Major advances in irrigation in the groundwater region of the High Plains began in Texas in the late 1930s. Its evolution followed the technological development of rotary well-drilling, deep well turbine pumps, right-angle gear drives, improved internal combustion engines and electric motors, and widespread availability of natural gas and electricity for pumping energy. Major drought and the availability of development capital through the Reconstruction Finance Corporation stimulated the initial expansion of irrigation; favorable crop prices and a widespread drought in the 1950s accelerated it after World War II. Initially, expansion of groundwater-based irrigation centered on graded furrow systems on extensive areas of favorable soils having relatively flat slopes. Most of the changes that followed have been associated with the introduction of new technologies.

Furrow irrigation developed using unlined ditches for on-farm distribution and siphon tubes for furrow application. Underground concrete pipelines came into use in the 1950s and plastic underground pipe in the late 1960s. The replacement of unlined ditches with underground pipe coincided with the adoption of aluminum gated pipe application to furrows. As plastics were improved to resist degradation by sunlight, plastic gated pipe was introduced in the late 1970s. Graded furrow application resulted in substantial end-of-furrow tailwater runoff, and reuse systems came into general service in the early 1960s. Tailwater runoff was collected in temporary field ditches, drained by gravity to a holding pond, and then was pumped through a pipeline, supplementing the supply from wells. Pipeline distribution from wells to the point of application and reuse systems for irrigation runoff resulted in relatively high-field application efficiencies.

The availability of affordable equipment such as aluminum pipe and impact sprinkler heads stimulated the expansion of sprinkler irrigation
after World War II. Later, development of center pivot sprinkler systems allowed irrigation of soils having rough terrain and sandy textures unsuited for surface irrigation. The major introduction of sprinkler irrigation occurred during the 1950s and 1960s; its expansion on the Texas High Plains illustrates the trend in center pivot sprinkler irrigation (Figure 6.1).

We shall examine the technologies of furrow and sprinkler irrigation, the two systems widely used in the groundwater-irrigated areas of the High Plains. With furrow irrigation, we emphasize technologies for limiting excessive water intake as well as management and efficient use of limited water supplies. These technologies include wide-spaced and alternate-furrow irrigation, tractor-wheel compaction of furrows, surge flow, reducing or eliminating runoff, and skip-row systems. With sprinkler irrigation, technologies have been introduced over the past three decades for improvement in center pivot systems and in management, and we compare the application-efficiency advantage of center pivot over furrow irrigation. Management practices include irrigation scheduling, limited irrigation, preplant irrigation, crop response to irriga-

Figure 6.1. Expansion of the use of sprinkler irrigation in the Texas High Plains, 1958-1989
tation, precipitation as a water resource, cultural practices, and actions to limit pumping energy costs.

Geographically, the High Plains represents the Ogallala Aquifer regions of central and western Nebraska, eastern Colorado, western Kansas, eastern New Mexico, the Oklahoma Panhandle, and the Texas High Plains; the central High Plains includes areas in Nebraska, Colorado, and Kansas; the southern High Plains, New Mexico, Oklahoma, and Texas.

FURROW IRRIGATION

Furrow irrigation, especially on moderately permeable soils (primarily 0.2 to 0.6 inch/hour basic-intake rate), is characterized by relatively large water applications and substantial losses to profile drainage and field runoff. Because of low-salinity groundwater in the High Plains, non-saline soils, and periodic leaching by precipitation, the need for irrigation-leaching requirements is very low. Irrigation management practices have been developed to reduce excessive water application in graded furrow systems and to limit losses to profile drainage.

Furrow-application efficiencies commonly range from 50 to 80 percent without tailwater reuse, with the higher values occurring on slowly permeable clays that lose little to profile drainage. Furrow-irrigated clay soils with tailwater-reuse systems have application efficiencies that compare favorably with sprinkler irrigation. In managing furrow irrigation for efficient water application and use, application depths need to be limited to the root-zone soil-profile storage capacity. Reducing application depths reduces losses to profile drainage and tailwater runoff, tends to lower the amount of soil water stored in the soil profile at harvest (which can significantly reduce precipitation storage between harvest and planting), and provides some additional storage capacity for precipitation following irrigation. Several practices have been used successfully to reduce water intake in graded furrows.

Wide-Spaced and Alternate-Furrow Irrigation

Conventional furrow spacing as practiced in the High Plains is usually 30 to 40 inches; alternate and wide-spaced furrow spacing is usually 60 to 80 inches. Wide-spaced furrow irrigation tests have been conducted in Nebraska, Oklahoma, and Texas in which application was reduced from about one-fourth to one-half compared with conventional furrow irrigation with only modest or no-yield reduction, thus increasing irrigation water-use efficiencies for crop yields (Crabtree et al. 1985; Fischbach and Mulliner 1974; Longenecker et al. 1969 and 1970; Musick and Dusek 1974;
Gravity-fed furrow irrigation in Lamb County, Texas.

Stone et al. 1979 and 1982). Many of the tests did not report tailwater runoff and net-water intake, but reduction in intake was probably substantially less than reduction in application.

In irrigating summer row crops (almost all irrigated crops except forages and winter small grains grown in narrow rows), a crop row should have one side adjacent to an irrigated furrow to prevent excessive water deficits. Many irrigated crops have higher yield potential when planted in narrow row spacings, and planting summer row crops in 30-inch rows and irrigating 60-inch furrow spacings have proven to be good practices for many crops. The use of wide-spaced furrows becomes less successful on steeper sloping and with coarse-textured soils, for crops such as corn sensitive to yield reduction from plant-water stress, and in very dry seasons.

The favorable yield response to wide-spaced and alternate-furrow irrigation is believed to be associated with reduced losses to profile drainage, to reduced tailwater runoff, and from reduced evaporation from partial wetting of the surface soil between the wide-spaced furrows. Precipitation is rather uniform in occurrence over a field and can limit water-deficit effects from nonuniform-irrigation water storage, especially in seasons of above-average precipitation.

