.5	57.5	51.0
Irr. Amt., ac-in/ac	15.3	15.6	17.3	17.3	17.3
No. of Irrigations	9	9	9	9	9
IWUE, bu/ac-in	3.44	3.47	2.98	3.32	2.95
3. Cotton					
Yield, lbs lint/ac	577	637	629	725	681
Irr. Amt. ac-in/ac	6.9	6.9	7.7	7.8	7.7
No. of Irrigations	3	3	3	3	3
IWUE, lbs lint/ac-in	83.6	92.3	81.7	92.9	88.4
4. Onions					
Yield, 50 lb sack/ac	1,042		1,028		1,064
Irr. Amt., ac-in/ac	28.6		25.3		24.3
No. of Irrigations	29		28		27
IWUE, sacks/ac-in	36.4		40.6		43.8
5. Potatoes					
Yield, 100 lb sack/ac	304		335		349
Irr. Amt., ac-in/ac	22.5		22.0		21.6
No. of Irrigations	18		20		21
IWUE, sacks/ac-in	13.5		15.1		16.2

[1] 1 bu = 56 lbs of corn at 15.5% moisture content
[2] 1 bu = 60 lbs of soybeans at 12% moisture content

surface drip (every furrow) produced much higher yields of large, high-valued potatoes than did LEPA, with differences attributed to possible spray-induced leaf diseases that could be controlled in the future by chemical treatment through LEPA emitters.

The 1985 LEPA vs. drip experiments focused on onions and cotton, which were irrigated at various frequencies and irrigation quantities (as multiples of ET--0.4, 0.7, 1.0 and 1.3 x ET). Onion yields were not significantly affected (0.05 probability level) by irrigation system, frequency, or quantity. However, row spacing had a significant effect, with peak yields produced by 4 rows/bed as compared to 2 and 3 rows/bed. Over all treatments, onion yields with LEPA were 2% higher than for drip (1,152 vs. 1,133 sacks/acre). Highest yields occurred at 4-day irrigation frequency for both treatments (vs. 2 and 8-day) and at amounts of 0.7 or 1.0 ET (amounting to 13 and 18.6 inches (330 and 472 mm), respectively).

Cotton yielded slightly more lint with LEPA (621 pounds per acre, or 696 kg/ha) than with drip (612 pounds per acre, or 686 kg/ha). Irrigation water use efficiency was slightly higher also for LEPA at 217 pounds per acre-inch (0.96 kg/m^3) versus drip systems at 210 pounds per acre-inch (0.93 kg/m^3). However, these differences were not significant (0.05 probability level). Irrigation water use efficiency for both systems varied inversely with irrigation quantity (Table VII-8).

Much higher yields were obtained from both LEPA and drip systems at 2 and 4-day frequencies than for 12-day intervals. At the 2-day frequency and at the 0.7 x ET irrigation amount, average yields were significantly higher for LEPA than for drip.

Because crop yields were similar for most treatments, Lyle and Bordovsky (1986) concluded that the choice between LEPA and drip irrigation

Table VII-8

Cotton Yields and Irrigation Water Use Efficiencies for LEPA vs. Drip Irrigation Systems, Halfway, Texas, 1985 (Lyle and Bordovsky, 1986)

Irrigation Quantity		Cotton Yield*, lbs lint/acre		Irrigation Water Use Efficiency*, lbs/ac-in	
Fraction of ET	Inches	LEPA	Drip	LEPA	Drip
0.4	1.6	565	535	353	334
0.7	2.8	665**	603**	238	215
1.0	4.0	658	658	165	165
1.3	5.2	595	655	114	126
Average	--	621	612	217	210

* Data are averages across 2, 4 and 12-day irrigation frequencies.
** Statistically significant difference (0.05 level).

should be based on factors besides yield, such as capital cost per acre, expected life, labor, pressure and energy requirements, and versatility (eg. chemigation).

Conversion to LEPA

Guidelines and general specifications for converting center pivots to LEPA were presented by New (1986) and Lyle (1986). The mainline operates at a pressure of 4-10 psi (28-69 kPa) at the downstream end depending on the location of the nozzle and whether pressure regulation is required. Discharge nozzles and emitters should be suspended 4-8 inches (100-200 mm) above the soil surface in most cases with some as high as 12-15 inches (300-380 mm) to clear the beds. A pressure gain of 5-6 psi (35-41 kPa) may occur in the drop tube depending on the elevation difference between the pipeline and the flow control nozzle. In fields where there is considerable elevation change, each LEPA drop should have a pressure regulator set at 6 psi (41 kPa).

The discharge nozzles should deliver water with a high degree of uniformity and in a nonerosive manner (Lyle, 1986). Types of LEPA nozzles include a bubble emitter. Several types of LEPA nozzles are available that insert into low pressure spray nozzles for center pivots. Devices include bubble emitters and double sock or tube applications. Equipment for LEPA conversion has been commercially available since 1983 and is reliable.

Disadvantages of the LEPA system are the capital cost of equipment and management ability. However, the cost of converting an existing center pivot irrigation system to LEPA ($2,000-4,000 per half-mile system) can be recovered in 1 to 3 years (New, 1986). Fuel consumption and cost will average 15 to 20% less than with typical center pivots equipped with spray drops, but will be about 10% higher than for furrow irrigation (Street, 1986).

Multi-Function Irrigation System (MFIS)

Capabilities of the LEPA system have subsequently been extended to encompass application of chemicals (chemigation) along with irrigation water through separate nozzle systems from the same basic moving pipe and tower structure (Lyle and Bordovsky, 1986). The new second generation LEPA system, known as Multi-Function Irrigation System (MFIS), can provide very accurate application of water-conserving chemicals such as antitranspirants, growth regulators, and soil surface evaporation suppresants. Traditional types of agricultural chemicals--fertilizers, herbicides, and insecticides--can also be applied and can possibly enhance conversion to conservation tillage. The high application efficiencies of 98-99% consistently obtained with LEPA are expected to minimize potential for chemical movement below the root zone or through the atmosphere. Also accurate placement of certain chemicals on the most critical plant parts or on soil surfaces as desired can be achieved with MFIS.

The Multi-Function Irrigation System has two independent adjustable nozzle systems (Lyle and Bordovsky, 1986). One set of nozzles is used for irrigation water along with chemicals that might be injected. The second nozzle system is used exclusively for chemical application. The two nozzle systems are completely adjustable in the vertical and horizontal directions by chain and sprocket drive systems powered by electric motors that are activated from a control platform. This allows positioning above, below or within a crop canopy. The nozzle positions can be controlled manually or electronically. An electronic controller can be programmed to raise and lower the sets of nozzles according to a pre-determined amplitude and frequency to completely cover a crop if desired. The system is propelled with conventional 480-volt, 3-phase electric motors. The improved propulsion, alignment and guidance system included in the design of MFIS utilizes variable frequency electric motors that are controlled by linear position transducers.

The MFIS system shows excellent promise for accurate and timely placement of water-conserving chemicals, fertilizers and pesticides along with negligible runoff and deep percolation (Lyle and Bordovsky, 1986). It offers a substantial improvement especially over surface irrigation methods in which the distribution uniformity of the chemical is no better than that of the applied water.

Low Pressure, Lateral Move Irrigation System

Linear or lateral move irrigation systems can offer several inherent advantages over center pivot systems: (a) application pattern does not vary with length of lateral; (b) smaller hydraulic friction loss due to lower flow rates toward the distal end; and (c) more efficient use of land (through avoidance of unirrigated corners which account for 20% of land area). However, lateral move systems are significantly more expensive, cannot be operated continuously even at peak water use periods, and may require system downtime to make a "dry move" to the opposite end of the field.

Research has been conducted at the Water Management Research Laboratory near Fresno, California to develop an improved lateral move, low pressure system with various types of application modes (Howell and Phene, 1983). Design equations for lateral move systems were presented for system capacity, peak gross application depth, required travel speed, and flow rate. A graphical relationship was developed between flowrate, (Q), travel speed (S), and operating time ratio (F/T_r) for given values of peak water requirement (P), field width (W), and application efficiency (E). The operating time ratio is defined as the ratio of number of days required to complete one irrigation (F) to the fraction of net operating time each day (T_r), i.e. operating efficiency. Frequent irrigation in small quantities of 0.4 to 0.8 inches (10 to 20 mm) with high application efficiency can be an efficient and practical operating mode for lateral move systems (Howell and Phene, 1983). But, time required for system transportation (dry moves) must be minimized or eliminated in peak water use periods and may require increased system flow rate to compensate.

A lateral move system was designed and tested by Howell and Phene (1983) with cotton on a Hansford sandy loam soil in Central California. Water was delivered to the 4 inch (102 mm) diameter, 650 feet (200 m) long mainline by pumping from a concrete-lined ditch parallel to the direction of travel. The test system had 15 support towers and pressure-regulated distribution manifolds, with one drop line per row at 3 feet (0.9 m) spacing. Seven different types of line- and point-source applicators were tested:

1. Trickle drag lines at 16.2 psi (112 kPa) pressure
   a. uniform emitter spacings and flowrate
   b. gradient emitter spacing and flowrate
2. Overhead spray nozzles at 24.2 psi (167 kPa) pressure
3. Over-canopy spray nozzles with gradient discharge (i.e. heaviest at leading edge), 12 psi (84 kPa)
4. Below canopy applicators (on drops)

a. spray nozzles, 12 psi (84 kPa)

b. tapered orifice nozzle in flat hose 17.1 psi (118 kPa)

c. flow control orifice in flat hose, 12 psi (84 kPa).

Small, frequent irrigation application rates to replace the evapotranspiration rate were used in the experiments. Furrow diking was not necessary because of low application rates and level soil surface, but "slot-mulch tillage" was included in the same experiments. Tower speeds were 2,300 to 4,300 ft/day (690-1,300 m/day).

The Uniformity Coefficient, C_u, was measured for each system. In stationary tests, C_u values exceeded 98 percent on all application systems except the tapered orifice nozzles on drops. However, in moving tests, the irregular travel dynamics (alignment and speed control) of the system apparently limited C_u to a maximum of about 90 percent. For example, coefficients of uniformity and application efficiencies for overhead spray nozzles and below-canopy spray nozzles were below 90 percent (Table VII-9). The overhead and below canopy spray nozzles produced the highest irrigation water use efficiencies (Table VII-10).

Pressure reduction to less than 29 psi (200 kPa) did not reduce water distribution uniformity from the lateral move system (Howell and Phene, 1983). No apparent advantage was observed from either of the gradient-source application systems (trickle or spray). The trickle drag systems caused mechanical problems involving primarily the power required to pull the lines. More research on system travel dynamics is necessary.

Summary

Sprinkler systems are used by farmers on 37% of the irrigated acreage in the Texas High Plains. The acreage has remained fairly constant in the

Table VII-9

Spray Nozzle Uniformity and Application Efficiency with Linear-Move System at Fresno, California (from Howell and Phene, 1983)

Application Method	Uniformity Coefficient C_u, %	Application Efficiency, %	Indicated System Efficiency, %
Overhead Spray Nozzles	82	70	57
Below Canopy Spray Nozzles	67	87	58

Table VII-10

Cotton Yields and Irrigation Water Use Efficiencies (IWUE) for Low-Pressure Lateral Move Application Methods, Fresno, California (Howell and Phene, 1983)

Application Method	Water Applied, in.	Lint Yield, lbs/ac	IWUE, Yield Per Applied Water, lbs/ac-in
1. Trickle drag lines	22.3	547	24.5
2. Overhead spray nozzles	19.8	614	31.1
3. Over canopy spray, gradient discharge	20.2	489	24.3
4. Below canopy			
a. Spray nozzles	22.6	729	31.7
b. Tapered orifice nozzles	22.3	454	20.4
c. Flow control orifice	23.1	557	24.0

last decade. Both stationary and moving types of sprinkler systems are used, but a growing acreage has come under center pivot systems that utilize high pressure sprinkler nozzles, low pressure spray nozzles, or more-advanced LEPA nozzles. Distribution uniformity, affected by wind and evaporation, and runoff are major factors in design and operation of sprinkler systems.

Center pivots are capable of supplying frequent, relatively light irrigations (as compared to furrow irrigation). However, they have limited ability to apply sufficient water to meet peak ET rates of crops without creating potential runoff problems. Runoff is especially a problem on slowly permeable soils in the High Plains and/or with low pressure spray nozzles which have a relatively small wetted area.

Average irrigation system efficiencies of 71 and 64 percent were obtained with high and low pressure center pivots respectively at Etter and Bushland. These values were higher than determined by SCS-USDA in field evaluations. Runoff was reduced from both high pressure (impact) and low pressure (spray) nozzles when conventional tillage was supplemented by deep ripping or furrow diking, or was replaced by minimum tillage.

A low-energy precision application (LEPA) system has been developed on the High Plains to distribute water at very low pressure of 1-5 psi (or 7-35 kPa) at a height of less than one foot (0.3 m) above the soil surface using drop tubes from moving overhead lateral pipelines.
Orifice-controlled emitters supply water to only one furrow, so instantaneous application rates are high. Therefore, furrow dikes are a recommended component of the system and greatly reduced runoff both from irrigation water and rainfall in experiments. Average values of application efficiency with furrow dikes and distribution uniformity have

averaged 99 percent and 96 percent, respectively, which indicates a system efficiency of 95 percent. The LEPA irrigation system consistently provided higher irrigation efficiency than furrow and center pivot systems and also improved crop yield and irrigation water use efficiency and while lowering the energy requirement.

Direct comparisons were made between the LEPA system and drip irrigation (both surface and buried) on corn, soybeans, cotton, onions, and potatoes. Yields over two or three years of testing were relatively similar for LEPA and drip systems for corn, soybeans, cotton and onions, but yields were lower for LEPA with potatoes. With the LEPA system, irrigation water use efficiencies were lower for onions and potatoes, higher for corn and soybeans, and similar or slightly higher for cotton, as compared to drip systems. Alternate furrow irrigation was more efficient than every-furrow irrigation for both LEPA and drip. Factors such as capital cost, equipment life, management, and energy requirements are important in selecting between LEPA and drip.

Highest irrigation water use efficiencies in cotton occurred with LEPA using irrigation quantities of only 40 percent of cumulative ET since the previous irrigation. Peak yields were obtained by applying 70 and 100 percent of cumulative ET with irrigation intervals of 2 to 4 days.

The multifunction irrigation system (MFIS) is an advanced version of the LEPA system that involves both an irrigation emitter and a chemigation nozzle for each irrigated furrow. Both sets of nozzles are adjustable vertically and horizontally. The MFIS system has shown excellent promise for accurate placement of many types of agricultural chemicals without runoff or deep percolation losses.

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CHAPTER VIII

IRRIGATION WATER MANAGEMENT FOR SPECIFIC CROPS

With limited groundwater in the Texas High Plains and high pumping costs, applied water plus rainfall is inadequate on most farms to supply the moisture necessary for maximum crop yield (Lyle and Bordovsky, 1985). The soil-crop-water system should store maximum amounts of both rainfall and irrigation water in the root zone for timely utilization. Deep, dense-rooted, drought tolerant crops such as cotton, wheat, sunflowers, and grain sorghum should be chosen for limited irrigation.

A diversified cropping program is desirable for limited irrigation situations because peak water demand periods or most sensitive growth periods can be staggered among various crops (Lyle and Bordovsky, 1985). For example, a diversified cropping program might include:

Crop	Peak Water Demand Period
Winter Wheat	April and May
Sunflowers, early	June-mid July
Cotton	mid-July and August

Crop rotations which provide a summer fallow period for some acreage can help distribute the irrigation water demand more evenly by storing summer rainfall and possibly eliminating pre-plant irrigation the following year. For example, this cropping system could consist of sorghum/wheat-fallow (2 years), cotton/wheat-fallow (2 years), or sorghum/wheat-fallow/cotton (3 years). When cotton followed wheat and summer fallow, there was an average yield increase of 130 pounds cotton lint per acre (146 kg/ha) as compared to cotton preceded by grain sorghum (Bordovsky et al., 1978).

Water use strategies will be discussed individually for major crops in the Texas High Plains. The focus of this discussion will be on maximizing water use efficiency and minimizing total water use. The projected economic benefits are beyond the scope of this undertaking.

Grain Sorghum

Sorghum is a relatively drought resistant crop due to its physiological properties. Although the root system may extend to 6 feet (1.8 m) or more, 60 to 90% of the water uptake usually occurs in the top 3 feet (0.9 m) of soil profile (Hess and Hamon, 1985). Soil moisture depletion levels of more than 50% can be tolerated, with 80% depletion being tolerated in the ripening stage.

Sorghum has been the most widely tested crop for evaluation of irrigation water management in the Southern High Plains (Musick, 1984). Yield of grain sorghum and measured ET rates appear to be linearly related (Stewart, 1985). A summary of 26 years of ET versus yield data from Bushland, Texas is shown in Figure VIII-1. Above the threshold value of 5 inches (126 mm) of ET needed to produce the first increment of sorghum grain, the yield was increased 350 pounds per acre-inch of ET (i.e. 1.55 kg/m^3). Researchers in other parts of the world have produced similar results.

Irrigation of sorghum increases the plant growth and evapotranspiration rate over dryland treatment, and thus increases the grain yield. Stewart et al. (1983) developed a curvilinear relationship between ET and water applied (Figure VIII-2). This relationship indicates successively lower increases in crop ET as the amount of irrigation water

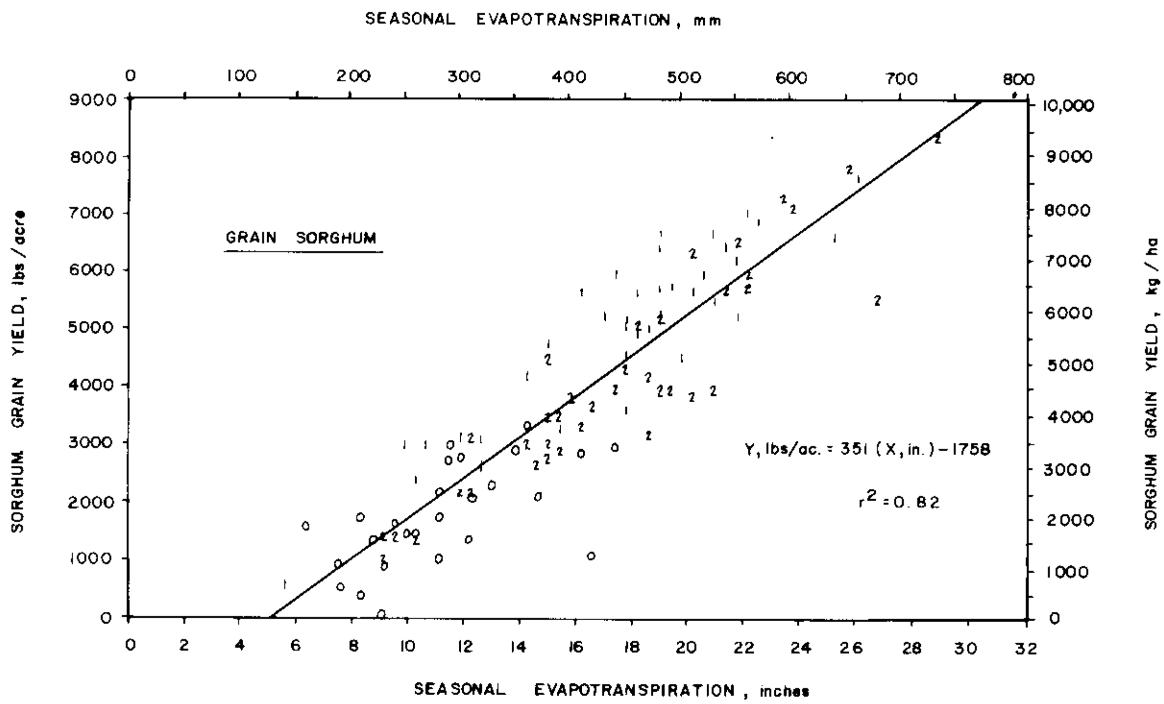

Figure VIII-1. Relationship between yield of grain sorghum and seasonal evapotranspiration at the USDA Conservation and Production Research Laboratory, Bushland, Texas (Stewart, 1985).

