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Principles and Practice

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Principles and Practice

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ABSTRACT

Plant- and soil-water principles applicable to irrigation of crops in the Southeastern United States are reviewed. The primary region of application has soils chiefly classified as Udalfs and Udults existing in the udic water regime and thermic temperature regime. The region has more than 40 inches (102 cm) of mean annual precipitation, with less than 5 inches (12.7 cm) of absolute water deficit, and a mean annual soil temperature at the 20-inch (50-cm) depth between 59° and 72° F (15° and 22° C). Most aspects of crop management are discussed, to some degree, in the context of irrigation practice to achieve high yields in this climate and these soils. The response of common crops in the region to irrigation is examined and used to establish irrigation practice.

For typical crop, soil, and climate situations, procedures are outlined for selecting irrigation equipment and for operating the equipment to provide the dependable soil-water control necessary for meeting a crop's water needs. The recommended procedures emphasize crop and soil characteristics and the maintenance of a critical soil volume at less than a specified soil-water suction. Equal emphasis is placed upon excessive water application and the leaching of nitrogen or other mobile nutrients out of the root zone. The option of supplying certain chemicals, particularly readily leached nutrients, through the irrigation system is discussed.

Index terms: climate, crop management, crops, drainage, drip irrigation, drought, erosion, fertilization, irrigation, irrigation-system design, land-resource areas, nutrient management, plant processes, plant rooting volume, soil management, soils, soil-water control level, soil-water control zone, soil-water flow characteristics, soil-water retention, soil-water suction, Southeastern United States, Southern Coastal Plain, Southern Piedmont, sprinklers, tensiometers, tillage, water resources.

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Introduction: Resource Characteristics

The basic relationships of plant growth, soil, and water that have been discovered and defined through years of research are applicable in any climate and geographic region, and have been described by Slatyer (1967), Kozlowski (1968), and Hillel (1971). The application of basic principles to particular plant-soil-water systems, however, presents unique problems. The object of this publication is to review current understanding of plant, soil, and water principles and apply them to irrigation in the Southeastern United States. The practices associated with irrigated agriculture in arid regions are not appropriate in this humid region, where excess water can be as frequent a problem as a water deficit. Rather, irrigation of crops in this climate and on these soils requires appropriately tailored working principles for the effective use of all resources. Consideration is given, therefore, to management of all the soil and cultural variables that affect performance of a given crop in this particular climate.

The rapid increase in irrigated areas, particularly in Georgia, reflects a change in attitude toward irrigation by farmers of the region (table 1). In Alabama, Florida, Georgia, North Carolina, South Carolina, and Virginia the increase has been entirely in sprinkler irrigation and has occurred mostly in the Southern Coastal Plain. Georgia had the largest increase in irrigated area between 1975 and 1978. Peanuts, corn, tobacco, and truck crops accounted for 89 percent of the irrigated area in 1977 (table 2). Several factors have contributed to the increase in irrigation. Institutions have readily provided financing to qualified farmers for purchase of irrigation equipment, and organizations making production loans have rated the use of irrigation as a significant asset. The low labor requirements of some systems like center-pivot, cable-tow, and solid-set and the availability of systems to meet particular crop situations have also been factors. The low power and water-supply requirements of drip or trickle systems and the possibility of applying agricultural chemicals through irrigation systems have been other incentives to acquire equipment.

Too frequently, however, equipment is purchased and water applied before the farmer understands how to use the irrigation system in relation to other facets of crop culture, and crops fail or less than potential benefits are realized. On the other hand, if proper technology is applied to irrigation culture, we can expect 200 bu/acre (12,544 kg/ha) of corn and 6,000 lb/acre (6,720 kg/ha) of peanuts, double the present average yields. Irrigation can no longer be considered an emergency operation to prevent crop failure during a drought. Instead, it must be integrated into a complete strategy for crop management. Potentially, more than one crop a year can be produced in this region. Many crop species are adapted to the climate, but a few species have become economically more important, and these receive particular attention in this publication. They are corn, soybeans, peanuts, cotton, snap beans, cucumbers, southern peas, peaches, and pecans.