Some irrigators use wide-spaced furrows in wide bed-furrow systems in which wheel traffic is maintained on the wide beds, not in the
irrigation furrows (Longenecker et al. 1969; Allen and Musick 1972; Allen 1985). Tractor wheels in furrows reduce water intake, accelerate water advance, increase nonuniformity among wheel-track and nonwheel-track furrows, and increase surface runoff. Using a wide-spaced bed-furrow system with wheel traffic on the beds improves uniformity of advance down the field and eliminates the normally high runoff from wheel-track furrows or the labor required for readjusting the nonuniform flow-rate advance. Wide-spaced and alternate furrow irrigation systems that partially wet the soil profile provide some additional storage capacity for precipitation. In alternate furrow systems where the same furrow is irrigated each time, furrow dams or dikes can be used in the nonirrigated furrows to minimize storm runoff (Stewart et al. 1983).

**Tractor-Wheel Compaction of Furrows for Water-Intake Control**

Furrow compaction by tractor wheels can effectively reduce excessive irrigation water intake in graded furrows. In tests on a day loam in the Texas High Plains, a tractor-wheel pass was used in 60-inch spaced furrows to increase bulk density to a 3-inch depth in the furrow bottom from a loose-soil condition to about 1.6 grams per cubic centimeter. The increased soil density in furrows reduced water intake during six irrigations for corn on a one-fourth-mile furrow length by 33 percent (Musick et al. 1985; Musick and Pringle 1986). The practice greatly reduced percolation losses below a caliche layer that limited rooting depth (Figure 6.2). Irrigations were applied at about 50 percent of the profile soil-water depletion and the reduction in intake by furrow compaction more closely balanced water-intake quantity with profile-storage capacity at the time of irrigation. The tractor-wheel furrow compaction was removed by primary tillage after harvest.

**Surge-Flow Irrigation**

Surge flow is a surface-irrigation technique developed at Utah State University in the late 1970s and extensively tested in the Great Plains and in the western states in the 1980s (Stringham 1988). A controller-valve assembly is used for intermittent water application of constant or variable duration. The most common application for surge flow is furrow irrigation using gated pipe. An available water supply (primarily from wells in the High Plains) irrigates more soil than is irrigated in conventional continuous flow by alternating the surges to a set of furrows on each side of a controller-valve assembly. A larger area can be irrigated proportionate to the reduction in water intake by surge application. Surge flow can be
managed for nearly continuous tailwater runoff by using a short-cycle time (less than 15 minutes) during the runoff phase, during which surge advances tend to catch up with recession flow to provide nearly continuous furrow flow on lower field sections. This permits lower-field wetting with reduced tailwater runoff.

A time-controlled valve alternates water-inflow surges to a set of furrows on each side of the valve. The on-and-off flow cycles are effective in reducing water-intake rates for many soils and soil conditions. The primary reason for the reduced-intake rate associated with the off cycle is believed to be the effect of surface-tension forces developed during the desaturation off cycle, causing soil surface-layer consolidation (Kemper et al. 1988; Saleh and Hanks 1989). Soil loosened by tillage benefits most. The surge effect is reduced when the surface soil is consolidated by wheel traffic, tillage, or previous irrigations.

In seasoned irrigation tests for corn on a nonswelling clay loam, surge flow reduced intake by 32 percent when the soil was in a loosened condition from tillage compared with continuous flow. The reduction averaged 17 percent for seasonal irrigations when the surface soil was
Surge-flow system with solar-powered controls on top. Chase County, Nebraska.

consolidated from previous irrigation (Musick et al. 1987). Also, surge flow resulted in similar profile storage from irrigation, similar corn yields, and improved down-the-field uniformity of profile wetting.

Reducing or Eliminating Field Runoff

Many farmers manage irrigation in graded furrow systems to reduce or eliminate tailwater runoff for crops having drought tolerance. As pumping yields of wells have declined and energy costs have increased, farmers in the Texas High Plains have reduced tailwater runoff from about 30
to 40 percent of water applied when pumping costs were lower to about 15 to 20 percent in recent years (Musick and Walker 1987). About 60 percent of the furrow-irrigated area is on slowly permeable swelling clays (Musick et al. 1988). About one-third of the total water intake on these soils results from initial filling of shrinkage cracks. After approximately three to five hours of flow time, when lateral wetting from furrows greatly slows, the slowly permeable B2t horizon below the tillage depth controls the intake rates, which drop to a basic rate of about 0.1 inch per hour. The low basic rate limits the additional intake volume and the additional lower field yield response from extending the duration of tailwater flow.

Stewart et al. (1983) developed and successfully tested a limited irrigation dryland (LID) system on a clay loam designed to prevent irrigation tailwater and storm runoff from leaving a field. Water was applied for grain sorghum to fully irrigate the upper one-half of a 1,900-foot length of run. Tailwater from the fully irrigated section was used on the next one-fourth field section. The lower one-fourth field section was dryland sorghum with furrow dams to retain and use precipitation and thus prevent storm runoff. Irrigation was applied to alternate 30-inch furrow spacing, and furrow dams were maintained for the complete field length of the alternating nonirrigated furrows. The average results from a three-year test on three LID treatments have been compared with full irrigation and dryland cropping (Table 6.1).

Skip-Row Systems

Graded furrow-irrigated skip-row systems involve planting alternating strips of two or four rows of summer row crops and leaving one, two, or four rows unplanted. In the most common system, farmers plant two 30- or 40-inch rows, leaving one row unplanted, and irrigate the one furrow between the paired crop rows. This practice greatly reduces average field-irrigation water-intake depth in graded furrow systems. Skip-row planting and irrigation of fewer furrows than crop rows have been tested for sorghum and corn (Musick and Dusek 1982) and for cotton (Newman 1967; Longenecker et al. 1963, 1969, and 1970).