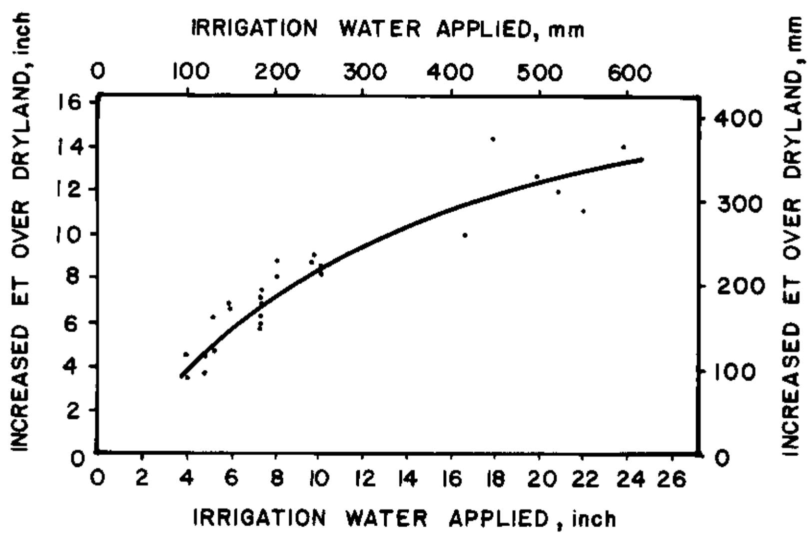

Figure VIII-2. Increase in evapotranspiration rate of grain sorghum over dryland as a function of the amount of applied irrigation water (Stewart et al., 1983).

is increased. Irrigation studies generally have found diminishing sorghum yield responses to incremental increases in levels of irrigation.

Musick and Sletten (1966) determined that the maximum water use rate for adequate watering (4 irrigations) of grain sorghum averaged 0.30 inches per day (7.6 mm/day) for a sampling interval between irrigations and occurred at boot through heading stages. Maximum seasonal water use from seeding to harvest by a medium maturity hybrid sorghum was 24 inches (610 mm) for Bushland, Texas and Garden City, Kansas. When the number of irrigations was reduced from four to one, total seasonal water use was decreased from 24.0 to 13.7 inches (610 to 348 mm), reflecting a decrease in water use rate during grain development (Figure VIII-3). Average sorghum grain yields with one, two, three and four irrigations were 3,100, 5,500, 7,000, and 7,400 pounds per acre (3,500, 6,200, 7,850, and 8,300 kg/ha).

Seasonal rainfall of 9 inches (230 mm) can sometimes prevent sorghum yield differences between treatments that receive from one to four seasonal irrigations (Musick, 1984). Musick and Dusek (1971) determined that for sorghum the root zone profile does not need to be fully rewetted by each irrigation for efficient water use. During a 2 year test, seasonal water application of 2 inches (50 mm) on level borders yielded 11% less sorghum grain than 4-inch (100 mm) applications. However, irrigation water use efficiencies were 57% higher for the 2-inch irrigation at 530 pounds per acre-inch (2.34 kg/m^3) than for 4-inch applications which yielded 338 pounds per acre-inch (1.49 kg/m^3).

Light applications are easier to achieve with sprinkler irrigation (including center pivot and LEPA) than with furrow irrigation, but peak ET

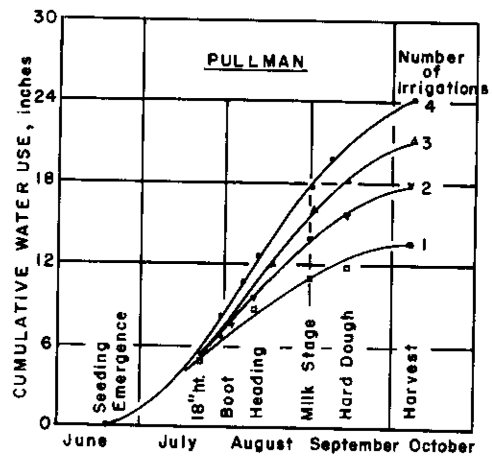

Figure VIII-3. Cumulative water-use curves for grain sorghum irrigation treatments receiving one, two, three, and four irrigations on Pullman soil (Musick and Sletten, 1966).

rates may be harder to meet in some cases. Surge flow irrigation offers a means of achieving lighter applications on some High Plains soils.

Effect of Irrigation Timing on Sorghum Yield and Water Use Efficiency

The extent to which available soil moisture can be depleted before incurring yield reductions can be an important reference point for timing irrigations of sorghum. Musick and Sletten (1966) found that when available soil moisture was depleted to less than 30 percent available or 2 inches (50 mm) in the 0-4 foot (0-1.2 m) depth range in Pullman soil, significant sorghum yield reductions occurred. The rate of yield reduction was 33 percent for each inch (25 mm) of depletion below 2 inches (51 mm) whereas only slight yield reduction occurred when available soil moisture was depleted from 4 inches (100 mm) down to 2 inches (50 mm).

Grain sorghum shows a remarkable ability to compensate and adjust to stress conditions (Stewart, 1985). However, certain stages of growth are more sensitive to water stress than others. Irrigation should be based on avoiding water deficits during the periods of peak water use (flowering to early yield formation period).

Newman (1966) reported that if only one summer irrigation is applied, maximum yield and efficiency are obtained when the application is timed at the boot stage, generally 45 to 50 days after planting. Recommended growth stages when either 1, 2, 3 or 4 seasonal irrigations should be applied are illustrated in Figure VIII-4.

Irrigation studies in the Southern High Plains have generally indicated that good yield responses and efficient use of water are achieved when water is applied at the mid-boot and flowering stages (Musick, 1984).

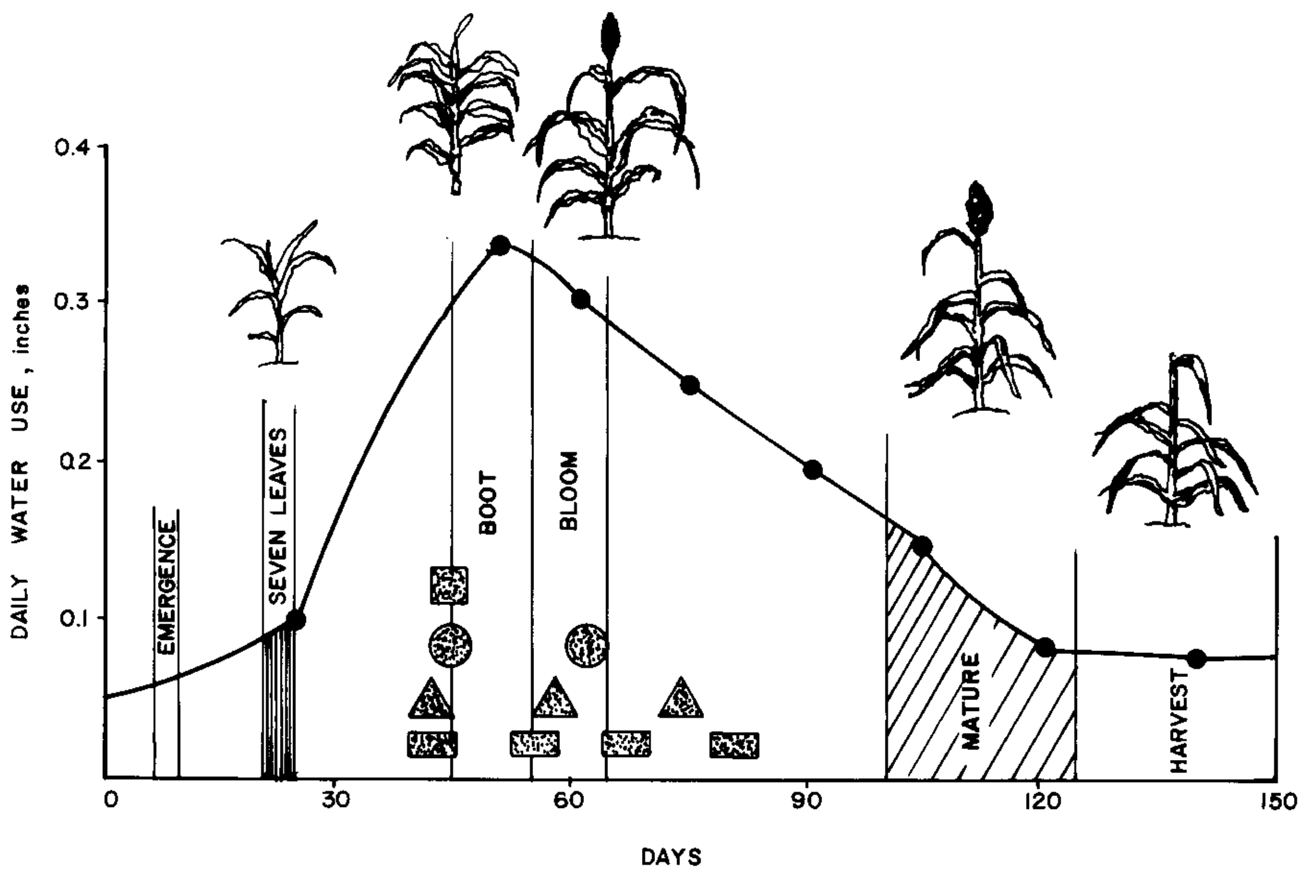

Figure VIII-4. Stage of plant growth and timing of irrigations for maximum yield and water use efficiency of grain sorghum (Newman, 1966).

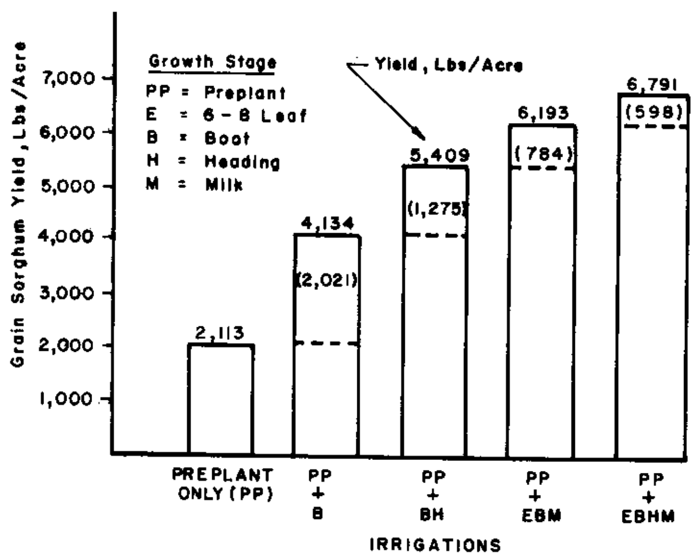

Figure VIII-5. Highest 2-year average grain sorghum yields resulting from combinations of one, two, three and four irrigations applied at specified growth stages, including preplant irrigation only, showing the yield increase attributed to each additional irrigation, Etter, 1969 and 1972 (Shipley and Regier, 1975).

And, much lower response and efficiency occur when water is applied only at the 6- to 8-leaf stage and at the milk to soft dough stage.

Shipley and Regier (1970) found that withholding a 4-inch (100 mm) irrigation during various sorghum development stages reduced yields by these amounts:

Stage	Yield Reduction, %
6-8 leaf	12
Boot to late bloom	35
Heading and bloom	45

Shipley and Regier (1975) reported that maximum yields of sorghum grain on the Texas High Plains were obtained when irrigation and rainfall during the growing season totaled 22-24 inches (560-610 mm). They determined yield response and irrigation water use efficiency at Etter from one, two, three, or four seasonal irrigations of 4-inches (100 mm) each applied at four stages of development. There were large differences in yield and water use efficiency depending upon the stage of sorghum growth when the irrigations were applied (Figure VIII-5). Excellent yield responses were obtained when irrigations were applied at the mid-to-late boot stage (late July) and/or the heading-and flowering stage (early August). By contrast, irrigations applied either earlier (6-to-8-leaf stage; early July) or later (milk-to-soft dough; late August) gave much lower irrigation water use efficiency (Musick, 1984), as shown in Table VIII-1.

The data of Shipley and Regier (1975) showed that if 4-inch (100 mm) irrigations are restricted to once, twice or three times per season, the best times to apply them to sorghum are as follows:

Table VIII-1

Average Irrigation Water Use Efficiency and Yield Increase From 4-Inch Irrigation of Grain Sorghum at Etter (Musick, 1984, based on Shipley and Regier, 1975)

Stage of Development When Irrigated	Average Grain Increase per 4-inch Irrigation, lbs/acre	Number of 4-inch Irrigations				
		1	2	3	4	Ave.
		Irrigation Water Use Efficiency, lbs/ac-in				
a. 6-8 leaf	454	0	90	156	208	114
b. Mid to late boot	1,755	505	460	386	404	439
c. Heading to flowering	2,113	481	545	536	537	525
d. Milk to soft dough	432	23	122	137	150	108

No. Irrigations	Optimum Stage to Apply
1	Mid to late boot, or heading and flowering
2	Mid to late boot, and heading and flowering
3	6-8 leaf, mid to late boot, and heading and flowering

Hence, the two most critical stages were boot (panicle development stage) and heading (panicle extension stage). A preplant irrigation plus a seasonal irrigation during the middle to late boot stage gave the highest water use efficiency.

Similar results were obtained by Malm and Hsi (1968) at Clovis, New Mexico, where seasonal irrigation at the boot stage and at flowering increased yields by 1,930 and 2,630 pounds per acre (2,160 and 2,950 kg/ha), respectively. By contrast, irrigations applied both early, plant height of 6-8 inches (150-200 mm), and late (dough stage) increased yields by only 360 and 400 pounds per acre (403-448 kg/ha), respectively.

Musick and Dusek (1971) obtained relatively high average sorghum grain yields of 6,075 pounds per acre (6,810 kg/ha) from two 4-inch (100 mm) seasonal irrigations over a 3-year test period. The irrigations were applied at the early boot stage during major vegetative growth and the other at either heading or milk stages. Seasonal rainfall averaged 6.5 inches (165 mm), and a 3.7-inch (94 mm) irrigation at emergence was applied. Yield reductions averaged 15 percent when seasonal irrigations of 2-inches (50 mm), rather than 4-inches (100 mm), were used, but irrigation water use efficiency increased.

In later experiments (Musick, 1984) seasonal irrigation at early boot and early grain filling stages produced 6,170 pounds per acre (6,915 kg/ha) while 4 seasonal irrigations produced 6,970 pounds per acre (7,810 kg/ha).

Non-irrigated sorghum yielded 3,000 pounds per acre (3,360 kg/ha). Thus the greatest response occurred from two well-timed irrigations.

When the soil root zone is wet at the beginning of the season from preseason rainfall or preplant irrigation, the first seasonal irrigation can be delayed until plants begin to show some afternoon water stress symptoms because sorghum has good ability to recover normal growth following irrigation (Musick, 1984). An irrigation during the early part of the 30-day period in which sorghum generally fills its seeds can ensure normal seed filling during most of the period until the plant again becomes more tolerant of water stress. The most critical effects occur when plant water deficts reduce seed numbers, which is why a 2-3 week period just before and during heading or pollination is the most critical.

An early planting date for sorghum in the region (e.g. early May) results in a greater likelihood of rainfall during the growing season than a late planting date (Stewart and Burnett, 1987). However, the vegetative growth period is lengthened and the reproduction period falls during the hottest, driest part of the growing season. A later planting (June 15th or after) provides a shorter growing season but with greater rainfall probability during peak water demand periods (Figure VIII-6). Sorghum planting dates could be staggered to make more efficient use of limited irrigation water and available rainfall, provided that insect and disease problems are not increased.

Eck and Musick (1979) evaluated the effects of plant water stress at different stages of growth on grain and forage yields of grain sorghum at Bushland. Sorghum received a pre-plant irrigation and one seasonal irrigation totaling 6 inches (150 mm) plus 7.3 inches (185 mm) of seasonal rainfall. Subsequent 3.1-inch (79 mm) irrigations (0-4 in number) were

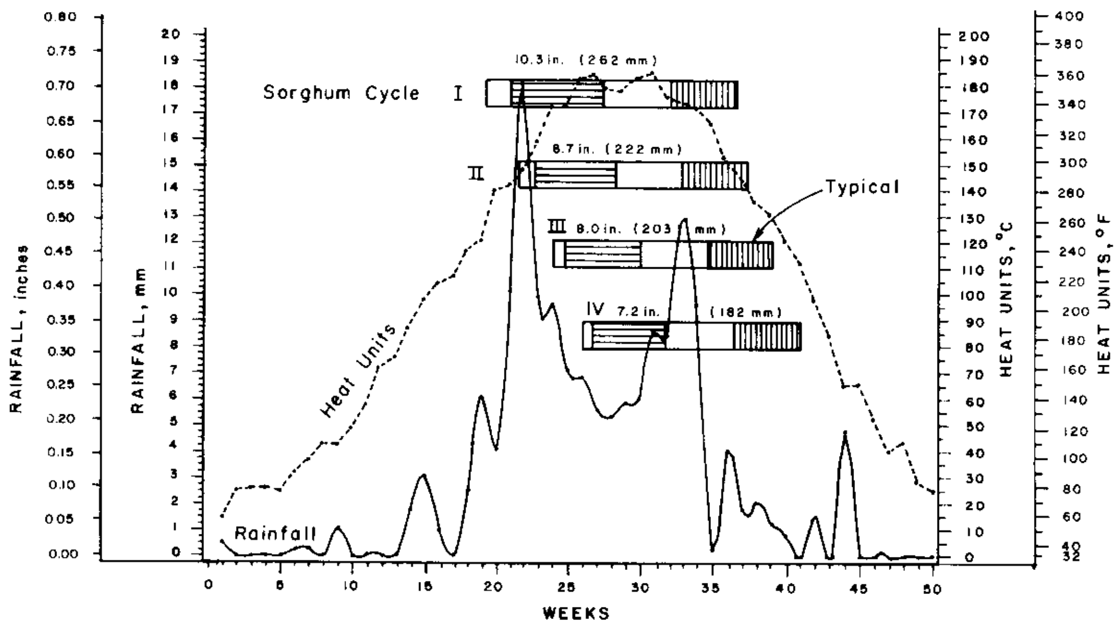

Figure VIII-6. Comparison of four alternate sorghum growth cycles with weekly precipitation and heat units above 32°F (0°C) exceeded in 50% of the years for Bushland, Texas (Week 0 = January 1). Median seasonal rainfall is shown above the boxes (Stewart and Burnett, 1985).

applied to plots to allow stress periods (determined by leaf water potential) of 0 to 56 days duration beginning at early boot, heading, or early grain filling. Grain yields were not significantly affected by 13-15 day periods of mild stress that began at early boot, at heading or at mid-grain filling (Table VIII-2). Grain yields were significantly reduced by more severe stress periods that continued for 27 days or longer (i.e. when two or more consecutive irrigations were missed), especially when the stress period began in early boot or heading stage. Longer stress periods of increasing severity (35-56 days) caused large grain yield reductions. When stress of 27 days or longer was initiated at early boot stage, both seed size and seed numbers were decreased. But only seed size was reduced when the 27+ day stress began at heading or later. Because most of the forage was produced by boot stage, forage yields were significantly reduced only when three or more irrigations were deleted (i.e. 35-56 day stress). The highest water use efficiencies of 258-295 pounds per acre-inch (1.14-1.30 kg/m^3) occurred with stress periods of about two weeks or less rather than longer stress periods.