Table 1.—Area irrigated in the Southeastern U.S.A., 1978, and change since 1975

State	Irrigated area (acres)[1]	Change since 1975 (%)
Alabama	65,300	103
Arkansas	1,698,500	0
Florida	3,056,000	59
Georgia	784,800	241
Louisiana	662,695	0
Mississippi	501,895	52
North Carolina	161,170	43
South Carolina	49,592	27
Tennessee	19,200	0
Texas	8,950,000	9
Virginia	61,320	41

[1]To convert acres to hectares, multiply by 0.405.

Source: Irrigation Journal (1978).

Table 2.—Georgia irrigation survey, 1960-77[1]

	1960	1970	1975	1977
Total irrigated acreage[2]	98,133	144,629	266,001	592,088
Apples	.....	......	152	1,100
Corn	18,368	30,418	76,996	250,227
Cotton	7,255	2,627	1,116	9,270
Nurseries	1,952	1,453	424	602
Pasture	18,742	5,440	4,613	10,668
Peaches	1,785	1,542	721	1,995
Peanuts	6,360	38,227	91,334	190,544
Pecans	......	485	1,356	4,662
Soybeans	......	795	4,725	21,728
Tobacco	22,202	42,402	54,518	46,081
Truck crops	13,269	20,061	26,223	39,727
Turf nurseries	......	......	1,557	1,764
Vineyards	......	......	145	240
All other crops	8,200	1,179	2,121	7,411
Golf courses (greens and tees)	......	....	......	1,816
Golf courses (fairways, greens, and tees)	.....	......	.....	4,253
Number of irrigation systems	2,549	6,572	7,038	8,343
Portable pipe	.....	6,365	5,026	4,179
Cable-tow	.....	69	1,090	2,585
Center-pivot	.....	87	478	983
Side-roll-lateral	.....	3	11	36
Solid-set	.....	32	122	135
Drip-trickle	.....	.....	.....	21
Unclassified	.....	16	311	404
Number of power units:				
Gasoline engine	.....	2,985	2,009	1,936
L.P. gas engine	.....	1,116	1,377	1,033
Diesel engine	.....	2,292	3,434	4,180
Electric motor	.....	179	329	441
Number of water sources:				
Ponds	1,680	5,542	5,684	5,388
Streams	344	448	574	823
Wells	525	582	1,118	1,771