Farmers widely practice skip-row planting and irrigation of fewer furrows in the irrigated-cotton area of the south Texas High Plains, a region of limited groundwater storage and many small wells. Newman (1967) conducted tests at Lubbock, Texas, by planting two 40-inch cotton rows and leaving out either one or two skip rows and then evaluating limited irrigation of the one furrow between the paired rows. In the plant-two, skip-one system, average irrigation water-use efficiencies for lint production were increased by 52 percent and in the plant-two, skip-two system by 21 percent, compared with the conventional every-row-
Table 6.1. Comparison of LID Treatments, Full Irrigation, and Dryland Cropping, Three-year Average, Bushland, Texas

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Applied Irrigation (Inches)</th>
<th>Grain Yield (Lb/acre)</th>
<th>Seasonal $^1$ ET $^2$ (Inches)</th>
<th>Water-use Efficiency ET (Lb/acre-inch)</th>
<th>Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryland</td>
<td>—</td>
<td>2,260</td>
<td>11.5</td>
<td>190</td>
<td>—</td>
</tr>
<tr>
<td>Full irrigation</td>
<td>20.3</td>
<td>6,460</td>
<td>24.2</td>
<td>265</td>
<td>208</td>
</tr>
<tr>
<td>LID-10.0 inches</td>
<td>9.2</td>
<td>5,080</td>
<td>20.5</td>
<td>245</td>
<td>308</td>
</tr>
<tr>
<td>LID-7.5 inches</td>
<td>6.8</td>
<td>4,580</td>
<td>18.3</td>
<td>247</td>
<td>340</td>
</tr>
<tr>
<td>LID-5.0 inches</td>
<td>4.7</td>
<td>3,990</td>
<td>16.2</td>
<td>245</td>
<td>385</td>
</tr>
</tbody>
</table>

$^1$Seasonal rainfall averaged 9.8 inches.
$^2$ET = evapotranspiration.

Source: Stewart et al. (1983), "Yield and Water-use Efficiency," Agronomy 75:629-34.

planted and every-furrow-irrigated system. Although irrigation water is used efficiently in skip-row planted and irrigated systems, seasonal precipitation is used less efficiently because of increased loss to evaporation from the bare soil separating the paired crop rows.

SPRINKLER IRRIGATION

Sprinkler irrigation generally conserves water. Application efficiencies of sprinkler and furrow irrigation of moderately and slowly permeable soils indicate a 20 to 25 percent application-efficiency advantage with sprinkler irrigation on moderately permeable soils but little advantage on slowly permeable soils with tailwater reuse (Musick et al. 1988). In inventories conducted in the Texas High Plains by the Soil Conservation Service (SCS), furrow-application efficiency estimates averaged 59 percent for moderately permeable soils and 72 percent for slowly permeable soils without considering tailwater reuse; when the SCS conducted 223 center pivot sprinkler evaluation tests on the Texas High Plains in the early 1980s, application efficiencies averaged 83 percent.

There is an advantage of sprinkler over furrow irrigation for reducing groundwater pumped to irrigate corn on moderately permeable soils (Figure 6.3). The figure’s probability distribution curves of groundwater pumped represent the irrigation of sixty-five corn fields in Parmer and Castro counties of the Texas High Plains during 1983 and 1984 (Rettman and McAdoo 1986). The curves indicate a high degree of similarity in groundwater amounts pumped for all sprinkler-irrigated fields and for furrow-irrigated fields having slowly permeable soils. The median application (50 percent probability occurrence) indicated that an additional 12 inches of water was pumped for furrow-irrigated fields on moderately
permeable soils. For the 20 percent of the fields that received the highest water application, an additional 19 inches of water was pumped. These results obtained in a groundwater area with high-yielding wells suggest that conversion from furrow to sprinkler irrigation on moderately permeable soils can permit substantial reduction in groundwater pumping and probably substantial reduction in losses to profile drainage below the root zone.

The use of electric operating controls in the late 1960s and the associated ease of movement increased the attractiveness of center pivot systems to irrigators. The improved controls enabled irrigators to move the systems without applying water and provided variable speed of application. The center pivot's higher application efficiency and its automation led to an extensive replacement of furrow systems with sprinkler systems. Based on irrigation surveys by state Agricultural Extension Services and the Texas SCS, the 1989 sprinkler-irrigated area on the High Plains was estimated to average 48 percent of the total acreage irrigated for a six-state area.

Sprinkler irrigation in the High Plains is primarily accomplished with center pivot systems, which accounted for 96 percent of the total in the Texas High Plains in 1984 (Musick et al. 1988). Most machines are one-fourth mile long and irrigate about 130 acres of a 160-acre quarter-section of land. In the relatively flat terrain of the High Plains a recent
trend has been the installation of new systems of one-half-mile machines that irrigate an area similar to four one-fourth-mile systems at about the initial cost of three one-fourth-mile machines (L. L. New, personal communication, 1990). Turnkey installation costs in 1990 for one-fourth-mile systems were about $35,000 (without the end gun) compared with about $100,000 for one-half-mile systems (W. L. Harman, personal communication, 1990).

Reduction in labor is a major attraction of center pivot systems. Duke (1989) wrote, "While a single irrigator may be able to handle irrigation of 1,000 to 2,000 acres under center pivot machines, he can seldom keep up with more than 300 to 500 acres of surface irrigated land, depending on the type of delivery system used. Where minimal tillage is needed and labor intensive operations such as planting and harvest can be handled
by seasonal labor or custom operations, the savings in labor costs can go far toward paying the extra capital and operating expense of sprinkler irrigation systems."

Many improvements have been made over the years in the design, management, and use of center pivot systems. Improved technologies include (1) tires having higher flotation for improved traction and reduced rutting, (2) electric drive systems, (3) reduced-pressure application with computer-designed sprinkler-nozzle packages for more uniform application, (4) management techniques for use with reduced-pressure systems to reduce or eliminate surface runoff, (5) multifunctional systems for applying water and chemicals (chemigation, the application of fertilizers and pesticides through an irrigation system), (6) improved sprinkler heads for jet breakup into desired droplet size and distribution patterns, (7) positioning of spray and low-energy precision application (LEPA) heads on drop tubes much closer to the crop or soil surface for reducing wind drift and evaporation losses (Lyle and Bordovsky 1983), (8) remote monitoring through radio telemetry and computer on-off control capability, (9) use of LEPA on new systems and as retrofit packages, and (10) management techniques such as reduced tillage and circular planting of row crops (using pivot-tower tire tracks as guides) with positioning of the drops between the circular crop rows.