Preplant Irrigation

Precipitation between fall harvest and spring increases soil water storage at planting. Additional rainfall of 1-2 inches (25-50 mm) just before planting is helpful to seedling emergence and stand establishment. Fortunately, the 30-day period with highest probability of rainfall in the Texas High Plains is mid-May to mid-June, which coincides with normal planting time for sorghums.

Preplant irrigations are often excessive with graded furrow systems, depending upon soil conditions, tillage depth, and length of furrows. The

Table VIII-2

Sorghum Stress Treatments, Resulting Yields and Seasonal Water Use Efficiencies (SWUE), Bushland, Texas (Eck and Musick, 1979)

Treatment No.	Stress Period		Number Irrigations	Water Applied, inches/yr	Grain Yield[1], lbs/acre	SWUE, lbs/ac-in
	Days	Growth Stages				
1	0	None	4	18.5	6,680a	258
2	14	Early boot to heading	3	15.4	6,235ab	274
3	28	Early boot to early grain filling	2	12.2	4,760c	245
4	14	Heading to early grain filling	3	15.4	6,700a	295
5	27	Heading to late grain filling	2	12.2	4,950c	254
6	13	Early-to-late grain filling	3	15.4	5,330ab	274
7	27	Early grain filling to maturity	3	15.4	5,850b	258
8	15	Mid grain filling to maturity	4	18.5	6,650ab	256
9	35	Early boot to mid-grain filling	2	12.2	3,830d	195
10	56	Early boot to maturity	0	5.9	3,100de	234
11	42	Early boot to late grain filling	1	9.1	3,010e	184

[1] Means followed by the same letter are not significantly different ($p<0.05$).

volume of water utilized in preplant irrigation could frequently be used more efficiently if divided into two seasonal irrigations after the crop is established.

Preplant irrigation of 8 inches (200 mm) or more (Unger and Allen, 1985) has become traditional practice. However, irrigation water use efficiency with grain sorghum was twice as great for seasonal irrigations yielding 420 pounds per acre-inch (1.85 kg/m^3) as for preplant irrigations yielding 206 pounds per acre-inch (0.91 kg/m^3) based on 8 years of data (Musick, 1984). Subsequent research determined that only 23-33% of preplant irrigation water can be accounted for in soil profile water storage at planting time (Allen and Musick, 1986), with the remainder lost to deep percolation and evaporation.

Eliminating the preplant irrigation increased irrigation water use efficiency for grain sorghum by 33-56 percent (Musick, 1985). Allen and Musick (1986) determined that eliminating the preplant irrigation at Bushland reduced sorghum grain yields by 6 percent, but increased seasonal water use efficiency by almost 15 percent and reduced irrigation water requirements by 43 percent.

Effect of Certain Cultural Practices

Seasonal water use efficiency of grain sorghum on the Texas High Plains was evaluated as a function of row spacing under limited irrigation (Musick and Dusek, 1969). Rainfall during the growing season was 5.7 to 8.0 inches (145 to 203 mm). Double-row sorghum with two 12-inch (0.3 m) rows on 40-inch (1 m) beds consistently increased yield over single-row sorghum for limited irrigation. The double row spacing caused a major increase in irrigation water use efficiency from 272 pounds per acre-inch

($1.20\ kg/m^3$) for single rows to 428 pounds per acre-inch ($1.89\ kg/m^3$) for double rows when a single 4-inch (100 mm) irrigation was applied at heading or at the milk stage of grain development. However, seasonal water use efficiency was only slightly higher for double rows as compared to single rows, producing about 280 pounds per acre-inch ($1.24\ kg/m^3$). The double-row spacing increased yields about 16.6 percent or 800 pounds per acre (897 kg/ha) over single 40-inch (1 m) rows at higher yield levels associated with well-timed irrigations. But, yield was not increased by double-row sorghum where plants were subjected to moisture stress.

It normally takes about 5 inches (125 mm) of preseason rainfall to end up with 1 inch (25 mm) of additional soil moisture at planting time (Musick and Stewart, 1980). This 20 percent efficiency is even lower than the typical 33 percent efficiency of storing preplant irrigation water, probably because it accumulated over a longer period of time with subsequently greater evaporation basis. Conservation tillage offers a good method for improving soil moisture storage, and eliminating or reducing preplant irrigation requirements for grain sorghum (Musick and Stewart, 1980; Unger and Allen, 1985).

Baumhardt et al. (1985) determined that no-tillage management of wheat residue during 11 months fallow increased soil water storage as compared to disk tillage and as a consequence increased dryland sorghum grain yields and seasonal water use efficiency. However, with limited irrigation, no-tillage did not significantly affect seasonal water use efficiency as compared to disk tillage. At Lubbock, grain sorghum yields were higher with no-tillage of wheat residue than with disk-tillage, both for dryland (17% increase) and irrigation (66 percent increase), although the irrigation result was for an unusually hot, dry year (Baumhardt et al., 1985). The associated water use efficiency values were not reported.

Based on 8 years of data, Unger and Allen (1985) obtained 44 percent higher dryland grain sorghum yields with no tillage than with disk tillage. Yields were as follows: no tillage--3,150 pounds per acre (3,530 kg/ha), and disk tillage--2,190 pounds per acre (2,455 kg/ha). For irrigated sorghum, grain yield averaged 4,540 pounds per acre (5,090 kg/ha) with no tillage and 3,640 pounds per acre (4,080 kg/ha) with disk tillage plots when 6-inches (150 mm) of irrigation water was applied in the growing season. And with 12 inches (300 mm) of irrigation water in the growing season, the yields were 5,760 pounds per acre (6,460 kg/ha) and 5,320 pounds per acre (5,960 kg/ha) for no tillage and disk tillage, respectively. Therefore, Unger and Allen (1,985) obtained higher yields from no tillage for dryland and two levels of limited irrigation.

Precipitation storage in a wheat/fallow/dryland sorghum rotation during 11-month fallow following wheat harvest was increased an average of 1.1 to 3.0 inches (27-75 mm) (Unger, 1978). Average precipitation storage efficiency ranged from 22.6 percent for no mulch to 46.2 percent for 10,700 pounds per acre (12,000 kg/ha) of residue. The highest mulch rates resulted in almost complete filling of the soil reservoir. As a consequence, yields in the subsequent sorghum grain crop increased as mulch rates increased, and compared to the no mulch treatment sorghum grain yields were more than doubled at the two highest residue levels of 7100 and 10,700 pounds per acre (8,000-12,000 kg/ha). Average seasonal water use efficiencies increased from 126 pounds per acre-inch (0.556 kg/m^3) with no mulch to 261 pounds per acre-inch (1.15 kg/m^3) with the highest mulch rate (Unger, 1978) while grain yields doubled from 1,590 to 3,560 pounds year (Baumhardt et al., 1985). The associated water use efficiency values were not reported.

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In a 3-year rotation involving irrigated wheat-dryland grain sorghum-dryland sunflowers, the no-tillage treatment resulted in the greatest soil water storage during fallow between wheat and sorghum (Unger, 1984). The next highest soil moisture storage values resulted from sweep tillage, followed by disk-, moldboard-, and rotary-tillage. Because of greater soil moisture storage, dryland sorghum on no-tillage plots experienced less water stress during low rainfall periods of the growing season and therefore produced higher grain yields than sorghum with other tillage methods.

Irrigation Rate vs. Cost

From field data on yield versus seasonal irrigation amount after a 5 inch (127 mm) preplant irrigation, Shipley and Regier (1975) developed an empirical equation that can be used to estimate the depth of seasonal irrigation water to apply (W, inches/year) for maximum profit at Etter:

$$W = 17.57 - \frac{Pw}{0.298\ Ps} \qquad \text{(VIII-1)}$$

Where Pw = price of water, \$/acre-inch

Ps = price of sorghum grain, \$/hundred lbs.

The total irrigation amounts (W) are tabulated in Table VIII-3. The calculations show that when the cost of water exceeds \$8.00 per acre-inch (\$0.078/m^3) and the price of sorghum is less than \$4.00 per cwt (\$0.088/kg), sorghum growers should apply less than 10 inches (250 mm) of seasonal irrigation water. The maximum amount applied should not exceed 13 inches per year (330 mm/yr) under present price/cost relationships for sorghum and water.

Corn

Irrigated corn acreage in the Texas High Plains was expanded from 50,000 acres (20,000 ha) in 1965 to a peak of 1.2 million acres (490,000 ha) in 1977 (Musick, 1984). This expansion paralled the adoption of center pivots and occurred during generally favorable rainfall years. However, the irrigated corn acreage declined to 557,000 acres (225,000 ha) in 1982.

Corn is normally planted in the Texas High Plains about a month earlier than sorghum, and grain matures at about the same time as sorghum (Musick, 1984). The earlier planting of corn as compared to sorghum allows more efficient use of the typical wet season in late May through June and promotes greater vegetative development (Musick, 1984). This extra rainfall (e.g. 20% in Table VII-4) can permit deleting one or perhaps two earlier season irrigations when above-average rainfall occurs. Stages of corn growth are: (1) vegetative growth, (2) flowering (tasseling, silking and pollination), (3) grain filling, and (4) ripening.

Corn roots can reach a depth of 80 inches (2 m) in deep soil, but 80% of the water uptake often occurs in the top 32-40 inches (0.8-1.0 m) depth

Table VIII-3

Estimated Inches of Seasonal Irrigation (W) to Obtain Maximum Profit Based on Data from Etter, Texas and Price Relationships for Water and Sorghum Grain (Based on Shipley and Regier, 1975)

Price of Sorghum Grain, $/100 lbs	Cost of Water, $/acre-inch				
	2	4	6	8	10
	----Seasonal Irrigation Water, inches-----				
2	14.2	10.8	10.1	4.1	0.8
3	15.3	13.1	10.9	8.6	6.4
4	15.9	14.2	12.5	10.9	9.2
5	16.2	14.9	13.5	12.2	10.9

Table VIII-4

Corn vs. Sorghum Yields and Water Use Efficiencies With Adequate Irrigation, 1975-78, Bushland, Texas (Musick, 1984)

Parameter	Corn	Sorghum	Corn, % Higher
1. Seasonal Water Use			
a. Irrigation, inches	19.0	16.4	15.8
b. Rainfall [1], inches	10.7	8.9	20.2
c. Soil Moisture Depletion, inches	0.6	2.1	--
d. Total Water Use, inches	30.3	27.4	10.6
2. Grain Yield (14% moisture), lbs/acre	8650	7060	22.5
3. Water Use Efficiency, lbs/acre-inch	288	258	11.6

[1] Higher rainfall for corn due to 3-week longer growing season.

(Hess and Hamon, 1985). Tolerable soil moisture depletion levels are about 40 percent during the establishment period (i.e. 60 percent available soil moisture level) and up to 65 percent depletion (35 percent ASM) during other growth stages except for the ripening period which can tolerate up to 80 percent depletion (20 percent ASM). Musick and Dusek (1980A) reported that extension of secondary nodal roots into moist subsoil is important for moderating the late afternoon stress in corn.

Corn has been found to be much more sensitive to water stress than grain sorghum and therefore requires a different water management strategy. Where water supply is limited, it may be advantageous to meet full water requirements on limited acreage to obtain high corn yields rather than spreading limited water over a larger area. By contrast, recommended strategy for irrigating grain sorghum with limited water which can include spreading the water over more areas.

Irrigation water management conditions for corn and sorghum were compared in a 4-year experiment at Bushland that involved water deficits during various growth stages (Musick, 1984). For adequate irrigation, corn required an average of 16 percent more irrigation water than sorghum, using 19.0 inches (483 m) and 16.4 inches (416 mm), respectively. Also, corn produced nearly 23 percent higher grain yields than sorghum at 8,650 vs. 7,060 pounds per acre (9,695 vs. 7,913 kg/ha) as shown in Table VIII-4. However, at lower irrigation levels of 12 to 16 inches per year (305-406 mm/yr) from 3 or 4 seasonal irrigations, sorghum out-yielded corn by as much as 50 percent (Figure VIII-7).

Musick (1984) used 30 years of daily rainfall and evaporation data for Bushland together with crop coefficient curves to simulate seasonal irrigation water requirements for corn and sorghum (1951-1980 seasons).

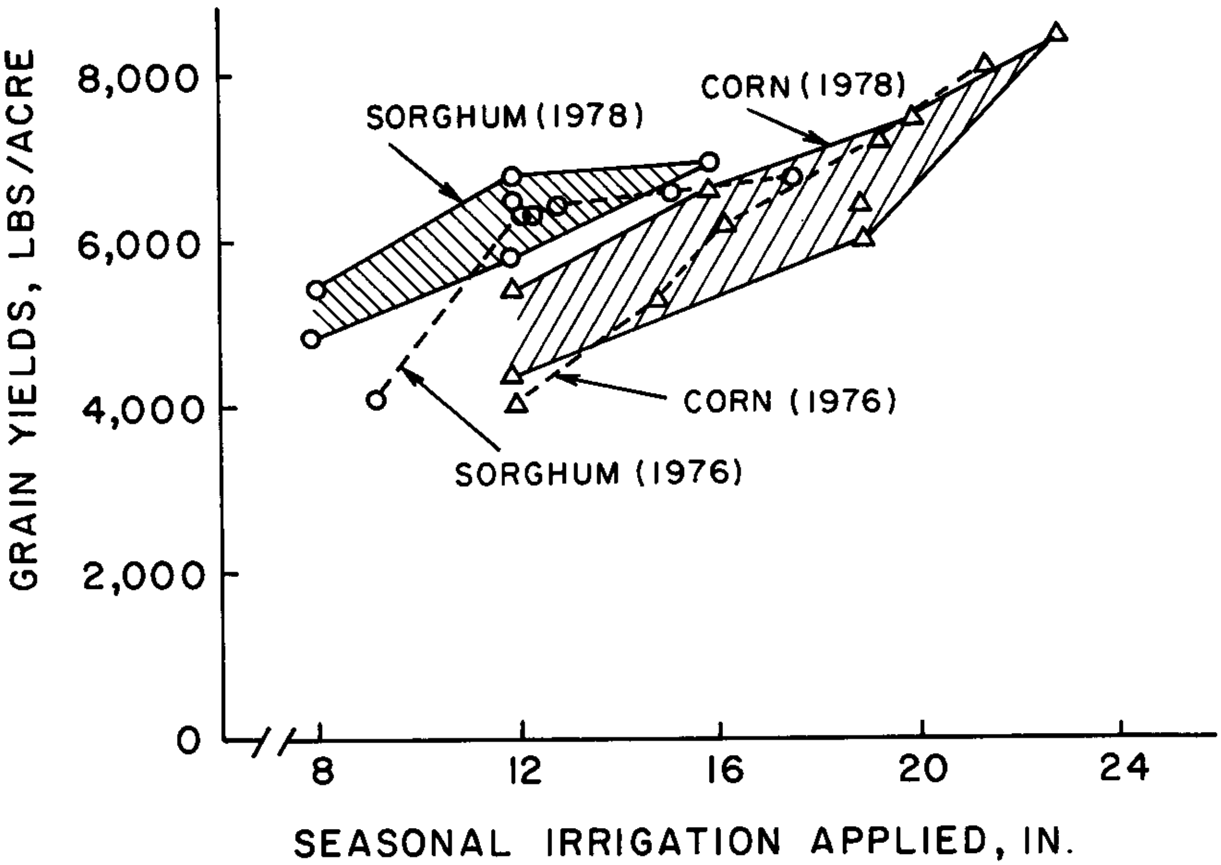

Figure VIII-7. Corn and sorghum yield response to seasonal irrigation treatments representing water application and stress periods during different development stages, Bushland, Texas, 1976 and 1978 (Musick, 1984).

During two major drought periods, irrigation water requirements were estimated to be about 12 inches (305 mm) higher for corn as shown in Table VIII-5. This difference is equivalent to about 3 seasonal irrigations. In near-normal seasons, water requirements were estimated at 4 inches (100 mm) higher for corn, which is equivalent to one graded-furrow irrigation. There were very few years in which the calculated number of seasonal furrow irrigations fell below 2 for sorghum or 3 for corn.

Water Use Efficiencies

Irrigated corn yields and water use efficiencies in response to seasonal irrigation amounts of 0-18.9 inches (0 to 480 mm) were determined for a 3-year period at Bushland (Musick and Dusek, 1980A). Corn grain yields were correlated with seasonal water use as shown in Figure VIII-8, which indicates that for the Southern Great Plains 13.6 inches (345 mm) of seasonal ET were needed to obtain the first increment of corn yield. Seasonal ET's for peak corn yields ranged from 26.3 to 31.1 inches (667-789 mm) for the 3-year study.

Seasonal water use efficiencies (SWUE) for corn receiving 6.3 inches (160 mm) or more of irrigation water ranged from 27 to 333 pounds per acre-inch (0.12 to 1.47 kg corn/m^3 water) (Musick and Dusek, 1980A). Low values of SWUE usually occurred when irrigation was limited during pollination and/or grain filling. In all 3 years, maximum yields were obtained from 15.75 inches (400 mm) of irrigation water applied in 5 irrigations (excluding preplant). For these full irrigation treatments, irrigation water use efficiency values were 540 to 614 pounds per acre-inch (2.38 to 2.71 kg/m^3) and SWUE values were 283 to 331 pounds per acre-inch (1.25-1.46 kg/m^3).

Table VIII-5

Calculated Average Seasonal Irrigation Water Requirements for Corn and Sorghum Based on Daily Rainfall and Pan Evaporation Data for 1951-1980 and Crop Coefficients (Musick, 1984)

Crop	Estimated Irrigation Water Requirement[1]	
	Normal or Wet Years, inches/year	Drought Years, inches/year
Corn	12-16	28-36
Sorghum grain	8-12	16-22
Difference	4	12-14

[1] Calculated for 80% application efficiency.

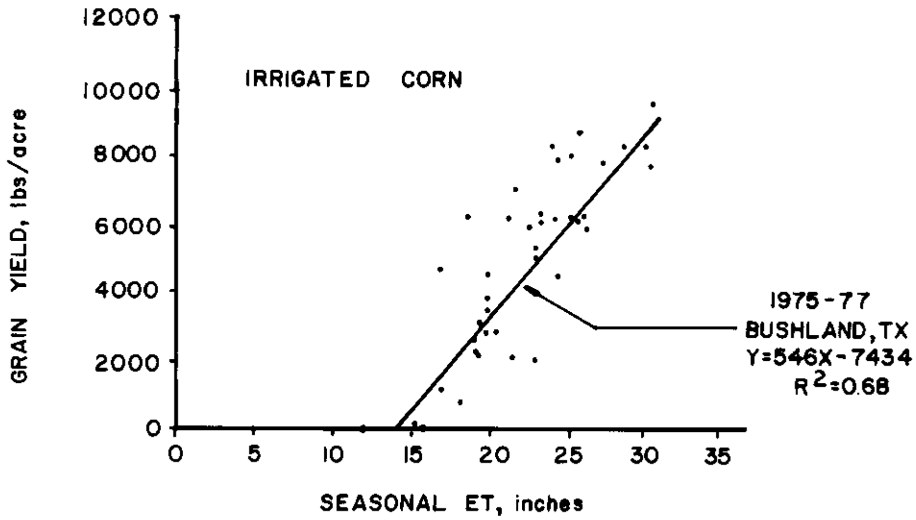

Figure VIII-8. Seasonal ET and grain yield relationship for irrigated corn, 1975-77, Bushland, Texas (Musick and Dusek, 1980A).