Following the escalation of pumping energy costs after the OPEC price increases of 1973, system conversion from high pressure to medium and low pressure was widely adopted along with selection of low-pressure sprinkler packages by those investing in new systems. Herrmann (1990) gave the ranges of high, medium, and low pressure as having pivot-input pressures of 50 to 70 pounds per square inch (psi), 35 to 50 psi, and less than 35 psi, respectively. In 1989 an SCS inventory of counties in the Texas High Plains showed that the percentage of low-pressure center pivot systems in use was primarily associated with the age of the systems and averaged 74 percent for the 1.75 million acres of sprinkler-irrigated crops. New indicated that about four hundred LEPA systems were in use in the Texas High Plains in spring 1990 (L. L. New, personal communication, 1990).

Reduced-pressure technology involves reducing high-discharge jet angles of 23 to 27 degrees for conventional impact heads to 5 to 7 degrees for low-angle, reduced-pressure heads, increasing use of spray-nozzle systems, using drop tubes to position spray nozzles near the top or into the crop canopy, and positioning LEPA heads on drops about 8 to 16 inches above the soil surface. LEPA heads can be operated in a spray mode for crop germination, a bubble mode that applies water in an umbrella pattern with a 16- to 18-inch diameter at the soil surface, or in a chemigation mode that uses a splash plate to direct a spray pattern up
into the canopy for insecticide application to taller crops such as corn. One person can change the application mode on a one-fourth-mile system in about 45 minutes.

Efficient application and uniform distribution of sprinkler-irrigation water involve reducing droplet wind-drift and associated evaporation losses and reducing or eliminating field runoff. Application losses were estimated by New et al. (1990) as 2 to 4 percent for LEPA heads in the bubble mode, 12 percent for spray nozzles, and 15 to 25 percent for impact sprinklers. Wind-drift losses have been reduced by lowering the jet trajectory angle on impact heads and by placing spray and LEPA heads on drop tubes. Wind speed and direction affect spray distribution and drift losses. In areas having a continental climate such as the High Plains, nighttime wind speeds normally decrease sufficiently to enhance application efficiency and distribution uniformity. Successive center pivot irrigations can be scheduled to alternate day and night at a given site.

Runoff losses have been reduced by using faster travel speeds that result in smaller applications, basin tillage (furrow dams or dikes), in-row ripping for increased intake rates, surface crop residue management, circular planting, and by keeping tractor-tire traffic out of the drop-applicator furrows with drops positioned in alternate furrows. Improved sprinkler-package designs also limit the kinetic energy of water droplets and lessen the effects of surface-layer dispersion and consolidation (surface crust) on reducing intake rates.

Sprinkler irrigation enhances management of reduced tillage and maintenance of crop residues on the soil surface; in addition, crop emergence has been improved substantially by the ability to apply a small irrigation (0.7 to 1.0 inch) rapidly through a center pivot after planting. Rainfall after planting can cause a surface crust on some soils that prevents crop emergence. A small sprinkler application can be used to soften the surface crust and thus ensure the crop stand.

IRRIGATION SCHEDULING

Irrigation scheduling, the forecasting of water-application timing and amount for optimal crop production, is essential for efficient management and use of irrigation water. Rational scheduling requires knowledge of plant available soil water storage capacity, rooting depth, soil water content, and the expected changes in soil water over a subsequent five- to ten-day period. Water-use rates are affected by weather conditions that influence evaporative demand and by precipitation.

Farmers use water budgets for irrigation scheduling based on soil-water contents, irrigation applied, losses to deep percolation and surface
Computer-based irrigation-scheduling programs use meteorological data, crop coefficients (a function of crop development), and reference crop ET for predicting actual crop ET. The early scheduling programs used mainframe computers and access terminals; more recently, researchers have developed and validated scheduling software programs for personal computers.

Center pivot sprinkler systems are usually scheduled to apply predetermined application depths, and timing of application is allowed to vary. In graded furrow systems, however, both the timing and the amount can vary widely. Center pivot systems can be operated to refill the soil profile partially and to maintain some storage capacity for precipitation that may occur following irrigation. On low-water storage-capacity soils, however, maintaining profile-storage capacity for precipitation following irrigation is generally not advisable. On these soils, it is more important to maintain a fully wet profile, thus providing a margin of safety should the system malfunction or the crop encounter an unusually high water-use period.

Computer scheduling is most widely practiced in the Great Plains for center pivot irrigation of corn. On the low-water storage soils, scheduling can be managed for both high yields and efficient water use by
avoiding rapidly developing water deficits and excess application that results in water losses to profile drainage and leaching of nitrates (Heer- mann et al. 1976). Computer scheduling can also be accomplished by using crop-growth simulation models such as Ceres Maize for sprinkler-irrigation management for corn grown in the southern Great Plains (Howell et al. 1989). The growth models also forecast crop yields.

Scheduling can be based on root-zone soil-water contents determined from core samples or neutron probes or from root-zone soil-water potentials determined from tensiometers or gypsum blocks. Approaches involving measurement of plant water stress such as leaf-diffusive resistance and water potentials are usually limited to research projects.

The hand-held infrared thermometer is a recent scheduling tool that allows rapid, quantitative field measurements of plant-water stress. The instrument is small, portable, and is operated as a "gun" that measures thermal radiation (i.e., plant temperature) emitted from all parts of the canopy within view of the instrument. Crop stress increases canopy temperature from reduced transpirational cooling and can be assessed by comparing canopy temperature elevation for a desired field site with the temperature of a nearby site that is known to be adequately irrigated and nonstressed.
A more precise stress assessment involves the calculation of a crop-water stress index from an energy-balance equation involving canopy air temperature difference and current meteorological data (Jackson 1982). The preferred diurnal time of measurement is during the period of maximum stress, normally within a plateau of high evaporative demand following solar noon for approximately the next three hours. The method performs best on clear days with relatively high solar radiation and when it is used to target plant leaves to exclude low-transpiring plant parts such as sorghum heads and corn tassels and to minimize soil background in the target area. Clouds affect canopy temperatures from variable incoming solar radiation, which can be a problem in using infrared thermometers in the High Plains environment.