Response to Water Stress

Corn is less sensitive to water deficits during the vegetative growth and late grain filling stages, but irrigation practices should emphasize the prevention of water deficits during the flowering stage, followed in importance by the grain filling stage (Hess and Hamon, 1985). Water stress during pollination can have disastrous effects on corn grain yield (Eck, 1984). Decreased grain yield results mainly from reduced grain count per ear and is caused by water deficits during the flowering period which results in silk drying (Hess and Hammon, 1985). Water deficit during the grain filling stage reduces the kernel size. Musick (1987) identified three stages (in order of importance) in which corn seed numbers are reduced under moisture stress: (a) pollen shedding before silks emerge, i.e. reduced pollination; (b) continuation of stress past pollination and into grain development; and (c) reduced leaf area during major vegetative growth.

Westgate (1986) determined that corn grain numbers decreased from 500 per ear when water was abundant, with silk water potential at pollination of -3 to -5 bars (-300 to -500 kPa), to essentially zero grains per ear at a silk water potential of -12 (-1,200 kPa). This reduction in grain count is essentially irreversible. However, pollen dessication decreased the number of grains per ear by less than 10 percent for pollen water potentials ranging -2 to -12 cb (-200 to -1,200 kPa).

Moisture stress conditions severely restrict corn yields especially if they occur during tasseling and pollination associated with seed setting, as was illustrated by the 1980 drought season (Musick, 1984). Despite high water useage of 28 to 37 inches (710-940 mm), corn yields (Figure VIII-7) were much lower than for the near normal years depicted by Table VIII-4. In fact, when one or two successive irrigations were deleted during tasseling and pollination, grain yields were below 2,000 pounds per acre (2,240 kg/ha) and were likewise severely reduced when similar moisture stress was allowed during the seed filling stage.

Effect of Limited Irrigation

Limited irrigation, also known as deficit irrigation, is defined as applying less water than is needed to meet potential or maximum evapotranspiration by the crop. It is extensively practiced on drought tolerant crops of grain sorghum, wheat, and cotton. With these crops, water use efficiency is often increased with limited irrigation when significant seasonal rainfall is received (Eck, 1984).

Limited irrigations that involved stress during pollination greatly decreased corn yields (Musick and Dusek, 1980A). The vegetative growth period was the least sensitive to moisture-stress yield reductions and the grain filling stage was intermediate. These results were consistent with data from other western states. Maximum ET rates were 0.3 in/day (8 mm/day) under normal summer conditions and 0.4 in/day (10 mm/day) with hot, dry winds in mid-July, which may be the critical tasseling-silking period.

Musick and Dusek (1980A) concluded that limited irrigation of corn should not be practiced because large yield reduction will probably occur. Planned water deficits, if they are used, should be limited to the early vegetative stage well ahead of tasseling. Water stress during the late vegetative stage can reduce ear length and grain numbers. Where water supplies are limited, it would be better to reduce the area planted to corn to that which can be adequately watered. The remaining area can be planted to grain sorghum which takes 3/4 as much water as corn primarily because of a shorter growing season. Water deficits in corn may be easier to manage using sprinkler irrigation with frequent, light applications that distribute water deficits throughout the growing season.

Harbert et al. (1978) obtained the highest corn yield when it was irrigated twice with 3 inches (75 mm) per irrigation at 10-day intervals during each of the three growth stages: vegetative growth, tasseling through pollination, and grain filling. The middle stage was found to be the most critical in which sufficient irrigation water must be supplied to prevent 34 percent yield reduction. Applying only one irrigation of 3 inches (75 mm) total during the tasseling-pollination period resulted in half the yield from corn that received 6 seasonal irrigations of 3 inches (75 mm) each.

Wendt et al. (1977) examined the effects of using soil moisture tensions of 50 and 200 centibars (cb) (50-200 kPa) as determined with tensiometers, to schedule irrigations when total irrigation water applied ranged from 9.74 to 21.01 inches on corn at Halfway. Corn yields generally increased as irrigation level increased. Irrigation water use efficiencies were highest for the two lowest irrigation levels (512-652 pounds per acre-inch) and were least for intermediate and high irrigation levels (365-469 pounds per acre-inch). Every-furrow irrigation treatments out-yielded the comparable alternate-furrow irrigation treatments by 5 to 23 percent. Increasing the soil moisture tension level from 50 to 200 cb (50-200 kPa) pre-tasseling before applying irrigation water reduced yields by about 3 percent for both alternate and every furrow irrigation. Increasing soil moisture tension from 50 to 200 cb during or after tasseling reduced yields by 7 percent and 20 percent for alternate and every furrow irrigation, respectively. Statistically significant differences in yield did occur between the two soil moisture criteria when used after tasseling.

Lyle (1977) likewise studied irrigated corn at soil moisture tension values of 50 and 200 cb (50-200 kPa) using the LEPA system with 5 psi (35 kPa) pressure on drop tubes. Irrigation amounts were 0.6, 1.0, and 1.4 times ET accumulated since the last irrigation. Corn irrigated at 200 cb (200 kPa) throughout the growing season yielded 7-16 percent less grain than when the 50 cb level was used. There was no significant difference in corn yields between the 1.0 and 1.4 ET irrigation levels, but there was a statistically significant decrease in yield between the 1.0 ET and the 0.6 ET irrigation levels applied at 200 cb soil moisture tension. The highest yields were obtained with the higher water application with an overall yield range of 128-185 bushels per acre (8,030-11,600 kg/ha), but the opposite trend occurred with irrigation water use efficiencies (IWUE). Values of IWUE were about 10 percent higher for treatments involving the 200 cb soil moisture tension scheduling criteria as opposed to 50 cb. And, IWUE values increased with decreasing irrigation level in all cases; for example, for 50 cb tensiometer levels, irrigation water use efficiencies were 719, 502, and 409 pounds per acre-inch (3.17, 2.21, and 1.80 kg/m^3) for 0.6, 1.0, and 1.4 ET irrigation levels, respectively. These irrigation levels corresponded to 11.8, 18.5, and 25.4 inches (300, 470, and 645 mm) irrigation water per year.

A limited irrigation study of corn was conducted at Etter in 1973 by Shipley and Regier (1976) using 950 foot (290 m) long graded furrows at 40 inch (1 m) spacing on a Sherm silty clay loam. Pre-plant irrigation was not necessary, but all treatments received one 4-inch (100 mm) irrigation approximately 35-days after emergence. Thereafter, irrigations of 4-inches (100 m) each were applied to test plots at one, two, three or four of the following four growth stages:

1. Pre-tassel--55-60 days after emergence
2. Tassel--70-75 days after emergence
3. Blister--85-90 days after emergence
4. Milk--100-105 days after emergence.

Rainfall during the growing season totaled only 4.4 inches (112 mm). Irrigation treatments and yields averaged across three plant populations are shown in Table VIII-6 together with irrigation water use efficiencies. The yield data were low, probably because of relatively low rainfall and an early irrigation cutoff (Musick, 1987).

The maximum yield and water use efficiency within each grouping of total irrigation water applied (8, 12, or 16 inches) occurred when one of the irrigations was applied during the tasseling stage (Shipley and Regier, 1976). Incremental yield increases for each successive irrigation, based on the maximum response in Table VIII-6, were as follows:

Irrigation 2--30.0 bu/acre (1,880 kg/ha)

Irrigation 3--24.9 bu/acre (1,560 kg/ha)

Irrigation 4--15.2 bu/acre (954 kg/ha)

Irrigation 5--8.7 bu/acre (546 kg/ha)

These data reflect diminishing returns from each successive irrigation.

Shipley and Regier (1976) found that 14 days of plant water stress beginning at tasseling reduced yields by 39 percent as shown in Table VIII-6 (Treatment 14 vs. 16). By contrast, equivalent stress periods starting 14 days before or 14 days after tasseling (Treatments 15 and 13) or during the milk stage (Treatment 12) reduced yields by an average of 17

Table VIII-6

Summary of Irrigation Treatments and Corn Yield at Etter, Texas in 1973
(Shipley and Regier, 1976)

	Post-Emergence Irrigation Water Applied in Various Growth Stages, inches							
Treatment No.	Early Vegetative Growth, June 5 Day 35[1]	Pre-tassel, June 27 Day 57	Tassel, July 12 Day 72	Blister, July 26 Day 86	Milk, August 7 Day 98	Total Water Applied, inches	Average Corn Yield, bu/acre	IWUE, lbs/ ac-in
1	4					4	18.1	253
2	4	4				8	32.6	228
3	4		4			8	48.1	337
4	4			4		8	36.4	255
5	4				4	8	21.1	148
6	4	4	4			12	65.8	307
7	4	4		4		12	50.9	238
8	4	4			4	12	59.0	275
9	4		4	4		12	60.0	280
10	4		4		4	12	73.0	341
11	4			4	4	12	42.5	198
12	4	4	4	4		16	74.5	261
13	4	4	4		4	16	88.2	309
14	4	4		4	4	16	58.8	206
15	4		4	4	4	16	78.5	275
16	4	4	4	4	4	20	96.9	271

[1] No. days shown refer to time period following corn emergence.

percent from the peak yield of 96.9 bushel per acre (6,080 kg/ha) (Treatment 16).

Drought Stress and Nitrogen Fertilizer

Eck (1984) determined the effects of drought stress on yield and nitrogen requirement of corn grain at Bushland. Drought stress periods of approximately of 0, 2, and 4 weeks were applied during vegetative growth and grain filling stages, although adequate watering was provided during pollination. Annual nitrogen application rates were also varied from 0 to 312 lbs/acre (0 to 350 kg/ha). Data from 3 years indicated that 2 and 4 weeks of stress during vegetative growth reduced the yield of adequately fertilized corn (125-187 pounds per acre, or 140-210 kg N/ha) by 20-23 and 44-46 percent, respectively. A 2-week stress period had about the same effect whether applied during early vs. late vegetative growth stages. For these N-levels, seasonal water use efficiencies were highest for the adequately-watered corn at 234 to 245 lbs/acre-inch (1.03-1.08 kg/m^3) as compared to 220 lbs/acre-inch (0.97 kg/m^3) and 186-190 lbs/acre-inch (0.82-0.84 kg/m^3) for the 2- and 4-week vegetative growth period stresses, respectively. Moisture stress of 2 to 4 weeks during grain filling caused shortening of the grain-filling period. Corn yields were reduced an average of 1.2 percent for each day stress was imposed before normal maturity.

Center Pivots for Corn Irrigation

Most of the corn in the Texas High Plains is irrigated with center pivots. An irrigation application of 1.0 to 1.5 inches (25-38 mm) provides sufficient water for the crop until the machine can complete a circle (New, 1986). It also minimizes runoff and early season depletion of subsoil moisture that is ideally reserved for high crop water use periods. Application losses are normally less and crop response is better from a single 1.5 inch (38 mm) irrigation than from two 0.75 inch (19 mm) irrigations. However, smaller and more frequent irrigations may be appropriate in some cases with the LEPA irrigation system.

Water application rates per area of application are higher with LEPA irrigation because water is applied over a smaller area of soil (New, 1986). Runoff will likely occur, especially on clay soils, without furrow dikes, deep chiseling or other tillage practices to improve the water infiltration rate of the soil. Farming in a circle helps control runoff by holding water in the furrow and is strongly recommended for all center pivots. Circular farming is essential when growing corn irrigated with LEPA because the tall growth causes the LEPA bubblers to ride up in the corn stalks when dragged across straight rows.

Wheat

Wheat Production in the Texas High Plains

Wheat is a major drought tolerant crop on the Texas High Plains supporting the transition toward reduced water application and dryland agriculture (Musick and Walker, 1986). In recent years, there has been a small increase in acreage of irrigated winter wheat and cotton while a major decline has occurred in irrigated corn and sorghum, according to the 1984 irrigation inventory taken by the Soil Conservation Service--USDA (Musick and Walker, 1986). Irrigated winter wheat was produced on 1.10 million acres (446,800 ha) in a 41-county region overlying the Ogallala Aquifer, making it the second leading crop behind cotton in 1984. The average water application rate was estimated at 12.3 inches per year (313 mm) which was just over half the amount needed for corn and 12 percent less than grain sorghum. Higher yielding varieties and improved irrigation timing have helped maintain yields with less water.

A 31-county area in 1984 produced 893,500 acres (361,700 ha) of irrigated wheat with an average yield of 52.2 bushels per acre (3,510 kg/ha) (Musick et al., 1985). That same year, 1,288,800 acres (521,800 ha) of dryland wheat yielded 18.5 bushels per acre (1,240 kg/ha).

Wheat Yields and Water Use Efficiency

In research at Bushland, grain yields of tall wheat varieties during the 1950's and 60's were generally in the range of 50 to 60 bushels per acre (3,340-4,030 kg/ha) under adequate irrigation and seasonal water use efficiencies averaged 1.67 to 2.0 bushels per acre-inch (0.44-0.53 kg/m^3) (Musick, 1984). In research since 1978 with newer short (dwarf) wheat varieties, grain yields have been 83 to 106 bushels per acre (5580-7120 kg/ha) under adequate irrigation, with SWUE's averaging 3.3 bushels per acre-inch (0.87 kg/m^3) and IWUE's averaging 3.2 bushels per acre-inch (0.85 kg/m^3).

Seasonal water requirements for wheat when managed for grain production have remained the same at about 25 to 29 inches (635-737 mm). Water requirements would be about 4 inches (100 mm) higher (about one additional furrow irrigation) when seeded early for grazing plus grain production. Thus, average seasonal water use efficiencies have increased dramatically due to genetic improvement and better water management. Most of the water management research has been done with level borders or furrow irrigation.

In the Southern High Plains, most irrigated wheat is grown on beds and furrows with 40-inch (1 m) furrow spacing with two planted rows 10 inches (0.25 m) apart both in the furrow and on beds (Musick and Dusek, 1980B). These rows are planted with 8 or 10 inch (0.20-0.25 m) disk drills with the disks set facing the beds to maintain the bed/furrow shape. The active rooting depth for winter wheat in the High Plains for water extraction is 44 to 60 inches (1.1-1.5 m); however, more than 90 percent of the water uptake usually occurs in the top 36 inches (0.9 m) (Hess and Hamon, 1985). Allowable moisture depletion is about 60 percent of available soil moisture.

Wheat is planted in late September to mid-October. A later planting date may cause reduced yields due to lack of fall tillering and lower head numbers (Musick and Dusek, 1980B). Planting about one-month earlier (early September) will increase growth of vegetation and tillers for grazing (Undersander, 1980; Musick and Dusek, 1980B), but it also increases the cost inputs for water and fertilizer.

Limited Irrigation Strategy

The soil profile should be wet at planting or soon afterwards. Crop-residue management can assist in this regard. Loosening the soil by primary tillage causes preplant irrigations on a Pullman clay loam to be relatively large such as 6 to 8 inches (150-200 mm). Amounts are influenced by tillage depth (Unger and Allen, 1985).

Wheat development can be characterized in five stages: (a) vegetative growth, (b) floral initiation, (c) jointing, (d) boot, (e) heading (flowering), and (f) grain filling (Musick, 1984). Rapid growth occurs from spring tillering (mid-March) to physiological maturity (i.e. maximum grain weight) in mid to late June (Musick and Dusek, 1980B). Dry matter accumulation rates above the crown level were about twice as rapid with adequate water as compared with water stressed plants.

Overwatering during the spring vegetative period, when combined with relatively high nitrogen levels can cause lodging later, while mild water deficit during this stage has little adverse effect (Hess and Hamon, 1985). Irrigation should be scheduled to avoid water deficit during the flowering stage to prevent irreversible yield reductions. Water deficits during ripening have had little effect on yields unless hot, dry winds cause grain shriveling. According to Musick (1987), potential for lodging has been reduced with genetic improvement, permitting higher water and nitrogen rates for higher yields.

A successful limited irrigation strategy for winter wheat on Pullman clay loam has been to apply a fall irrigation to store soil moisture for plant growth and then irrigate again in April at the jointing stage with a second spring irrigation at the boot to early flowering (heading) stages (Musick, 1987). An additional irrigation may be required if the May rains fail to materialize during grain filling. Least efficient response to irrigation has occurred at grain filling except in a year with an unusually cool, wet spring followed by a dry grain filling period.

Wheat raised for both cattle grazing and grain requires nearly twice the applied nitrogen fertilizer and water to attain higher forage yields than wheat raised for grain alone (Undersander, 1980). This early planted wheat may require an irrigation for pre-plant or stand establishment and an additional fall irrigation of 3 to 4 inches (75-100 mm) during October or early November prior to cattle placement (Musick, 1984; Undersander, 1980). In a dry winter an additional irrigation of 3 to 4 inches (75-100 mm) may be needed before cattle are removed in March. Afterwards 2 to 4 such irrigations may be needed for grain production (Undersander, 1980).

Wheat Response to Irrigation Timing and Amount

Musick (1984) reported irrigation water use efficiencies (IWUE) obtained for winter wheat with either one, two or three 4-inch irrigations applied at jointing, late booting, or early-to-mid-grain filling stages (Figure VIII-9). The highest response was to the early season irrigation (jointing) with IWUE values of 4-6 bushels per acre-inch (1.1-1.6 kg/ha) as compared to 3-4 bushels per acre-inch (0.8-1.1 kg/m^3) for irrigation during the boot stage (Musick et al., 1985). Irrigation during jointing reduced tiller loss from moisture stress, increased number of heads and seeds per head. Late season irrigation (grain filling) was least efficient with IWUE values of 2.0-2.6 bushels per acre-inch (0.53-0.69 kg/m^3).

Musick et al. (1984) determined the effect of spring irrigation treatments with applications of 0-12 inches (0-305 mm) in level borders on grain yields and water use efficiency values for 3 years (1979-81). As shown in Table VIII-7, highest seasonal and irrigationwater use efficiencies occurred when one 4 inch (100 mm) irrigation was applied at either the boot or the jointing stage. Lowest water use efficiencies occurred when one 4-inch (100 mm) irrigation was applied at the grain fill stage, due partly to increased rainfall in late May through mid-July. Peak yields occurred with the highest level of irrigation (i.e. a 4 inch (100 mm) irrigation at each of three growth stages) which boosted yields by 71 percent over the control that received no spring irrigation. Seasonal water use was about 25-28 inches (650-700 mm) for wheat seeded around October 1 for grain production. Seasonal precipitation (October -early

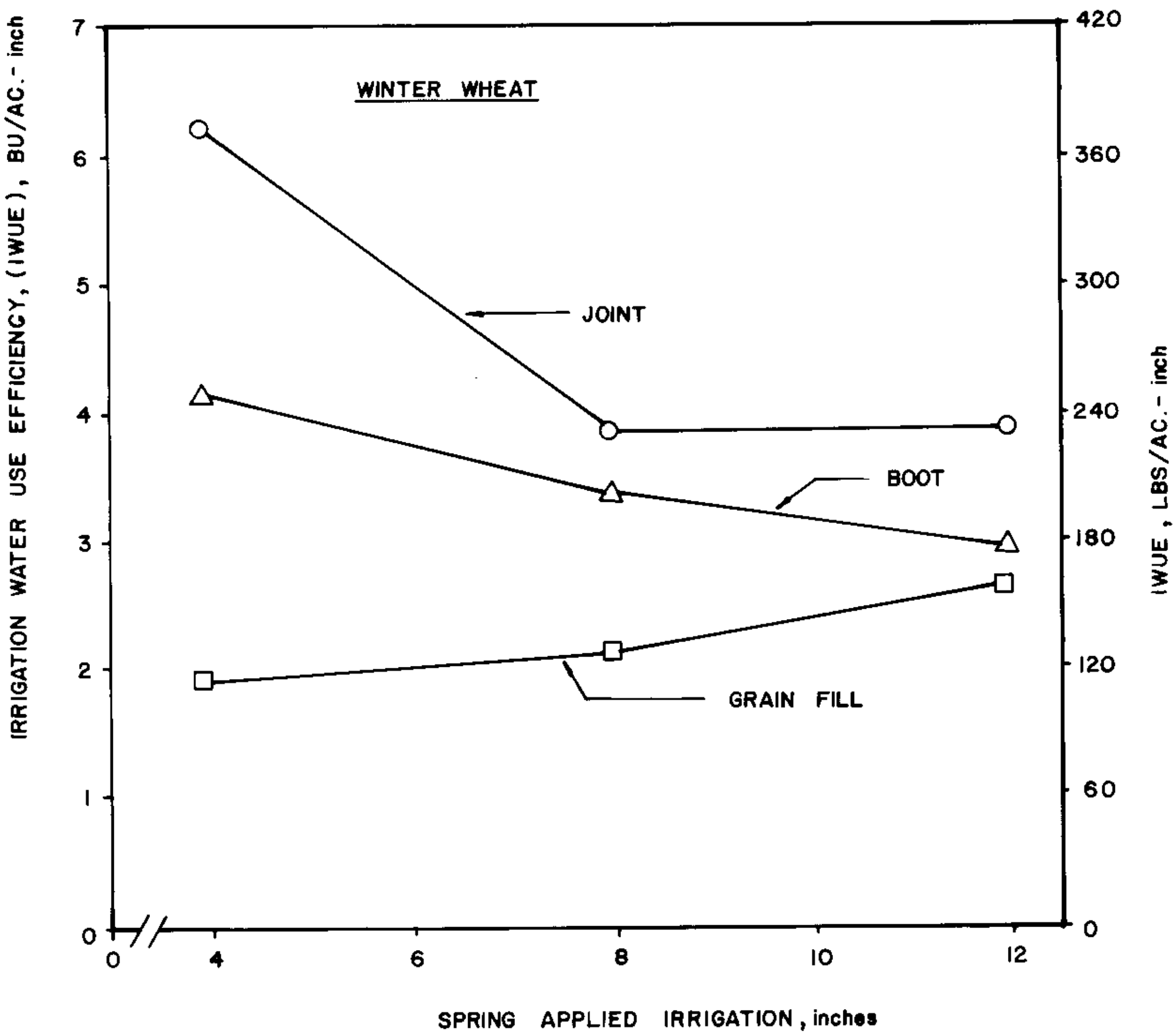

Figure VIII-9. Average 3-year spring irrigation water use efficiencies for applications at joint, late boot, and early to mid-grain fill for treatments that received one, two, or three applications, Bushland, Texas, 1979-81 (Musick, 1984).

Table VIII-7

Effect of Spring Irrigation Treatments[1] on Wheat Grain Yields and Water Use Efficiencies, Bushland, Texas 1979-81 (Musick et al., 1984)

Spring Irrigation Treatment (Stage of Growth)	Total Spring Irrigation inches	Seasonal Water Use (Ave.) inches	Grain Yields Ave/acre		Seasonal WUE Ave/ac-in.		Spring Irrigation WUE Ave/ac-in	
			lbs	bu	lbs	bu	lbs	bu
T-1 None	0	17.8	3,400	56.7	194	3.23	--	--
T-2 Joint (J)	4	21.8	4,335	72.3	205	3.41	249	4.14
T-3 Late Boot (B)	4	21.5	4,380	73.0	206	3.43	249	4.15
T-4 Grain Fill (GF)	4	23.2	3,845	64.1	191	3.19	115	1.92
T-5 J + B	8	26.0	5,040	84.0	197	3.29	209	3.48
T-6 J + GF	8	24.0	4,980	83.0	207	3.45	201	3.34
T-7 B + GF	8	23.7	4,665	77.8	200	3.34	172	2.87
T-8 J + B + GF	12	28.3	5,670	94.5	201	3.35	192	3.21
					200	3.34	198	3.30

[1] Preplant and emergence irrigation of 4.0-4.5 inches (100-115 mm) were applied to the 1980 crop only and a fall irrigation of 4.0 inches (100 mm) was applied only to the 1981 crop. Seasonal precipitation (October-early June) averaged 8.8 inches (223 mm) for 1979-81.

June) averaged 8.8 inches (223 mm) or about one-third of seasonal water use for high yielding wheat. This study shows that irrigation water can be used efficiently for wheat over a wide range of spring applications of from 4 to 12 inches (100-305 mm) where applications are reasonably well scheduled.

Undersander and Regier (1985) at Etter found that two irrigations at either boot and milk stages or at heading and milk stages tended to have the highest wheat yield response per acre-inch of irrigation water applied over the 3-year study (1975, 1983, 1984). Skipping an irrigation during milk to soft dough stages was detrimental to yield. Undersander and Regier (1985) observed little benefit from irrigation at jointing stage, which is the opposite of the 1978-84 research findings of Musick et al. (1985) who obtained maximum water use efficiencies by irrigating at jointing, followed in effectiveness by irrigation at the boot stage and at grain filling. This difference in response can perhaps be explained in part by the fact that each year of the Undersander and Regier (1985) study was a good wheat year with high yields from only a pre-irrigated treatment (Musick, 1987).

Research at the North Plains Research Station at Etter (Undersander, 1980) showed that one or two 4-inch irrigations applied in winter or spring provided the greatest response when irrigation was provided at the boot stage and least response at the milk stage (Table VIII-8). Each of the 1, 2, 3, or 4 seasonal irrigations when applied at appropriate growth stages increased wheat yields by successively smaller amounts (Table VIII-9).

When the value of the expected wheat yield is less than the cost of a 4-inch (100 mm) irrigation, that additional irrigation will not be profitable. For example, with wheat priced at \$2.00 per bushel (\$0.079/kg) and \$4 per acre-inch ($\$0.04/m^3$) water cost, Table VIII-9 shows

Table VIII-8

Wheat Yield Response to Winter and Spring Irrigation[1], 1977-78 (Undersander, 1980)

Treatment	Irrigation Date[2] 12/12	4/20-21 Boot	5/11-12 Bloom	5/25-26 Milk	Total Irrigation in.	Yield/ac bu	Yield/ac lbs	IWUE/ac-in lbs	IWUE/ac-in bu
1					8	35.0	2,100	263	4.38
2		X			12	52.4	3,140	262	4.37
3			X		12	41.4	2,480	207	3.45
4				X	12	37.8	2,270	189	3.15
5	X	X			16	63.5	3,810	238	3.97
6	X		X		16	48.3	2,900	181	3.02
7	X			X	16	42.7	2,560	160	2.67

[1] Wheat planted September 27, 1977, and watered up with 5 inch (125 mm) irrigation on September 28, and a 3 inch (75 mm) irrigation was applied October 3, 1977. Precipitation not reported.

[2] Irrigation of 4 inches (100 mm) applied at the specified times.

Table VIII-9

Wheat Yield Response to Irrigation Levels at North Plains Research Station, Etter, Texas (Undersander, 1980)

Number of 4-Inch Irrigation(s)	Yield Increase Per Irrigation bu/acre	lbs/acre	kg/ha
Preplant + 1	13.1	786	881
Preplant + 2	7.9	474	531
Preplant + 3	3.6	216	242
Preplant + 4	2.0	120	134

that the first seasonal irrigation will be profitable while the second irrigation will only break even, and succeeding irrigations are uneconomical.

Response of tall wheat with an averge height of 38 inches (960 mm) was compared to short wheat varieties that had an average height of 30 inches (770 mm) in terms of yield and water use efficiency (Musick et al., 1984). Higher yields were obtained with the short wheat varieties which increased water use efficiency for grain production. Average irrigation water use efficiency of 3.16 bushels per acre-inch (0.837 kg/m^3) was obtained from 40 treatment-years of tests with the short wheats, which represents a 52 percent increase over the average value from the 1955-70 experiments with tall wheat varieties. Applying water to wheat any time the plants begin to show stress symptoms usually resulted in increased yields and efficient use, (Musick et al., 1984). Dryland wheat had less than half the yield and seasonal water use efficiency values than irrigated wheat in these experiments, which indicates that limited irrigation is an efficient production mode for use of irrigation water in the High Plains.

Musick and Harman (1985) developed a regression equation that relates yield of a typical short, high yielding wheat (TAM 105) to irrigation water application (I, inches) as follows:

$$\text{Yield, bu/ac} = 27.0 + 4.39\ I - 0.075\ I^2 + 0.270\ N \qquad \text{(VIII-2)}$$

where N = actual rainfall as a percent of average rainfall between April 1 and June 15. For average rainfall conditions (N = 100), the above equation predicts yields of 53, 70, 84, 96, and 105 bushels per acre (3,560, 4,700, 5,650, 6,460, and 7,060 kg/ha) for 0, 4, 8, 12, and 16 inches (0, 100, 200, 300, and 406 mm) of irrigation water respectively. Accordingly, irrigation water use efficiencies were 4.0, 3.75, 3.5, and 3.2 bushels per acre-inch (1.1, 0.99, 0.93, and 0.85 kg/m^3), respectively, for the irrigation levels of 4, 8, 12, and 16 inches per year.

Howell et al. (1985) studied canopy temperatures of four winter wheat varieties (one tall and three short varieties) under four irrigation regimes. The crop water stress index (CWSI) was found to be linearly related to measured leaf water potential of winter wheat. These regression equations were useful for determining crop water stress and when to irrigate, while the soil water balance was used to determine the amount of irrigation water to apply.

Conservation Tillage and Water Management for Wheat

Continuous winter wheat receiving no-till or limited tillage at Bushland was successfully furrow-irrigated with slightly higher yields and water use efficiencies than clean tillage (Allen et al., 1976). Wheat was seeded with 5 drill rows per 40-inch (1 m) bed spacing, with two drill rows in each furrow. The number of irrigations for the 3-year test was as follows:

a. Dryland

b. Limited irrigation treatment: 0-1 fall and 1-3 spring irrigations, totaling 10-11 inches per year (250-280 mm)

c. Adequate irrigation treatment: 0-1 fall and 2-5 spring irrigations, totaling 14-15 inches per year (360-380 mm).

Highest yields were obtained with adequate irrigation regardless of tillage method. Both wheat yields and water use efficiencies increased as the amount of tillage decreased under both adequate and limited irrigation levels (Table VIII-10). The highest irrigation water use efficiencies were

Table VIII-10

Average Grain Yield and Irrigation Water Use Efficiency for No-Tillage and Limited Tillage Furrow Irrigation of Continuous Winter Wheat, Bushland, Texas, 1972-74[1] (Allen et al., 1976)

Treatment	Wheat Yield lbs/ac	Irrigation Water Intake inches	Irrigation Water Use Efficiency		
			lbs/ac-in.	bu/ac-in.	kg/m^3
1. Dryland	1,136	0	--	--	--
2. Adequate Irrigation					
a. No-Tillage	2,950a[2]	14.0b	130a	2.16a	0.574a
b. Limited Tillage	2,730ab	13.9b	115b	1.92b	0.508b
c. Clean Tillage	2,690ab	15.4a	102bc	1.70bc	0.450bc
3. Limited Irrigation					
a. No-Tillage	2,600b	10.5d	141a	2.35a	0.620a
b. Limited Tillage	2,480bc	10.4d	136a	2.27a	0.600a
c. Clean Tillage	2,330c	11.6c	105bc	1.75bc	0.462bc

[1] Seasonal precipitation for all treatments averaged 13.2 inches (335 mm) with a range of 8.7-16.3 inches (221-413 mm).

[2] Column values for individual years followed by the same letter are not significantly different at the 5 percent level.

obtained with no-till and limited tillage within the limited irrigation treatment. IWUE values for these two treatments were 2.35 and 2.2 bushels per acre-inch (0.62 and 0.60 kg/m^3), respectively. Despite the higher yields and IWUE values for no-till, Allen et al. (1976) recommended limited tillage as the most practical and dependable tillage treatment for continuous wheat. The yield increase with no-till was offset by additional cost of herbicide.

Wiese and Regier (1986) obtained average wheat yields of 54, 56, and 54 bushels per acre (3,630, 3,770, and 3,630 kg/ha), respectively, for conventional tillage, conventional furrow diked tillage, and no-tillage using short irrigation sets where furrow streams only advanced about two-thirds of the way down the fields. These experiments were conducted for 3 years in a wheat-sorghum-fallow rotation at Etter. Treatments with furrow diking during the 11-11½ month fallow period had the highest wheat yields. Across all tillage/precipitation management treatments, yields decreased an average of 29 percent from the upper 1/3 to the lower 1/3 of the field where irrigation water did not always reach. No-tillage and furrow diking were more beneficial for increasing yields at the lower half of the fields than at the upper ends. There were very large differences in fallow and seasonal precipitation among the 3 test years, and so irrigation amounts ranged from 8 to 13 inches (200-330 mm) among crop years.

Jones et al. (1985) compared stubble mulch (sweep) tillage with a no-till system on dryland wheat-sorghum-fallow rotation. A total no-till system decreased wheat yields about 3 bushels per acre (200 kg/ha) and increased sorghum yields about 500 pounds per acre (560 kg/ha). No-till fallow after wheat increased soil infiltration and reduced runoff. But no till with sorghum residues increased runoff due to formation of a thick soil crust, which was overcome by stubble mulch (sweep) tillage of sorghum residues rather than no-till. They determined that a minimum tillage system which uses no-till after wheat harvest and stubble mulch tillage after sorghum harvest is the most desirable tillage system.

Unger and Allen (1985) reported that a satisfactory no-tillage system has not been developed for continuous irrigated wheat. However, an increase of 270 pounds wheat per acre (303 kg/ha) has been obtained where no-tillage and limited tillage were alternately applied as compared to continuous clean-tillage.

Alternating Irrigated and Dryland Wheat

Unger (1977) hypothesized that alternating years of dryland and irrigated wheat would result in more efficient utilization of precipitation and irrigation water. In level border plots on Pullman clay loam, wheat was grown in alternating years with and without irrigation using disk, sweep or no-tillage. For comparison, wheat was also grown under continuous dryland with sweep tillage and with continuous irrigation using disk tillage. For the alternating-year irrigation/dryland system, dryland wheat yields and seasonal water use efficiencies were slightly greater than for the continuous dryland system (both treatments receiving sweep tillage). The yield increase was attributed to higher soil water content at planting after the irrigated year, although precipitation storage between crops was greater for the continuous dryland system. Soil water storage between crops of continuous winter wheat was less for higher antecedent soil water contents and vice versa for both dryland and irrigated plots.

Sweep and disk tillage resulted in highest average water use efficiency values for irrigated and dryland wheat (Unger, 1977). No tillage reduced the irrigated wheat yields and water use efficiencies by 4-9 percent as compared to sweep and disk tillage due to weeds and residue interference with planting, which suggested an annual rotation between no-tillage and limited tillage. The best tillage combination consisted of sweep tillage after irrigated wheat and disk or sweep tillage after the succeeding dryland wheat crop. These results are somewhat at variance with the work reported by Allen et al. (1976) that was discussed previously.

Irrigated wheat yields were not increased by using the alternating irrigated/dryland system (Unger, 1977). For dryland wheat, however, both yields and water use efficiencies were higher with the irrigated/dryland system than with continuous dryland farming. Therefore, the irrigated/dryland system averaged slightly higher overall wheat yields and soil water storage between crops as compared to continuously irrigated or continuous dryland wheat. Unger (1977) concluded that the alternating irrigated/dryland system offers potential for greater wheat production with more efficient water use than is possible where equal areas use a mixture of continuous irrigation and continuous dryland production.

Strip Tillage

Growing irrigated winter wheat and grain sorghum in alternating 80-inch (2 m) wide strips (i.e. two 40-inch (1 m) rows per strip) increased grain yields by 12 percent for wheat and 20 percent for sorghum (Musick and Dusek, 1972). Winter wheat was planted between double-bed sorghum strips as a means of staggering periods of major water uptake and irrigations. The method also made use of lateral movement of soil moisture on Pullman clay loam soils. Irrigations were applied one to four times per growing season in graded furrows. Spring irrigations were applied during vegetative growth, late boot to heading, and early grain filling stages. The highest yields were obtained with the largest number of irrigations and the strip planting system. The use of soil moisture stored in adjacent strips during the non-growth period increased grain yields on the adjacent limited irrigation plots. This system may have limited practical applicability because of weed control problems.

Crop Rotation Effects

A two-year crop rotation consisting of dryland sunflowers/irrigated wheat/fallow provides a shorter, more timely fallow period and thereby increases crop yields on a total area basis as compared to wheat/fallow or wheat/sorghum/fallow rotations (Unger, 1981). Four tillage treatments--tandem disking, sweep plowing, limited tillage, and no-tillage were applied during fallow after wheat. In 4 years, the no-till and limited tillage treatments resulted in statistically significant increases in soil water content during 10-month fallow prior to sunflower planting and consequently greater soil moisture at planting. Average gains in soil water content during fallow ranged from 1.5 inches (38 mm) with disk tillage to 2.8 inch (72 mm) with no-tillage. No-tillage produced slightly higher yields of sunflower seed, with 1,230 pounds per acre (1,380 kg/ha), while disk, sweep, and limited-tillage yields were lowest at 1,105-1,125 pounds per acre (1,240-1,260 kg/ha). Seasonal water use efficiency values were 84 pounds sunflowers per acre-inch (0.372 kg/m^3). Wheat could be planted at near the optimum date following harvest of early-planted sunflowers as compared to late planting necessitated after sorghum harvest. Wheat yields after sunflower harvest for 4 years averaged 3,720 pounds per acre (4,170 kg/ha). A direct comparison was made for 1977 and 1978 between irrigated wheat yields following sunflowers (3,030 pounds per acre, or 3,400 kg/ha) and following sorghum (1,980 pounds per acre, or 2,220 kg/ha) (Unger and Wiese, 1979). Wheat following sunflowers did not suffer adverse effects of delayed planting nor residual herbicides as was the case with wheat after sorghum.

Cotton

In 31 counties of the Southern High Plains from Amarillo to Odessa, irrigated cotton is grown on 1,649,000 acres (667,000 ha) which represents 78 percent of the state's total for irrigated cotton and almost 24 percent of the acreage for all irrigated crops within the state (TWDB, 1986). Proper water management for cotton is vitally important both regionally and statewide.

Cotton Growth Pattern

Cotton is a long-season crop, requiring a growing season from planting to harvest of 150 to 220 days, depending on the cultivar and climatic conditions (Jordan, 1983A). Cotton should be planted when the soil temperature exceeds 61°F (16°C) for 3 consecutive days. Cotton is ordinarily planted in early May (Jones et al., 1956). Vegetative and reproductive growth of cotton occurs in 9 stages, most of which overlap due to the indeterminant nature of cotton (Jordan, 1983A):

1. Seed germination
2. Emergence
3. Leaf and stem growth

4. Squaring
5. Flowering--first bloom and peak bloom
6. Boll development
7. Mature bolls
8. Boll dehiscence
9. Defoliation/desiccation.

These growth stages are illustrated in Figure VIII-10 for a typical irrigated cotton crop.