Visual observations of stress are widely used in irrigation scheduling for drought-resistant crops in the High Plains. Symptoms of stress that can be observed visually include leaf roll, droop, or movement to reduce incoming radiation interception, stress-related chlorophyll degradation as indicated by changes in shades of green leaf color, slowed leaf expansion and accelerated senescence of older leaves, and evening or morning stress recovery or both. Although afternoon stress may be allowed under deficit irrigation of crops possessing drought resistance, the stress should be alleviated by irrigation before it becomes severe enough to prevent overnight recovery. Stress that develops to this point slows growth greatly, indicates that depletion of available soil water is near the lower limit, and can cause rapid loss of yield potential.

**LIMITED IRRIGATION**

Limited irrigation is a management strategy that uses limited water supplies to irrigate larger field areas by allowing crops to experience periods of slight to moderate plant-water stress; its main purpose is to increase total farm production or net returns by reducing the area of dry land crops. Adequate and limited irrigation are both widely practiced in the High Plains. Farmers practice limited irrigation primarily with drought-resistant crops that are also grown without irrigation. Occurrence of normal to above-normal precipitation is important for the success of limited irrigation in the High Plains; limited irrigation becomes less successful during major dry seasons.

A common practice is to about double the area that is fully irrigated for maximum yields. System designs by SCS in the Texas High Plains have allowed flexibility within the range of 3 to 10 gallons per minute (gpm)/acre compared with 7 to 10 gpm/acre for adequate irrigation to meet peak water requirements. Center pivot systems having LEPA drops in
alternate furrows (circle-planted) have been designed and operated for irrigation of cotton in the Texas High Plains with water supplies of 3 gpm/acre (L. L. New, personal communication, 1990).

While modest yield reductions are allowable in order to use available limited water supplies for irrigating larger areas, limited-irrigation management should be weighed carefully before being adopted. Musick (1989) summarized seven rules to apply in making the decision. (1) Consider only soils that are relatively deep and that have moderate to high water-storage capacity; (2) consider only crops possessing drought resistance (avoidance or tolerance or both); (3) consider increasing the contribution of precipitation to crop water needs; (4) consider crop growth stage and cutoff date in managing water; (5) consider the need for preplant irrigation; (6) in furrow systems, consider methods for reducing water intake and field runoff; and (7) consider modifying some cultural practices for limited irrigation.

PREPLANT IRRIGATION

Preplant irrigation is the system of irrigating to wet the soil profile partially or fully before planting a crop and has been widely practiced in the semiarid High Plains since the early expansion of pump irrigation from the Ogallala Aquifer in the late 1930s. Under some conditions, preplant irrigation is essential for the establishment of timely stands and for high yields. In many situations, however, the large application depths required for surface irrigation result in inefficient soil water storage and low-yield response. Smaller and more precise preplant irrigation-application amounts are possible with center pivot sprinkler systems to wet the soil partially, in preparation for planting. Also, early-season irrigations can be applied when water use rates are low, which provides flexibility in rewetting the soil profile, thus eliminating the need for large preplant-irrigation depths that increase soil profile drainage losses and leaching of nitrates.

Preplant irrigation accomplishes different objectives, including wetting the soil profile, germinating crop volunteer plants and weeds that can be killed by tillage before planting, and providing an adequate seed-zone soil physical condition and water content to facilitate planting and stand establishment (Musick 1987). The benefits are likely to be greatest in four situations: (1) when the soil profile is dry as planting approaches, (2) when seasonal irrigations are not applied to drought-tolerant crops or are reduced in amount, (3) when early planting is desirable and soil wetting by precipitation is not likely by the desired planting time, and (4) when preplant irrigation plus seasonal precipitation on deep, high water-
Metering water use is an effective and relatively inexpensive management tool. Texas A & M Research Station near Etter, Texas.

Storage soils can result in moderately high yields without seasonal irrigation. The benefits are likely to be low when soil profiles are moderately wet at the time of irrigation, when planting dates are flexible and can follow precipitation for stand establishment, and when seasonal irrigation provides adequate water to meet plant requirements.

Yields of preplant-only irrigated grain sorghum as a percentage of adequately irrigated yields were analyzed (Table 6.2). Multiyear tests were conducted at five locations in the central and southern High Plains. The locations have similar average seasonal precipitation of 8 to 10 inches, and each produced similar adequately irrigated yields. The comparisons indicate that preplant-only irrigated yields, expressed as a percentage of adequately irrigated yields, were higher in the central than in the southern High Plains. Seasonal water use is lower in the central High Plains, and the test sites had relatively deep soils.

Results from the five test sites indicate that when yields from preplant irrigation were low compared with adequate seasonal irrigation, the yield response to seasonal irrigation was relatively high. Also, when yields from preplant irrigation on the high-water-storage soils were relatively high compared with adequately irrigated yields, the yield response to seasonal irrigation was relatively low (Figure 6.4). The data are from a
Table 6.2. Yields of Preplant-Only Irrigated Grain Sorghum as a Percentage of Adequately Irrigated Yields, Various Soils, Central and Southern High Plains

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil</th>
<th>No. of Test Years</th>
<th>Yield as Percentage of Adequate Irrigation (Preplant Only)</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern High Plains</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bushland, Tex.</td>
<td>Pullman clay loam</td>
<td>7</td>
<td>40</td>
<td>Musick 1987</td>
</tr>
<tr>
<td>Clovis, N. Mex.</td>
<td>Pullman silty clay loam</td>
<td>3</td>
<td>54</td>
<td>Finkner and Malm 1971</td>
</tr>
<tr>
<td>Central High Plains</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garden City, Kans.</td>
<td>Ulysses clay loam</td>
<td>8</td>
<td>57</td>
<td>Erhart 1970</td>
</tr>
<tr>
<td>Garden City, Kans.</td>
<td>Richfield clay loam</td>
<td>6</td>
<td>66</td>
<td>Musick and Grimes 1961</td>
</tr>
<tr>
<td>Garden City, Kans.</td>
<td>Richfield silty clay loam</td>
<td>6</td>
<td>79</td>
<td>Hooker 1985</td>
</tr>
<tr>
<td>Tribune, Kans.</td>
<td>Ulysses silty clay loam</td>
<td>3</td>
<td>81</td>
<td>Stone et al. 1987</td>
</tr>
<tr>
<td>Colby, Kans.</td>
<td>Keith silt loam</td>
<td>3</td>
<td>95</td>
<td>Bordovsky and Hay 1975</td>
</tr>
</tbody>
</table>

three-year study with grain sorghum for treatments of preplant only and preplant plus three levels of seasonal irrigation on Keith silt loam at Colby, Kansas.