Dry cotton seeds may have a water potential of -1000 bars (-100,000 kPa) and soak up available soil water rapidly for the first two days after planting (Jordan, 1983A). Successful establishment requires growth of the tap root (radicle) to anchor the plant and provide an absorptive surface for nutrients and water. Growth of the radicle occurs faster initially and takes priority over elongation of the hypocotyl when water status of the seedling is low (Wanjura and Buxton, 1972). Following germination, the taproot elongates rapidly at 2 inches per day (50 mm/day) and reaches depths of 6-10 inches (0.15-0.25 m) before cotton emergence (Jordan, 1983A). The cotton stem (hypocotyl) emerges above the soil surface within 5-10 days. Germinated seedlings required 3, 7, and 13 days to emerge from 2 inches (50 mm) soil depth at soil water potentials of -0.3, -3.0, and -10.0 bars (-30, -300, and -1000 kPa), respectively (Wanjura and Buxton, 1972). Emergence may be delayed or prevented by soil crusting even with other factors favorable. Hypocotyl growth was greatly reduced while root growth was unaffected by soil strengths (impedence) of up to 3 bars (300 kPa) (Wanjura and Buxton, 1972). Compacted soil layers with high bulk density may reduce growth at the root tip so that cotton root extension

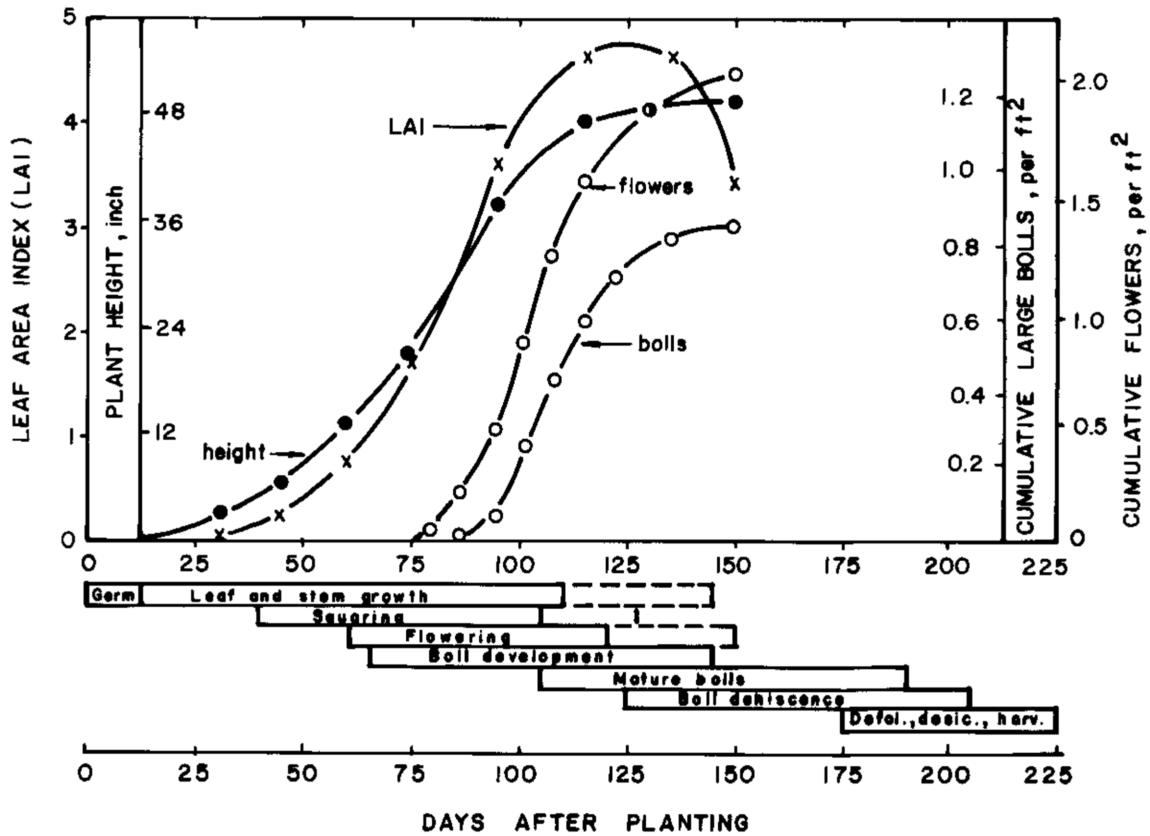

Figure VIII-10. Vegetative and reproductive growth for an irrigated cotton crop (upper) and a generalized crop growth stage calendar (lower) (Jordan, 1983A).

stops at around 14 bars (1400 kPa) soil strength (Davidson and Hammond, 1977).

At emergence, growth rates for both the stem and root are reduced by low water potentials; for example, at -10 bars (-1,000 kPa) soil water potential, growth rates were reduced 28 percent for the radicle and 87 percent for the hypocotyl (Wanjura and Buxton, 1972). Final rooting depth of cotton may exceed 6.5 feet (2 m); however, more than 90 percent of the total root dry matter may be found in the upper one foot (300 mm) of soil surface (Jordan, 1983A). Nevertheless, roots may proliferate in deeper layers as drying and subsequent root loss occurs near the soil surface. Deep roots are as effective for water uptake as surface roots, but they reduce soil water availability in the lower profile.

Once the cotyledons are carried above the soil surface, they expand rapidly and become photosynthetic (Jordan, 1983A). Leaves are formed on the main stem at the rate of one every 3-4 days depending on temperature. At the base of each leaf two buds are formed, from which either a vegetative or a fruiting branch will develop. Auxillary buds and additional branches subsequently form, and an excess of fruiting forms (squares) are produced.

Evapotranspiration and Water Deficits

The developing crop canopy plays an increasing role in the rate of evapotranspiration through its effects on net radiation, temperature and aerodynamics (Jordan, 1983A). When the canopy reaches a leaf area index (LAI) of 3.0, which is a practical upper limit for Texas High Plains cotton grown with limited water (Wendt, 1987), the actual evapotranspiration rate almost equals the potential evapotranspiration provided water is freely available to the roots. As available soil water is depleted below 65 to 75 percent, reduced water uptake causes the crop canopy to restrict actual evapotranspiration (ET_a). Actual water use (ETa) for an adequately irrigated Texas High Plains cotton crop is illustrated in Figure VIII-11. A lower peak would be expected for limited irrigation.

Each day, cotton plants develop internal water deficits in a diurnal pattern (Jordan, 1983A). Minimum leaf water potentials of -8 to -15 bars (-800 to -1,500 kPa) for moist soil and -15 to -30 bars (-1,500 to -3,000 kPa) for dry soil occur in early-afternoon. Maximum leaf water potentials occur before dawn and approach soil water potentials in the active root zone (e.g. greater than -2 bars (-200 kPa) for moist soils and -10 to -15 bars (-1,000 to -1,500 kPa) for dry soil). The diurnal water deficits are caused by atmospheric demand and the resistance to water flow from bulk soil to root, through the roots, stems and leaves and to the ambient air. Hence, the plant apparently adapts to a "baseline water deficit" in the approximate range of -8 to -15 bars (-800 to -1,500 kPa) of leaf water potential in the upper leaves at midday. General water deficits that are greater than normal are of most concern in water management. These deficits reduce the rate of cell expansion, thus limiting plant size and leaf growth.

Fruit Load Response to Water

Cotton has a high degree of reproductive flexibility, adjusting the fruit load rapidly in response to soil water supply and plant water deficits to maintain a delicate balance between vegetative and reproductive growth (Jordan, 1983A). Water deficits reduce the number of fruiting sites and increase the shedding of squares and young bolls.

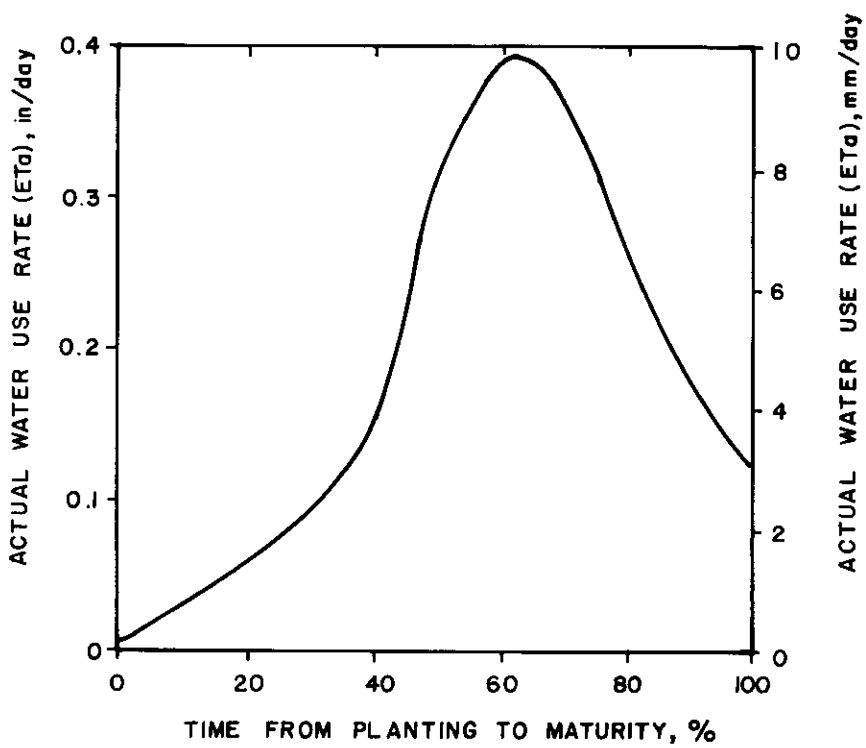

Figure VIII-11. Rates of actual soil water use (ETa) during the growing season for adequately irrigated cotton on the Texas High Plains (Thaxton and Swanson, 1956). From Jordan (1983A).

The production and retention of potential fruiting sites are sensitive to water supply (Jordan, 1983A). Once flowering has begun, flowers are produced on the same fruiting branch at 6-8 day intervals. After essentially a full canopy is developed (LAI = 3-5 for irrigated cotton), the high rate of water use coupled with low water holding capacity of some soils can create plant water deficits when irrigations are 10-14 days apart, with a subsequent shedding of squares and bolls. The fruiting forms closest to the main stem (first position) have a higher probability of retention than those at second, third or subsequent positions because of competition. Thus, dryland cotton which has fewer fruiting sites usually retains a higher percentage since more are first-position sites, as compared to a well-watered crop.

Rapid fruit shed can be caused by cloudy weather which disrupts the carbohydrate production (Jordan, 1983A). Water deficits between irrigations may cause fruit shed by altering the supply of nitrogen, carbohydrates, and phytohormones. During water deficit periods, cell division may continue but cell expansion is inhibited. Reapplication of water renews cell expansion with increased competition for nutrients so that some squares and bolls are shed. Similarly, excess rainfall or irrigation water can seriously reduce lint yield because excess vegetative growth is favored. Apparently, leaf expansion has a higher priority for available carbohydrates than boll growth under some circumstances.

Row Spacing and Plant Population

Current trends in cotton production are toward narrow rows of 10-30 inches (250-760 mm) and high plant populations (e.g. 200,000 cotton plants per acre). Plants adapted to narrow rows and high plant populations have fewer vegetative branches and fewer fruiting branches, reducing the number of bolls per plant (Jordan, 1983A). This helps achieve higher yield potential and shorter growing season, hence fewer irrigations are required and insect control costs may be reduced.

Total Water Use and Yields

Cotton lint yield is closely related to total water use, with maximum lint production occurring at about 27 inches (685 mm) of total water use under full-season irrigation (Jordan, 1983A). Approximately 13 inches (330 mm) of water may be required to obtain a measurable yield in irrigated cotton, while rank vegetative growth and reduced yield has resulted from more than 27 inches (685 mm) of total water use.

Different water use/yield relationships are obtained for dryland (rain-fed) than for irrigated cotton. Dryland lint yields are obviously lower but likewise have a much lower threshold above which measureable yields are produced (Jordan, 1983A). For example, 350 pounds lint (160 kg) was obtained from only 8 inches (200 mm) of total seasonal water use for a dryland crop grown in the Rolling Plains of Texas (Gerard et al., 1980).

Preplant Irrigation

Adequate levels of soil moisture at planting time are important to achieve early emergence, early fruit set, and high fruiting populations (Jordan, 1983A). A preplant irrigation of 3-6 inches (75-150 mm) increases the probabilities for doubling lint yield from 225 to 450 pounds per acre (250 to 500 kg/ha) without subsequent irrigation (Bilbro, 1974). Preplant irrigation can protect against crop failure in drought years.

Yield probabilities of cotton planted both early and late and grown with only a preplant irrigation or with no irrigation were determined from research at the Lubbock Experiment Station from 1960-1971 (Bilbro, 1974). As shown in Figure VIII-12, the expected average yields (with 50 percent probability) of early and late plantings of preplant-irrigated cotton were 473 and 449 pounds per acre (530 and 503 kg/ha), respectively. About 70 percent of the time the respective yields of early vs. late planted cotton will differ by less than 45 pounds per acre (50 kg/ha). Thus, the yield potential of preplant-irrigated cotton was not greatly affected by a wide range of planting dates. By contrast, the expected average yield (50 percent probability) of comparable dryland cotton based on data for 1914-1949 was only 219 pounds per acre (246 kg/ha). Besides increasing yields, the preplant irrigation significantly reduced yield variations. These results showed very clearly the value of a 3-6 inch (75-150 mm) preplant irrigation.

Irrigation Timing

The goal of limited irrigation of cotton should be to provide water during critical growth stages and allow greater deficits during less critical stages. Larger yield reductions are experienced when deficits occur during the peak flowering period as compared to either earlier or later in the flowering period (Jordan, 1983A). Timing and amount are extremely important, especially when irrigation water supply is not adequate to apply water at optimum times.

Stored soil moisture should be adequate to match crop water use. A small additional increment of available soil water may markedly increase cotton lint yields. Knowledge of water holding capacity of the soil and

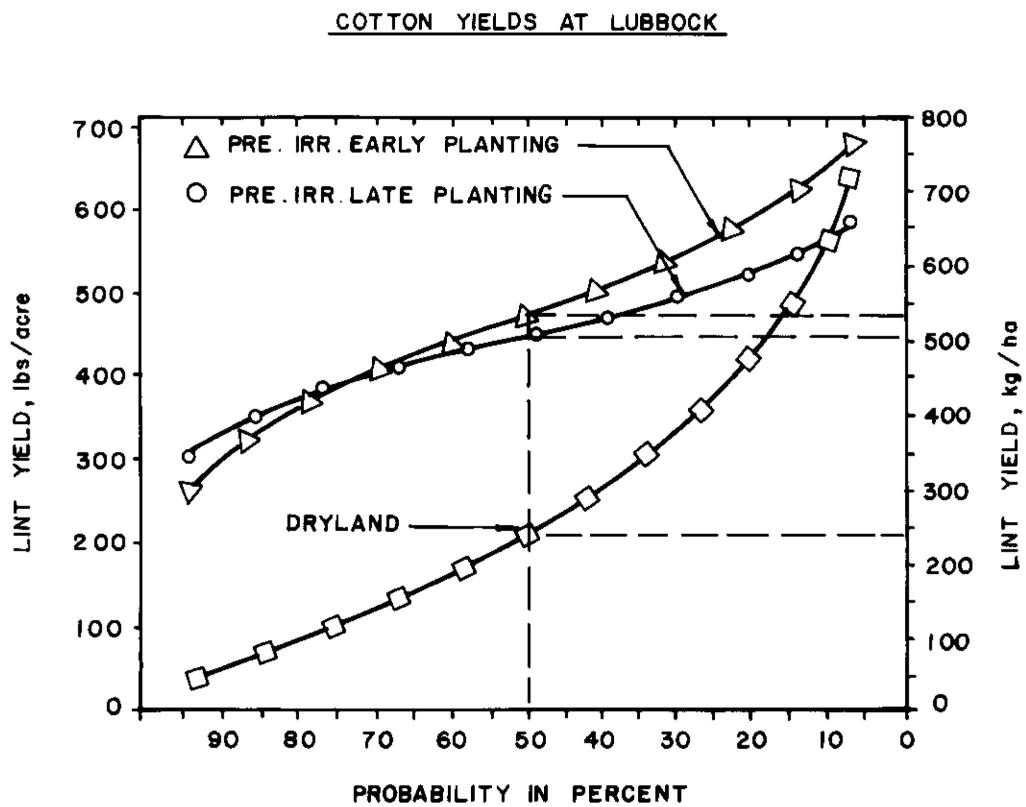

Figure VIII-12. Probability that lint yields of dryland and preplant irrigated cotton will be larger than given (Bilbro, 1972).

crop maturity enables producers to anticipate cut-off dates and save one or more irrigations.

Cotton is most responsive to water received from first bloom through peak bloom, but it has the ability to overcome moisture stress during early bloom (Lyle and Bordovsky, 1985). The importance of early fruit set to final yield is critical for areas where soil moisture may be short at mid-season (Jordan, 1983B). Although cotton can resume vegetative and reproductive growth following relief from water stress, if water deficits develop during peak fruiting, limited remaining growing season and higher insect potential may limit late-season attempts to recover from the water deficit.

Thaxton and Swanson (1956) determined that the most effective time to apply a single irrigation to cotton is just prior to peak bloom stage which occurs 20-35 days after most plants have reached first bloom. Proper irrigation timing to achieve high yield and water use efficiency is depicted in Figure VIII-13 for either one, two, three, or four seasonal irrigations (Newman, 1966 and 1967A). If rainfall does not materialize in the early growing season as expected, the first irrigation, or a single irrigation, should be applied prior to the first bloom. Assuming that soil moisture is adequate for germination and emergence, if producers can apply only one summer irrigation, they will obtain highest yields and water use efficiency when water is applied 20 to 30 days following bloom initiation. If limited to two irrigations, they should be applied at first bloom and at peak bloom about 30 days later. Recommended application times for 3 and 4 irrigations per season are shown in Figure VIII-13. Data from 9-years of research at Lubbock (1950-58) supported these recommendations. Longer

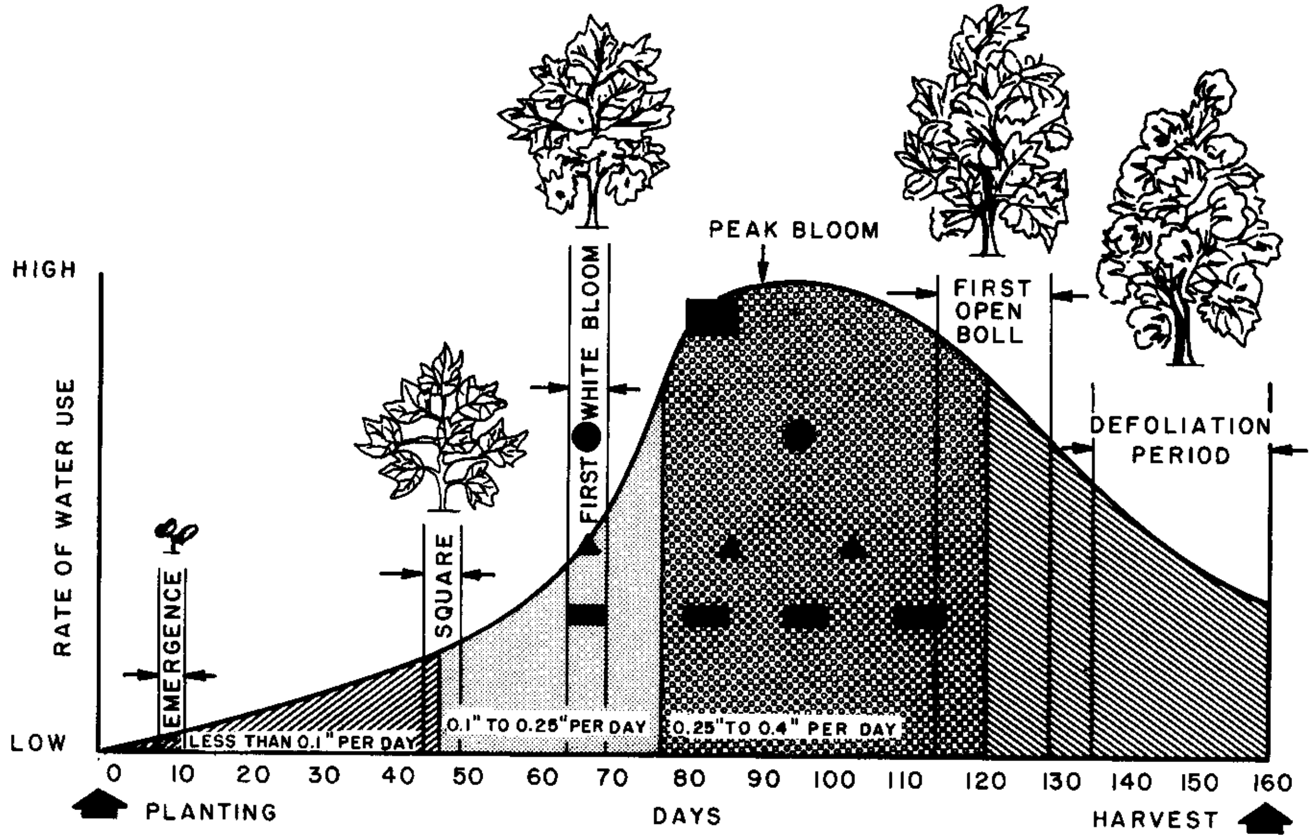

Figure VIII-13. Stages of plant growth and timing of irrigations for maximum yield and water use efficiency of cotton, assuming significant rainfall during the pre-bloom stage (Newman, 1966).

staple cotton can be adversely affected in terms of lint quality by irrigating before first bloom or too late in August (Newman, 1966).

Jones et al. (1956) recommended that farmers apply one or two preplant irrigations totaling 8 inches (200 mm) to wet the soil to 5 or 6 feet (1.5-1.8 m). Thereafter, they should apply two summer irrigations of about 4 inches (100 mm) each from first bloom (around mid-July) through mid-August. Irrigation water use efficiency values from this irrigation pattern on level furrows ranged from only 17-26 pounds per acre-inch (0.075-0.115 kg/m^3) for 1937-41 tests to a range of 18-31 pounds per acre-inch (0.079-0.137 kg/m^3) for experiments in 1950-54. In the latter experiments, 4 irrigations totaling 19.5 inches (495 mm) per year actually decreased yield as compared to 3 irrigations totaling nearly 16 inches (406 mm) per year. Maximum yield response and IWUE values were obtained from preplant (late April) followed by irrigation at peak bloom (early August). Moreover, irrigations in June were less efficient than those in July.

Skip-Row Planting

Skip-row planting of cotton leaves one or more fallow rows between two or more planted rows. The basic premise of skip-row planting is to store soil moisture in the fallow rows and increase the soil volume available for rooting and water extraction. It can be used both for dryland and limited irrigation of cotton (Lyle and Bordovsky, 1985). Weed control and furrow diking can be used to complement skip-row planting. The method may be useful under limited water situations to increase irrigation water use efficiency. When irrigation is used, one furrow is irrigated for two planted rows, thus reducing water applications, but the skipped fallow rows may increase soil evaporation after rainfall (Musick, 1987). Skip-row planted cotton must provide higher yields on a total-acre basis, higher water use efficiencies, or better quality lint to surpass solid planting (Lyle and Bordovsky, 1985).

Skip-row planting systems for dryland cotton have been evaluated on the Southern High Plains since 1923 (Newman, 1967B). These dryland tests showed that skip-row planting increased yields on the planted rows but did not increase average lint yields over solid-planted cotton on a total-acreage basis. Skip-row planting of cotton on dryland has produced acceptable yields with lower risk of complete crop failure than solid plantings (Jordan, 1983A).

At Lubbock, Newman (1967B) tested skip-row cotton using two 40-inch (1 m) row patterns (2 in/1 out and 2 in/2 out) versus solid planting. For all three planting systems, irrigation water was applied at 4 levels: dryland, one 4-inch (100 mm) preplant irrigation only, one 4-inch irrigation at peak bloom, and two 4-inch irrigations (preplant and peak bloom). Rainfall for the 3-year tests was below normal levels by 1.5 to 5.2 inches (38-132 mm) per year. For the preplant-only irrigation strategy, skip-row planted cotton yielded more than solid plantings. For the other three irrigation strategies, solid planted cotton out-yielded the skip-row cotton.

Solid-planted cotton produced significantly higher yields than both skip-row systems on a total-acre basis, with the 2 in/2 out system yielding the least (Newman, 1967B). There were also statistically significant differences in yields attributable to irrigation levels and timing. Average yields decreased in the following order: two 4-inch (100 mm) irrigations--356 pounds per acre (399 kg/ha); one 4-inch (100 mm) irrigation at peak bloom--296 pounds per acre(332 kg/ha); one 4-inch (100 mm) pre-plant irrigation--257 pounds per acre (288 kg/ha); and dryland--160 pounds per acre (179 kg/ha). (These data support earlier conclusions of Thaxton and Swanson (1956) that the time to apply a single irrigation is at peak bloom for solid planted cotton, but with preplant irrigation for skip-row cotton.)

Newman (1967B) obtained the highest irrigation water use efficiency of 51.8 pounds per acre-inch (0.228 kg/m^3) for the single peak-bloom irrigation for all three planting systems as shown in Table VIII-11. Averaged across all irrigation treatments, the 2 in/1 out skip-row pattern produced the highest irrigation water use efficiency of 48.8 pounds per acre-inch (0.215 kg/m^3). IWUE values were 21 and 51 percent higher for skip row cotton than for solid planted cotton.

Thus, skip-row planted cotton effectively utilized the extra soil moisture in fallow rows by producing more lint per planted row, but not enough to compensate for the area occupied by fallow rows (Newman, 1967B). As compared to solid planting, skip-row planting resulted in higher water use efficiency considering rainfall and precipitation on a planted-area basis but produced lower water use efficiency on a total-area basis.

Moisture Extraction vs. Irrigation Levels

Newman (1963) used a radioactive phosphorus tracer to determine cotton root growth under three levels of irrigation: preplant only (low); preplant plus one irrigation at peak bloom (medium); and preplant plus light summer irrigations each 7-10 days from "heavy square" stages through August 25 (high). Root development was similar for the 3 moisture levels until the mid-bloom stage, after which the low and medium irrigation levels produced additional root growth but the high moisture level did not. No

Table VIII-11

Irrigation Water Use Efficiency[1] (pounds per acre-inch) for Skip-Row and Solid Planted Cotton Under 3 Irrigation Strategies, Total-Acre Basis (Newman, 1967B)

Irrigation Treatment	Planting System			
	Solid	Skip-Row, 2 in/1 out	Skip-Row, 2 in/2 out	Mean
	---------IWUE, lbs/acre-inch----------			
Preplant Only (4 inches)	14.0	48.0	40.8	34.3
Peak Bloom Only (4 inches)	53.2	61.2	41.0	51.8
Preplant + Peak Bloom (8 inches)	29.5	37.1	35.5	34.0
Mean	32.2	48.8	39.1	40.0

[1] Averages for 3 years (1963-65)

roots were detected below 60 inches (1.5 m). A 2:1 ratio of root depth to plant height existed from emergence through the first bloom stage. At the 10-inch (250 mm) depth, roots extended laterally 30-inches (0.75 m) in both directions, as compared to 20 inches (0.5 m) laterally at a depth of 20-40 inches (0.5-1.0 m). These results suggest that no more than one row should be left fallow in skip-row patterns in order for cotton to effectively use the water stored beneath the non-planted rows.

Soil moisture response to cotton root extraction of water and to irrigation rates and frequencies is illustrated in Figure VIII-14 (Bilbro et al., 1960). The irrigation research was conducted on Pullman silty clay loam near Tulia, Texas using 4 irrigation levels: dryland (no irrigation), one 4.5 inch (114 mm) summer irrigation, two summer irrigations totalling 8.5 inches (216 mm), and five summer irrigations that totalled 14.0 inches (356 mm). At planting, the soil at 0-6 feet depth (0-1.8 m) was at field capacity, and subsequent increases in resistance of gypsum blocks were recorded weekly from 0, 9, 16, 29, 42, and 54 inches (0, 0.23, 0.41, 0.74, 1.07 and 1.37 m). Major reductions in soil moisture were indicated in the top 2.5 feet (0.76 m) in late July through mid-August for the 0, 1, and 2-irrigation treatments, and the wilting point was reached during this time despite a 2-inch (50 mm) rainfall. As the cotton root system developed and peak demands occurred, moisture was extracted from successively lower depths, which was similar to other experiments. However, at the 42-inch (1.07 m) depth, soil moisture remained at field capacity throughout the season, and only slight reductions in soil moisture were recorded during mid-August.

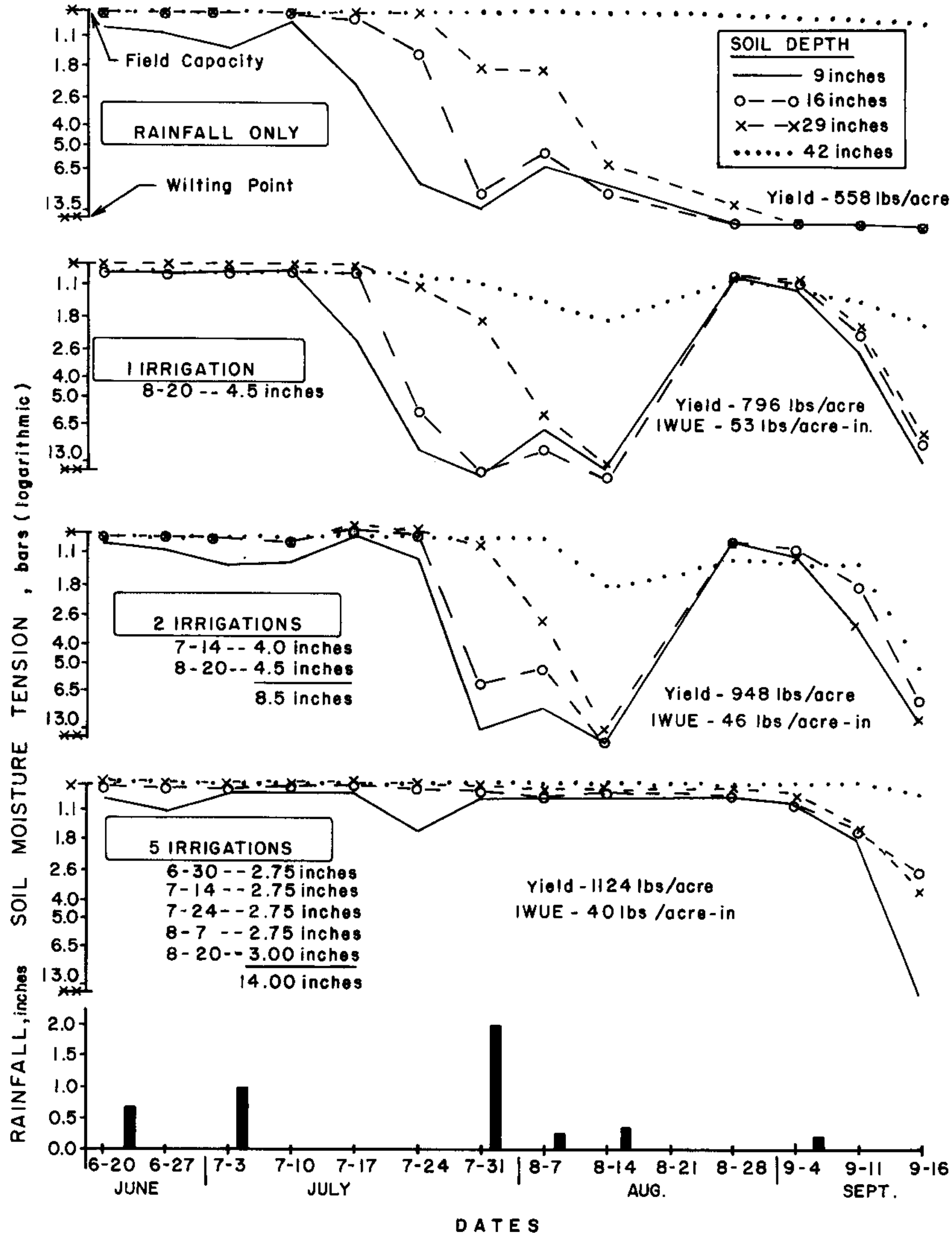

Figure VIII-14. Soil moisture tension (atmospheres) resulting from four irrigation levels for various soil depths and dates (Bilbro et al., 1960) (1 atm = 101 cb = 101 kPa).

Furrow Irrigation

Two furrow irrigations of cotton at Lubbock for 9 years (1950-58) produced the highest yield of 621 pounds per acre (696 kg/ha) (Newman, 1966 and 1967A). Ratios of yield to applied water (rainfall plus irrigation) of 26.1 pounds per acre-inch (0.115 kg/m^3) were highest when the two irrigations were applied at first bloom and peak bloom. Irrigation and rainfall amounts were not specified. Hence, the most effective irrigation period may last only 30 days for early maturing varieties or 50-60 days for late maturing varieties to correspond with fruiting patterns. With limited available water supplies, it can take more than 30 days in many cases to water a crop.

Newman (1966) obtained 7 percent lower cotton yields but 43 percent higher irrigation water use efficiency values using preplant irrigations of 4 inches (100 mm) rather than 8 inches (200 mm) from 2 years of research at Lubbock. Values of IWUE averaged 80 pounds per acre-inch (0.35 kg/m^3) for the 4-inch (100 mm) preplant treatments. The highest irigation water use efficiency value of 102 pounds lint per acre-inch (0.450 kg/m^3) was obtained with a 4-inch (100 mm) preplant irrigation followed by only one seasonal irrigation of 2 inches (50 mm) using alternate row irrigation. Thus, preplant irrigations usually should be limited to 4 inches (100 mm). Two seasonal irrigations (plus the preplant) always produced more cotton (17 percent average increase) than only one summer irrigation. The data showed that the size of preplant irrigation can be reduced especially when more than one summer irrigation is to be applied. Alternate furrow irrigation averaging 2 acre-inches per acre (50 mm) was more efficient with the same size furrow stream than every-furrow irrigation that averaged 4 acre-inch per acre (100 mm).

Cotton furrow irrigation studies were also conducted at Tulia on heavy-textured soils (Bilbro et al., 1960). Preplant irrigation was not used because the soil was initially at field capacity. Summer rainfall totaled 4.7 inches (119 mm). Five light furrow irrigations of 2.75 inches (70 mm) each produced 1,124 pounds cotton per acre (1,260 kg/ha) and maintained high soil moisture contents throughout the season. The IWUE was 40 pounds per acre-inch (0.18 kg/m^3) as shown in Figure VIII-14. One 4.5 inch (114 mm) summer irrigation on August 20 yielded 19 percent less than two 4.0-4.5 inch (100-114 mm) irrigations. But the single irrigation gave the highest IWUE value--53 vs. 46 pounds per acre-inch (0.23 vs 0.20 kg/m^3).

Alternate furrow irrigation, with furrow diking in the non-irrigated rows, offers excellent opportunity to capture significant amounts of rainfall (Lyle and Bordovsky, 1985). Significant cotton yield increases have been obtained by adding furrow diking to alternate furrow irrigation.

Sprinkler Irrigation of Cotton

Sprinkler-irrigated cotton on Amarillo loamy fine sand at Lubbock produced peak irrigation water use efficiency of 71.7 pounds per acre-inch (0.316 kg/m^3) from only one 3-inch (75 mm) sprinkler application in addition to 13.8 inches (350 mm) of seasonal rainfall (Newman, 1966 and 1967A). Yields increased but values of IWUE decreased as 3-inch (75 mm) sprinkler irrigations were increased from one to four in number. For example, with 4 irrigations of 3-inches (75 mm) each (i.e. 25.8 inches (655 mm) total irrigation plus rainfall), lint yields reached 888 pounds per acre-inch (3.92 kg/m^3) while irrigation water use efficiency decreased to

32.8 pounds per acre-inch (0.155 kg/m^3), which is probably sufficient to justify the cost of irrigation.

Land Leveling

Early irrigation water management guidelines for cotton in the High Plains (Jones et al., 1956) recommended that land should be leveled and floated. Crop residue management was also recognized as a major component of managing soil moisture, tilth, and wind erosion for cotton production.

An advantage of land leveling is improved control of furrow irrigation water and precipitation. Land leveling eliminated precipitation runoff and increased cotton yields on Amarillo loamy fine sand at the South Plains Research and Extension Center at Lubbock (Newman et al., 1966). Runoff averaged 1.5 and 2.5 inches (38 and 64 mm) per year from 0.5 percent slopes for irrigated and dryland cotton fields, respectively. Runoff averaged 2.1 and 3.6 inches (53 and 91 mm) per year from 1.2 percent furrow slopes. When land was leveled to 0.0 percent slope, runoff was eliminated from both dryland and irrigated furrows. Cotton yields under limited irrigation (preplant plus one summer irrigation at peak bloom) were increased by 85, 115, 121, and 134 pounds per acre (95, 129, 136, and 150 kg/ha) as slopes were reduced from 0.2, 0.5, 0.9 and 1.2 percent down to 0.0 percent. Dryland yields responded to an even greater extent (Newman et al., 1966).

It should be noted, however, that for Pullman clay loam, land leveling can create wet soil conditions and drainage problems from May-June rainfall and could adversely affect cotton (Musick, 1987).

Crop Rotations Involving Cotton

Results from a 36-year study of dryland cotton on the Texas High Plains showed similar lint yields from continuous cotton vs. a cotton-sorghum rotation (Bloodworth, 1955). However, the cotton-sorghum rotation did increase sorghum grain yields in comparison with continuous sorghum.

A 6-year crop rotation experiment involving cotton was conducted at Halfway from 1976-81 to evaluate the effect of rotation patterns on soil moisture utilization and crop yields (Bordovsky et al., 1979, 1980 and 1981). Two rotations were studied:

a. grain sorghum and cotton--2 year rotation;

b. grain sorghum, wheat fallow, and cotton--3 years.

Grain sorghum received 2 to 6 irrigations (including preplant) totaling 6.6-20.5 inches (168-521 mm) while cotton received 1 to 3 irrigations totaling 4.1-9.2 inches (104-234 mm). The 3-crop rotation maintained higher soil moisture contents throughout the second growing season than the sorghum/cotton rotation due to 3 inches (75 mm) more soil moisture stored in the prior summer fallow period. Nevertheless, higher cotton yields were not obtained possibly due to good summer rainfall. By contrast, during a dry growing season, cotton yields were significantly higher and soil moisture not significantly different between the rotations.

For most years, there was no significant difference in cotton yields following summer fallow in the 3-crop rotation versus following grain sorghum in the 2-crop rotation (Bordovsky et al., 1979, 1980, 1981). In normal or high rainfall years, the sorghum/wheat/fallow/cotton rotation resulted in higher soil moisture contents than the sorghum/cotton rotation but failed to convert this advantage into higher yields for either cotton or grain sorghum. In dry growing seasons, cotton yields were higher in only one year but soil moisture was generally not significantly higher. The preplant irrigation and perhaps tillage practices essentially eliminated differences in soil moisture status.

IWUE and Fertilizer Rates

Peak irrigation water use efficiency of 58 pounds per acre-inch (0.26 kg/m^3) was obtained with one 4-inch (100 mm) summer water application in cotton irrigation research on Amarillo loam soil near Lubbock (Newman, 1962). Yield results averaged over 4 cotton varieties and 5 N-P fertilizer levels are plotted in Figure VIII-15 together with irrigation water use efficiencies. The one summer irrigation (at peak bloom) produced over 93 percent as much cotton as two August irrigations (at early and late bloom stages), which produced the highest yields of 934 pounds per acre (1,050 kg/ha) and crop value considering quality classifications. For all irrigation treatments, peak yields were obtained at the highest fertilizer rate of 120-60-0 pounds per acre (134-67-0 kg/ha) and two summer irrigations totaling 7 inches (180 mm). For dryland the highest yields occurred at only 40-60-0 pounds per acre (45-67-0 kg/ha) fertilizer rate.