Water intake during preplant irrigation frequently exceeds profile-storage capacity and losses occur as rapid drainage below the root zone. In addition, in the absence of root extraction for an extended period of time following the preplant irrigation, slow profile drainage occurs as unsaturated flow on the deep-silt (loess) profiles in western Kansas. Profile drainage losses from preplant irrigation to planting were measured in the 2- to 3-inch range on Ulysses clay loam at Tribune, Kansas (Stone et al. 1987). The most efficient use of irrigation water on this soil was made when the water was applied as closely as possible to the time of plant need (Stone et al. 1980).

CROP RESPONSE

Corn is one of the most economically important irrigated crops grown in the High Plains. As a stress-sensitive crop, especially during pollination, it is most often grown with adequate water and other production inputs
for high yields (Musick and Dusek 1980). Adequate irrigation of corn for high yields has contributed to the dramatic trend in yield increase, (Figure 6.5). Other crops that are generally grown under adequate irrigation are alfalfa, soybeans, sugar beets, and vegetables. The major crops grown extensively under limited irrigation are winter wheat and grain sorghum in the central High Plains and wheat, grain sorghum, and cotton in the southern High Plains. Minor crops include barley, millet, forage sorghum, cool-season grasses, alfalfa for seed, sunflowers, and grapes (Musick and Walker 1987). Late-season water deficits can enhance yield quality such as improved cotton-fiber properties, grain protein, and grapes for wine. Some crops are grown under both adequate and limited irrigation and as dry land crops on different fields of the same farm.

Most crops grown with limited-irrigation tend to resist drought through the capability of plants to tolerate plant water deficits as growth continues, normally at a reduced rate, or through the ability to avoid and thus delay stress by deep-rooting, with a greater use of water from deeper in the profile, and/or by the use of shorter growing-season cultivars. Sunflowers provide an excellent example of drought avoidance by combining a very deep root system for water extraction with the relative short growing season of commercial hybrids.
Figure 6.5. Annual average irrigated corn yields for counties in the Ogallala Aquifer boundaries, 1960-1989 (western Kansas, 31 counties; eastern Colorado, 11; Texas High Plains, 41)

In the absence of root-restricting zones in the soil profile, deep-rooted crops such as sunflowers, sugar beets, and alfalfa extract soil water approximately to the 7- to 8-foot depth and wheat, sorghum, and cotton approximately to the 4- to 6-foot depth. Winter wheat has a longer vegetative growing period and thus a deeper root system than spring wheat. Extraction of available soil water in the lower one-quarter of the profile is normally limited by sparse rooting densities.

When deficits are allowed and irrigation water is applied stages of crop growth can have substantial effects on yield response. Yield sensitivity of grain sorghum is low during its early-season vegetative growth, increases substantially during the boot stage through flowering, and de-
Table 6.3. Average Grain Sorghum Yield Increases and Irrigation Water-use Efficiency, Etter, Tex., 1969 and 1972

<table>
<thead>
<tr>
<th></th>
<th>6-8 Leaf</th>
<th>Mid- to Late-boot</th>
<th>Heading to Flowering</th>
<th>Milk to Soft Dough</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grain-yield increase per irrigation (lb/acre)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1969</td>
<td>342</td>
<td>2,388</td>
<td>2,550</td>
<td>254</td>
</tr>
<tr>
<td>1972</td>
<td>499</td>
<td>1,096</td>
<td>1,708</td>
<td>696</td>
</tr>
<tr>
<td><strong>Irrigation water-use efficiency (lb/acre-inch)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1969</td>
<td>86</td>
<td>597</td>
<td>637</td>
<td>64</td>
</tr>
<tr>
<td>1972</td>
<td>125</td>
<td>274</td>
<td>427</td>
<td>174</td>
</tr>
</tbody>
</table>


dines during grain filling (Musick and Dusek 1971) (Table 6.3). Timing of water deficits involving development stages can result in a substantial range of sorghum yields from a given level of seasonal water use (Musick and Dusek 1971).

For some perennial crops such as cotton and alfalfa for seed, late-season irrigation may stimulate continued vegetative growth at the expense of economic yield. Cotton grown in the Texas High Plains needs a stress period near the end of August and the beginning of September for new fruiting cutout since late-season initiated bolls do not mature in this climatic environment (Krieg 1986). A late-season deficit that limits the continued vegetative growth of cotton hastens maturity and improves lint quality.

The timing of irrigation in relation to critical-development stages increases in importance as the number of seasonal irrigations are reduced and plants experience increasing levels of water stress (Table 6.4). A single seasonal irrigation for sorghum in the Texas High Plains should not be applied as the only irrigation either during early vegetative growth or during mid-to-late grain filling. However, at higher water levels involv-
ing additional applications for high yields, the yield contribution of early and late irrigations increases.

When growth-stage responses to limited irrigation of winter wheat and grain sorghum are compared in the High Plains, irrigation of wheat during early-spring vegetative growth can be more critical. This comparative growth period occurs about six months after planting winter wheat, compared with about one month after planting sorghum. Soil-water depletion at this growth stage is normally greater for wheat because of the much longer period for water use. Although wheat is more responsive than sorghum to irrigation during early vegetative growth, it is normally less responsive to irrigation during grain filling because of increasing spring precipitation that peaks during this period.

PRECIPITATION AND IRRIGATION

Precipitation increases in its importance for meeting crop-water needs in areas where farmers practice limited irrigation (Stewart and Musick 1987). In the irrigated semiarid central and southern High Plains, precipitation normally provides about 30 to 60 percent of seasonal crop-water requirements for high yields. In the major wet seasons, irrigation can be reduced substantially; in the major dry seasons, increased irrigation is needed to compensate for both reduced precipitation and increased evaporative demand from the prevailing warm, dry air.