LEPA and Drip Irrigation of Cotton

The increased control gained with LEPA and drip systems allows higher precision of irrigation water management. Cotton was irrigated with light, frequent applications at Halfway using the LEPA and drip irrigation systems (Bordovsky et al., 1985). Irrigation amounts were 0.4, 0.7. 1.0, and 1.3 times the estimated ET rate, and these amounts were applied at intervals of 2, 4 and 12 days. Total irrigation amounts were 1.6, 2.8, 4.0 and 5.2 inches (41, 71, 102, and 132 mm) beginning on August 8 and ending

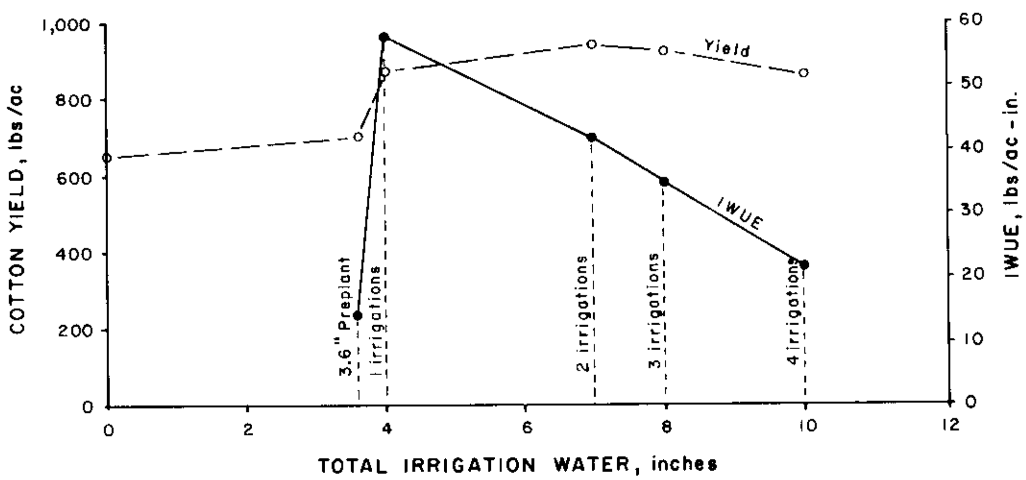

Figure VIII-15. Lint cotton yield and irrigation water use efficiency (IWUE) for 6 irrigation levels, averaged over 4 varieties and 5 fertilizer levels, Texas Agricultural Experiment Station, Lubbock, 1961 (Newman, 1962).

on August 28, which represents very low irrigation rates for High Plains cotton. Both the LEPA and drip systems delivered water to alternate furrows.

Yield results for the various irrigation treatments are summarized in Table VIII-12 (Bordovsky et al, 1985). There were no differences in cotton yields between systems when all treatments were averaged. However, LEPA gave statistically higher yields than drip at the 0.7 ET quantity (2.8 inches, or 71 mm) and also at the 2-day frequency. Cotton responded best to drip irrigation applied on a 4-day frequency and a quantity which equaled the estimated ET (4.0 inches, or 102 mm). Much higher yields were obtained from both systems at the higher irrigation frequencies (2 and 4-day) as compared to the 12-day frequency, which is more commonly-used for furrow irrigation.

For both LEPA and drip systems, the ratio of lint yield to irrigation water applied (i.e. an unadjusted "irrigation water use efficiency" function) was highest for the lowest irrigation amounts and increased with increasing application amount (Bordovsky et al., 1985). This lint yield/water use efficiency ratio was calculated (Table VIII-12) and averaged 217 pounds per acre-inch (0.957 kg/m^3) for LEPA-applied water and 210 pounds per acre-inch (0.926 kg/m^3) for drip irrigated cotton. These values do not represent a true IWUE and appear high because they do not include a comparison with a dryland control treatment, but are nevertheless useful for comparing the effects of treatments within this experiment. Dryland yields based on surrounding croplands and rainfall data were estimated at 350 pounds per acre (392 kg/ha) (Bordovsky, 1986). Using this value as an assumed dryland yield basis, IWUE values were estimated at 93 pounds per acre-inch (0.41 kg/m^3) for all LEPA treatments

Table VIII-12

Cotton Yield Response and Unadjusted Irrigation Water Use Efficiency[1] for LEPA vs. Drip Irrigation Systems for Various Irrigation Frequencies and Amounts, Texas Agricultural Experiment Station, Halfway, Texas, 1985. (Bordvosky et al., 1985)

		LEPA System				Drip System			
		Frequency, Days				Frequency, Days			
Irrigation (X ET)	Amount inches	2	4	12	Mean	2	4	12	Mean
		A. Cotton Yield:							
0.4	1.6	628	519	549	565	527	533	544	535
0.7	2.8	727	617	651	665[2]	585	643	581	603[2]
1.0	4.0	717	697	560	658	647	755	571	658
1.3	5.2	639	620	526	595	737	651	576	655
Frequency Mean		678[3]	613	572		624[3]	645	568	
System Mean					621				612
		B. Unadjusted Irri. Water Use Effic., lbs lint/ac-in:							
0.4	1.6	393	324	343	353	329	333	340	334
0.7	2.8	260	220	233	238	209	230	208	215
1.0	4.0	179	174	140	165	162	189	143	165
1.3	5.2	123	119	101	114	142	125	111	126
Frequency Mean		239	209	204		211	219	201	
System Mean					217				210

[1] Irrigation water use efficiency was not adjusted for dryland yield estimated at 350 lbs/acre.

[2] Means for irrigation amounts are significantly different between systems (0.05).

[3] Frequency means are significantly different between systems (0.05).

and 86 pounds per acre-inch (0.38 kg/m^3) for all drip treatments. These IWUE values are several times higher than obtained by Jones et al. (1956) for research in the 1937-54 time period. However, they are comparable to IWUE values obtained by Newman (1966) with limited furrow irrigation.

North Plains Cotton

Although cotton has not been grown to a significant extent north of Amarillo, Experiment Station research has been conducted recently at Etter to ascertain if new short-season varieties can be economically adapted to these cooler conditions (Regier, 1986). The research involved 12 early-maturing cotton varieties, 3 planting dates and 3 irrigation levels. Regier (1986) determined that planting date did not affect yield, but it did influence cotton quality. The irrigation study showed that a preplant irrigation followed by one or two 4-inch (100 mm) irrigations during the growing season did not increase yield over a preplant irrigation only. Seasonal irrigation did increase plant growth, which increased staple length but reduced gin turnout. It was concluded that cotton is a potentially economical crop on the Northern High Plains because of its yield potential in water-limiting situations. Yields appeared to be high enough to be profitable in spite of weather hazards such as cold temperatures and herbicide damage.

Summary of Crop Water Requirements and Efficiencies

The four main crops produced in the Texas High Plains have been the subject of water management research for several decades by the Texas Agricultural Experiment Station and the USDA/Agricultural Research Service. As expected, experimental results for yield and water use efficiency have varied for these four major crops, but many common principles have likewise emerged from this research. Definite improvements in water use efficiency have been made, and widespread application of these management principles is underway. Limited irrigation is now being widely practiced on drought tolerant crops that take advantage of expected rainfall. A 30-day period of fairly reliable rainfall occurs from mid-May through mid-June which coincides with sorghum and cotton planting and follows typical corn planting.

Sorghum has good ability to adjust to water stress. Sorghum grain requires 13 to 24 inches (330-610 mm) of seasonal water use (evapotranspiration) from precipitation, stored soil moisture and irrigation to achieve 3,000 to 6,700 pounds per acre (3,400-7,500 kg/ha) of grain sorghum yield. Dryland sorghum yields average about 1,600 pounds per acre (1,800 kg/ha), and yields up to 3,000 pounds per acre (3,400 kg/ha) are not uncommon. Peak water use rate is about 0.30 inches per day (7.6 mm/day). Irrigations should be timed to avoid water stress during periods of peak water use--boot, heading and flowering stages--to achieve reasonably good yields and maximum irrigation water use efficiency. Two well-timed seasonal irrigations of 4 inches (100 mm) per irrigation or the equivalent are adequate in normal years for good yields of medium maturity hybrids. Preplant irrigation is often not needed, and the same amount of water may be more efficiently used if applied at later stages of crop growth especially for conventional graded furrow irrigation systems. Conservation tillage can reduce the need for preplant irrigation of sorghum through improved soil moisture storage. Irrigation water use efficiencies may reach 400-500 pounds per acre-inch (1.8-2.2 kg/m^3) with limited but well-timed irrigations as compared to about 200-250 pounds per acre-inch

($0.88-1.10 kg/m^3$) with adequate irrigation. Saving irrigation water by withholding a 4-inch (100 mm) irrigation reduces sorghum grain yields by only about 10 percent during the early 6-8 leaf stage but by almost 50 percent if withheld at the heading and bloom stage.

Corn is much more sensitive to water stress than sorghum, wheat or cotton. Corn is planted earlier than sorghum which typically allows more efficient use of the May-June wet season than for sorghum. However, early planting dates required for corn increases the need for preplant irrigation for stand establishment. Moisture stress caused by low soil water availability or hot, dry conditions during the flowering (tasseling, silking and pollination) stage can severely restrict corn yield. Preplant irrigation is often necessary, and 3 or 4 seasonal irrigations of 4-inch (100 mm) each are essential for high corn yields in most years in the Texas High Plains. Drought seasons require one or two additional irrigations. Reduced irrigation of corn has generally resulted in significant yield decreases. Irrigation water use efficiency values are usually 250-450 pounds per acre-inch ($1.1-2.0 kg/m^3$) with adequate irrigation, although peak IWUE values of 500 pounds per acre-inch ($2.2 kg/m^3$) or more have been obtained with limited irrigation in good rainfall seasons. Center pivot irrigation allows frequent irrigations of 1 to 1.5 inches (25-38 mm) during peak water use periods on corn. The total seasonal water use (ET) for corn to achieve any grain yield is about 13 inches (330 mm), while seasonal ET's for peak yields are around 28-32 inches per year (710-810 mm). Peak ET rates are 0.3-0.4 inches per day (8-10 mm/day), depending upon weather conditions. Planned water deficits into the stress range are feasible only on soils with moderate to high water storage and during the early vegetative or grain ripening stages. Reduced acreage, rather than reduced irrigation, offers the primary way to adjust corn irrigation to limited water supplies.

Winter wheat is a major drought tolerant crop with a 9-month growing season. Wheat grows vegetatively during the drier fall to early spring period and develops grain during a period of increasing spring rainfall. Wheat is normally planted around October 1 and requires available soil moisture for germination and early growth, plus perhaps one late fall irrigation followed by 2 to 3 spring irrigations for good production. About one additional early irrigation (and additional applied fertilizer) is needed for early planted wheat that is grazed and also managed for grain production. Seasonal water use is around 26 to 28 inches (660-710 mm) for wheat (grain only) yielding 4,700-5,800 pounds per acre, or 85-100 bushels per acre (5,270-6,500 kg/ha). The highest yield response to irrigation usually occurs during jointing and boot stages (a relatively low rainfall period), during which irrigation water use efficiency values of about 230 pounds per acre-inch (1.0 kg/m^3) are realized from a 4 inch (100 mm) irrigation. Spring irrigations totaling 4 to 12 inches (100-305 mm) have resulted in good irrigation water use efficiencies above 170 pounds per acre-inch (0.75 kg/m^3). The least efficient irrigation is during grain filling, where IWUE values have been less than 115 pounds per acre-inch (0.51 kg/m^3), and is associated with increased rainfall. Short wheat varieties in recent tests have exhibited 50 percent higher irrigation water use efficiency values than tall wheat varieties in earlier tests. Wheat yields have been increased in some experiments using no-till, limited tillage, or furrow diking as compared to conventional tillage.

Cotton is a drought-tolerant long-season crop that lends itself to limited irrigation despite a somewhat complicated pattern of water use, deficits, and application. Cotton is the major irrigated crop on the Texas

High Plains and is second to wheat in dryland production acreage. Widespread production under limited irrigation has major impact on water demands and the state's water budget. Production, placement, and retention of fruiting sites are sensitive to soil water status. Early fruit set is important. Under dryland conditions, expected lint yields are in the range of 250 to 300 pounds per acre (280-336 kg/ha). Cotton requires over 13 inches (330 mm) of seasonal water use to produce good yields, and maximum yields occur at about 27 inches (685 mm) of seasonal water use. High water levels can decrease lint yield through excessive vegetative development and fall immaturity. A preplant irrigation of 4-inches (100 mm) is usually advantageous especially if spring rainfall is not excessive, but heavier preplant irrigations are not warranted. Cotton has the ability to overcome moisture stress at most growth stages, but the growing season length may not accomodate late-season regrowth. The most critical period for irrigation is early to mid-bloom. If available, a second irrigation should be applied at peak to late bloom. The irrigation cut off date for cotton is mid- to late August. For irrigated cotton, yield results generally favor narrow-row with high plant populations. Irrigation water use efficiencies for cotton have ranged from as little as 20-30 pounds per acre-inch (0.09-0.13 kg/m^3) for full irrigation to as high as 80-100 pounds per acre-inch (0.35-0.44 kg/m^3) for two well-timed furrow irrigations (preplant and peak bloom) in some experiments. A reasonable target for limited furrow irrigation appears to be 50 pounds per acre-inch (0.22 kg/m^3). Cotton irrigated with LEPA and drip systems produced around 90 pounds lint per acre-inch (0.40 kg/m^3). Land leveling on slopes of 0.5 percent or greater have increased yields by more than 100 pounds lint per acre (110 kg/m^3) for both furrow irrigated and dryland cotton.

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CHAPTER IX

SUMMARY OF SYSTEMS AND PRACTICES FOR CROP WATER MANAGEMENT

Systems and practices that can contribute to improved water management for both dryland and irrigated crops in the Texas High Plains have been discussed in earlier chapters. The water use patterns, seasonal requirements, and critical application periods for sorghum, wheat, corn and cotton in relation to irrigation water use efficiency were reviewed in the immediately preceeding chapter largely without regard to soil characteristics. The wide range of soils used for irrigated and dryland farming in the region can greatly affect decisions regarding systems, cultural practices, water application rates and timing. With the wide array of possible water management systems and practices that have been tested and placed in use, it is important for farmers and their professional advisors to maintain perspectives as to the applicability of each methodology.

Table IX-1 shows a proposed listing of practices that should be considered in managing irrigation water on field row crops, cereal crops, and vegetables on the Texas High Plains. These practices are summarized according to precipitation harvesting (including many cultural practices), irrigation systems and methods, and irrigation scheduling techniques. The relative importance or applicability of each practice is rated as high (H), medium (M), low (L) or not applicable (blank). The ratings vary greatly depending upon type of crop and general soil texture. The information in Table IX-1 can furnish needed perspective in considering innovations and research findings as a guide to possible adoption.

Table IX-1

Guide to Recommended Irrigation Water Management Methods For Texas High Plains

Recommended Water Management Practices	Field Row Crops (Cotton, Sorghum, Corn) Soil Type[1]			Cereal Crops (Wheat, Barley, etc.) Soil Type			Vegetables Soil Type		
	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
1. <u>Precipitation Harvesting</u>									
a. Soil Modification									
(1) Furrow Diking	M[2]	H	H				M	H	H
(2) Chiseling	L	H	H						
(3) Terracing Steep Slopes	M	L	L		M	M			
b. Cultural Practices									
(1) Crop Rotation	M	M	M	L	L	L	M	M	M
(2) Conservation Tillage/Residue Mgmt.	M	H	H	M	H	H			
(3) Weed Control	H	H	H	H	H	H	H	H	H
c. Controlled Soil Moisture									
(1) Soil Moisture Sensing or Measurement	M	M	M	M	M	M	H	H	H
(2) Restricted Late & Early Season Irri.	H	H	H						
(3) Utilization of Rainfall Probability Data	M	M	M	M	M	M			
2. <u>Irrigation Methods</u>									
a. Furrow Irrigation									
(1) Alternate Row Irrigation		H	H						
(2) Surge Flow		H	M		L	L		M	M
(3) Tail Water Recycle	L	M	H	L	M	H	L	M	H
b. LEPA (Linear & Center Pivot Configuration)									
(1) Alternate Row Watering	H	H	H						
(2) Furrow Diking	H	H	H				H	H	H
(3) Chemigation Capability	H	H	H	H	H	H	H	H	H
3. <u>Irrigation Scheduling</u>									
a. ET Accounting	H	H	H	H	H	H	H	H	H
b. Soil Moisture Sensing or Measurement	H	H	H	H	H	H	H	H	H
c. Water Balance Calculation	H	H	H	H	H	H	H	H	H
d. Crop Modeling	M	M	M	L	L	L	M	M	M

[1] Soil Type: Light textured--sands and loam sands; Medium textured--fine sandy loams and loams; Heavy textured--clay loams and clays.

[2] Code:

H = Highly Important Practice
M = Moderately Important
L = Low Importance
Blank = Not applicable

APPENDIX A

SELECTED CONVERSION FACTORS

APPENDIX A

Selected Conversion Factors

English to Metric	Metric to English
a. Yield:	
1 lb/ac = 1.120 kg/ha	1 kg/ha = 0.8922 lbs/ac
1 lb/ac = 0.00112 Mg/ha	1 Mg/ha = 892.2 lbs/ac
1 bu/ac = 62.73 kg/ha (corn)	1 kg/ha = 0.01594 bu/ac (corn)
1 bu/ac = 67.26 kg/ha (wheat)	1 kg/ha = 0.01488 bu/ac (wheat)
b. Irrigation Water Use Efficiency:	
1 lb/ac-in. = 0.004410 kg/m^3	1 kg/m^3 = 226.7 lb/ac-in.
1 lb/ac-in. = 0.04410 kg/ha-mm	1 kg/ha-mm = 22.67 lb/ac-in.
1 bu/ac-in. = 0.247 kg/m^3 (corn)	1 kg/m^3 = 4.05 bu/ac-in. (corn)
1 bu/ac-in. = 0.2646 kg/m^3 (wheat)	1 kg/m^3 = 3.78 bu/ac-in. (wheat)
c. Water Volume:	
1 ac-in. = 10.28 ha-mm	1 ha-mm = 0.0973 ac-in.
1 ac-in. = 102.8 m^3	1 m^3 = 0.00973 ac-in.
1 in. = 25.4 mm	1 mm = 0.03937 in.
1 ac-ft = 1,233 m^3	1 m^3 = 0.000811 ac-ft.
1 MAF = 1.233 km^3	1 km^3 = 0.811 million ac-ft (MAF)
d. Pressure/Tension:	
1 psi = 6.9 kPa	1 kPa = 0.145 psi
1 bar = 10,200 kg/m^2 = 100 kPa	1 kg/m^2 = 9.8 x 10^{-5} bars
1 centibar (cb) = 1 kPa	1 kPa = 1 cb
e. Pumping Rate:	
1 gpm = 0.0631 L/s	1 L/s = 15.9 gpm
f. Soil Bulk Density:	
1 lb/ft^3 = 0.0160 Mg/m^3	1 Mg/m^3 = 62.45 lb/ft^3

English to English	Metric to Metric
1 bu/ac = 56 lbs/ac (corn)	1 ha-mm = 10 m^3
1 bu/ac = 60 lbs/ac (wheat)	1 metric ton (mt) = 1 Mg
1 ac-in = 27,154 gal	
= 3,630 ft^3	
1 bar = 14.5 lbs/in^2 (psi)	
1 psi = 0.0690 bars = 69 cb	
1 atmosphere = 14.7 psi	
1 atmosphere = 1.013 bars	
1 bar = 0.9869 atmosphere	