The contribution of precipitation in meeting crop-water needs and thus in reducing irrigation requirements can be enhanced by (1) using precipitation for stand establishment without preplant irrigation, (2) irrigating to wet the profile partially, which allows some storage capacity for precipitation (by limiting application depths using sprinkler irrigation, wide-spaced furrows, wheel-track compaction of irrigated furrows, or surge flow to reduce water intake), (3) reducing or eliminating precipitation runoff (by using conservation tillage, furrow dams, and land leveling), (4) reducing applications during above-normal precipitation periods, and (5) managing irrigation to use more fully the available profile water storage by the end of the season, thus enhancing precipitation storage between crops.

The average long-term January-through-December precipitation patterns have been analyzed for sites in the central and southern High Plains (Figure 6.6). These graphs, presented as fifteen-day totals for three-day periods, moving from north to south—Colby, Kansas, to Amarillo and Lubbock, Texas—illustrate the normally dry winter months of the continental climate, the increasing spring precipitation patterns, and some north-to-south differences in summer distribution patterns.
Figure 6.6. Average fifteen-day precipitation, January through December, for central and southern High Plains
Early irrigation cutoff increases storage capacity for nongrowing-season precipitation between harvest and planting the next crop and thus increases the efficiency of precipitation storage. In a three-year test involving grain sorghum irrigation treatments on clay loams at Bushland, precipitation storage efficiency after the harvest declined from the 40- to 50-percent range when the soil profile was dry after harvest (from early irrigation cutoff at boot stage) to about 10 percent or less when the profile was wet after harvest (from late cutoff at dough stage of grain) (Figure 6.7). During major drought periods, paucity of precipitation may necessitate shifting limited water supplies to more stress-sensitive crops such as corn or soybeans, and crop areas under limited irrigation may need to be reduced.

**CULTURAL PRACTICES**

Cultural practices influence the successful management of irrigated-crop production, and those that are useful in facilitating management of limited irrigation are conservation tillage, plant densities, planting dates,
maturity-length cultivars, and cropping systems, including the use of fallow between crops to increase precipitation storage and to eliminate preplant irrigation. Some practices used for limited irrigation are also common to dryland agriculture in the High Plains.

Conservation tillage (including no-tillage) involves management of crop residues on the soil surface for increased precipitation storage. The dryland-cropping system of wheat-sorghum-fallow, two crops in a three-year sequence having about eleven months fallow between harvest and planting of each crop, has been successfully tested under limited irrigation at Bushland (Musick et al. 1977). The system has been employed as no-tillage, using herbicides for weed control, and as a combination of very limited tillage, combined with the use of herbicides. One-sweep tillage operation has been successfully practiced to loosen the surface soil, improving seed-zone physical conditions for planting, to control weeds before planting, and to inject anhydrous ammonia fertilizer under the sweep blades.

Three other cropping systems have been tested successfully for efficient use of limited irrigation: alternating equipment-width field strips of wheat and sorghum combined with wide-spaced furrow irrigation, with the outside crop rows benefiting from a border effect during the non-growing period of the adjacent crop strip (Musick and Dusek 1972 and 1975); double cropping of sorghum and wheat combined with no-till seeding (Allen et al. 1975; Musick et al. 1977); and combination systems of irrigated and dryland crops (Stewart et al. 1983; Unger and Wiese 1979; Unger 1984).

The use of moderate plant densities may be desirable for crops that do not tiller extensively in order to limit interplant competition for water and to allow more gradual development of water deficits. Under adequate irrigation, narrow row spacing for grain sorghum increases yields (Grimes and Musick 1960; Porter et al. 1960). With limited irrigation, the increased yield response from narrow row spacing may not occur. However, narrow row culture is not likely to reduce yield under limited irrigation when high plant densities are avoided (Musick and Dusek 1969). Use of moderate plant densities is of lesser importance for wheat because of tiller compensation when plant density is reduced.

In the water-limited areas of the south Texas High Plains where irrigated grain sorghum is a secondary crop to cotton, farmers plant sorghum early, using medium-maturity hybrids, and limit irrigation to early-season application before the cotton-irrigation season begins. However, north of the cotton production boundary (about 35° north latitude), grain sorghum is the primary irrigated crop in many counties and is planted early, using medium-late-maturity hybrids, and mostly irrigated for high yields.
Cablegation sequentially opens gates in order to flood furrows. Chase County, Nebraska.
LIMITING PUMPING ENERGY COSTS

National energy costs after 1973 varied significantly, peaking in 1984 for natural gas and in 1985 for electricity, two of the three major fuels used for pumping irrigation water. Prices climbed again in 1990 following disturbances in the Persian Gulf. Energy costs can be lowered for irrigation by reducing the pumping head and volume and by increasing pumping-plant efficiencies. Energy costs may be restricted also by management that reduces peak-load demand, high costs that electric utility suppliers subsequently pass on to users. Three significant trends have developed to contain pumping energy costs: (1) reduced water application for the drought-resistant crops that are widely grown under limited irrigation, (2) adoption of low-pressure application for center pivot systems, and (3) conversion from graded furrow to center pivot systems.

Comparing groundwater pumped from irrigation inventories in the Texas High Plains illustrates the reduction in water application. When three years of low pumping energy costs (1964, 1969, and 1974) were compared with three inventory years of much higher costs (1979, 1984, 1989), average water application for grain sorghum declined by 18 percent, for winter wheat by 19 percent, and for cotton by 35 percent (Musick et al. in press). Average water application for all other crops except corn declined by 15 percent. Groundwater pumped for corn increased by 17 percent in association with a trend in increasing yield (see Figure 6.5). The reduction in groundwater applied for most crops over time has partially offset the increased pumping energy costs.

The control of peak-load demands is an important factor in billing for utility power suppliers (Heermann et al. 1990). Stetson et al. (1975) reported that many power suppliers offer reduced rates for interruptible power to reduce peak loads, which can significantly decrease the cost of energy for irrigation. Scheduling/load-control programs can successfully decrease the peak energy demands by limiting the use of irrigation pumping to nonpeak periods.

Heermann et al. (1984) developed an integrated system for irrigation scheduling and power control during peak electrical-use periods. It monitors the irrigation system's operation, provides on-off control, schedules irrigation, and controls electric-power demand. The power supplier monitors the electrical demand and sends radio signals to a computer-based controller at the farm headquarters when it is necessary to interrupt the load. The computer-based system then stops irrigation on individual units based on a priority for all irrigation systems under control. The irrigator monitors all systems to see that they are operational when power is available, exercising personal priorities, and changes the priority using the computer-based controls when desired.
Minimizing pumping energy costs requires high-efficiency pumping equipment. The acceptable energy-efficiency standard for deep-well turbine pumps is 75 percent. Energy-efficiency tests of 360 irrigation pumping plants in the southern High Plains by New and Schneider (1988) averaged 59 percent. The study indicated that efficiencies were lower in areas having smaller pumping units and older equipment. Installation of new wells greatly declined during the 1980s. The low rate of replacement wells and the aging of equipment will probably result in the continued decline in pump efficiencies, thus further increasing pumping energy costs.

In the northern Plains in 1980, electricity was used as the pumping energy for 30 percent of the irrigated area, diesel for 25 percent, and natural gas for 32 percent (Sloggett 1983). Comparative values for the southern Plains were 22 percent electricity, 2 percent diesel, and 66 percent natural gas. Use of gasoline and liquid-petroleum gas accounted for the balance. The Department of Energy has projected increases in national rates for electricity and natural gas through 2010, based on 1989 dollars (adjusted for inflation; see Figure 6.8). The reported national prices for different user groups that were the closest to those of irrigators in the High Plains were average commercial-user rates for electricity and industrial-user rates for natural gas. Natural-gas prices closely parallel diesel prices on an energy-equivalent basis.

The much more stable prices projected would cause electricity increasingly to become the energy of choice for pumping irrigation water in the High Plains. Yet the lack of utility service at many well sites, the high costs of extending electric lines, and the peak-demand problems caused by irrigation pumping to electric-utility suppliers may limit future conversions from natural gas and diesel fuel to electricity. Thus further increases in pumping energy costs undoubtedly contribute to future decline in groundwater use for irrigation in the High Plains.

Skold and Young (1987), in an economic analysis of intermediate and long-range water costs for favorable and less favorable commodity prices, concluded that groundwater irrigation in the Ogallala Aquifer region remains profitable only because producers are living off previous investments in wells, pumps, and irrigation distribution systems and because government payments are sufficient to augment operating losses. The High Plains has experienced some decline in the production of crops dependent on groundwater irrigation in recent years and further declines are anticipated.

Irrigation technologies developed and adopted during the rapid expansion of groundwater-based irrigation in the High Plains following
World War II have had a major impact on conservation and on efficient water use. The major technologies include (1) on-farm underground-pipeline distribution that replaced open ditches, (2) gated pipe replacement of furrow siphon tubes that allowed much greater flexibility in adjusting furrow flow-rates, (3) tailwater-reuse systems for field runoff, and (4) center pivot sprinkler irrigation that replaced hand-move and side-roll systems. More recent developments have been the major extension of center pivot sprinkler irrigation to sandy soils and to rolling topography not suited to surface irrigation and the replacement of less efficient furrow systems with center pivot systems. The substitution of graded-furrow with center pivot sprinkler systems has greatly reduced labor requirements for irrigation.

A major limitation to attaining high field-application efficiencies with furrow irrigation has been excessive water application and field intake on the relatively long furrow-length fields (mostly one-fourth to one-half

Figure 6.8. Average national electricity rates (commercial users) since 1974, natural gas rates (industrial users) since 1967, and projections by Department of Energy to 2010
mile) and excessive losses to profile drainage below the crop root zone. Technologies that substantially reduce water intake are irrigation of alternate and wide-spaced furrows, including skip-row planting systems, tractor-wheel compaction of furrows, and surge-flow application. Other technologies for water-intake management include deep tillage for increased water intake on the slowly permeable soils and controlled traffic systems that exclude wheel traffic from irrigated furrows, for example, wide bed-furrow systems in which all wheel traffic is maintained on the wide beds. Many useful technologies for irrigation scheduling and timing of application have been developed, including computer irrigation scheduling, which is most widely used for center pivot application to adequately irrigated crops such as corn.

Because of the limited and declining groundwater supplies in important areas of the High Plains regional aquifer and the relatively high pumping energy costs, we have emphasized limited-irrigation management for efficient use of available water supplies. These technologies apply primarily to irrigation of drought-resistant crops on farms having inadequate water supplies for full irrigation. Useful methods include (1) timing irrigation in relation to critical crop-development states for water-deficit effects on yields, (2) reducing or eliminating the preplant irrigation, (3) reducing or eliminating field runoff, and (4) employing practices that effectively use precipitation for partially meeting crop-water requirements on irrigated land. Limited irrigation management probably should not be practiced on low water storage soils, for production of stress-sensitive crops, and during periods of major drought.

High pumping energy costs have contributed to a decline in irrigation in the High Plains. The U.S. Department of Energy projections suggest that in the future, electricity will become the dominant and preferred energy source for pumping irrigation water. The projected doubling of natural gas prices (adjusted for inflation) by 2010 will have the most adverse effect in the southern plains, where it is the predominant energy used for pumping water.

Future trends in technology will emphasize a continuation of present trends for more efficient application systems and for management that reduces losses to profile drainage below the root zone as well as losses associated with field runoff and soil evaporation. Over the next two decades, increased efficiencies in water application and use are projected to lead to a reduction in irrigation water requirements by 15 to 25 percent. A major challenge for research is to develop further the technologies needed for increasing water use efficiencies for irrigated crop production, both from irrigation and from precipitation on irrigated land. A major need is to increase the crop-yield levels and net returns attained by irrigators and to maintain competitive production from irrigated land.
The financial viability of irrigated agriculture in the High Plains is essential to the development and adoption of the new technologies.

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