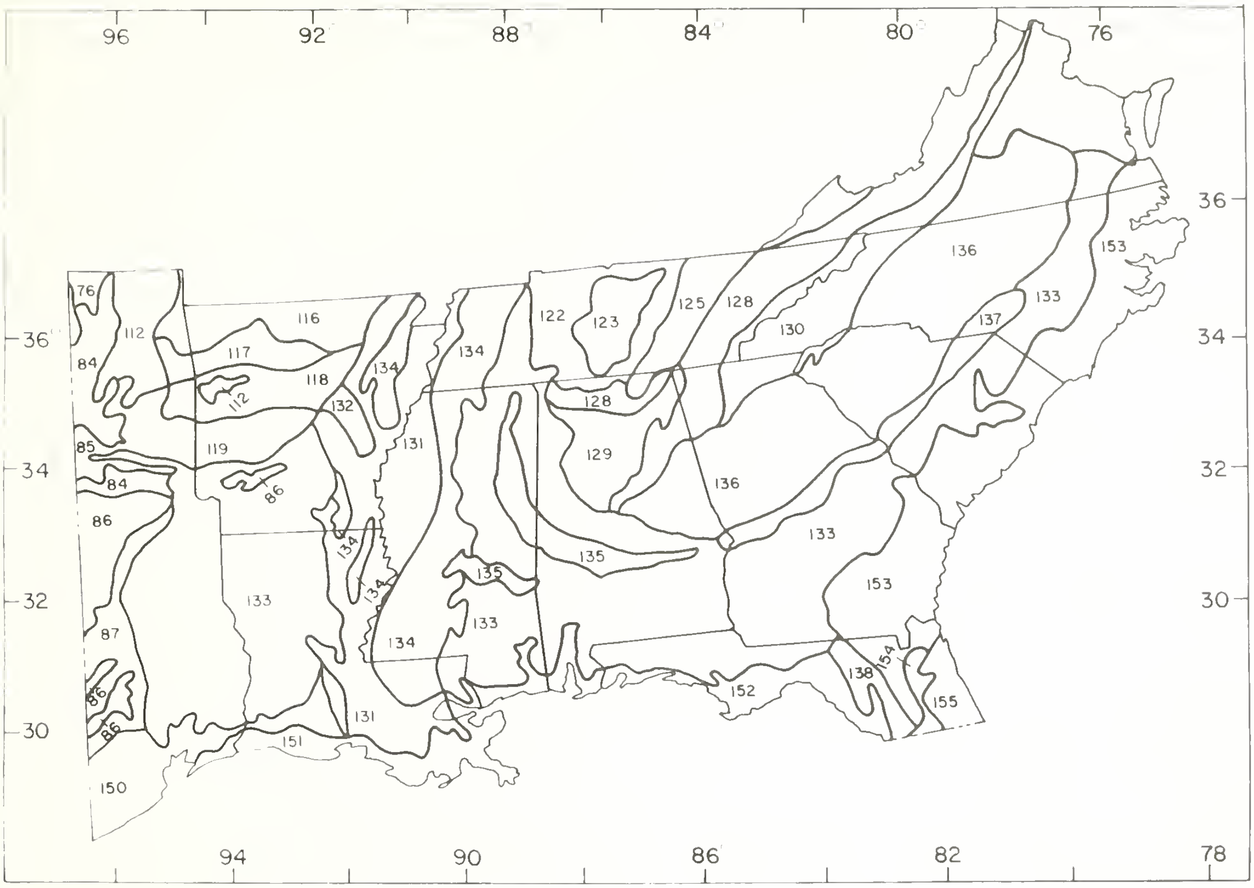
[1]Contributed by Robert E. Skinner, extension engineer, Cooperative Extension Service, University of Georgia.

[2]To convert acres to hectares, multiply by 0.405.

LAND

Figure 1 shows the land-resource areas in the Southeastern U.S.A. The Southern Coastal Plain (map symbol 133) extends from Virginia south through Georgia and west to Texas and makes up 93 million acres (37.7 million ha). North of this region, in Alabama, Georgia, South Carolina, North Carolina, and Virginia, lies the Southern Piedmont (map symbol 136), which makes up 37.8 million acres (15.3 million ha). These two areas will receive major attention, although the land area roughly circumscribed by 30° and 37° N latitude and 77° and 97° W longitude and at less than 1,000 feet (300 m) elevation is considered in the region of application.

Figure 2 further defines the area of application. The soils are classified chiefly as Udalfs and Udults and exist in the udic moisture regime and the thermic temperature regime. This means 59° to 72° F (15° to 22° C) mean annual soil temperature at the 20-inch (50-cm) depth and



76 Bluestem Hills
84 Cross Timbers
85 Grand Prairie
86 Texas Blackland Prairie
87 Texas Claypan Area
112 Cherokee Prairies
116 Ozark Highlands
117 Boston Mountains
118 Arkansas Valley and Ridges
119 Ouachita Mountains
122 High Rim and Pennyroyal
123 Nashville Basin
125 Cumberland Plateau and Mountains
128 Southern Appalachian Ridges and Valleys
129 Sand Mountain
130 Blue Ridge
131 Southern Mississippi Alluvium
132 Eastern Arkansas Prairies
133 Southern Coastal Plain
134 Southern Mississippi Valley Silty
135 Alabama and Mississippi Blackland Prairies
136 Southern Piedmont
137 Carolina and Georgia Sandhills
138 Northern Central Florida Ridge
150 Gulf Coast Prairies
151 Gulf Coast Marsh
152 Gulf Coast Flatwoods
153 Atlantic Coast Flatwoods
154 South Central Florida Ridge
155 Southern Florida Flatwoods

FIGURE 1.—Land-resource areas of 11 Southeastern States. (Source: U.S. Soil Conservation Service 1965.)

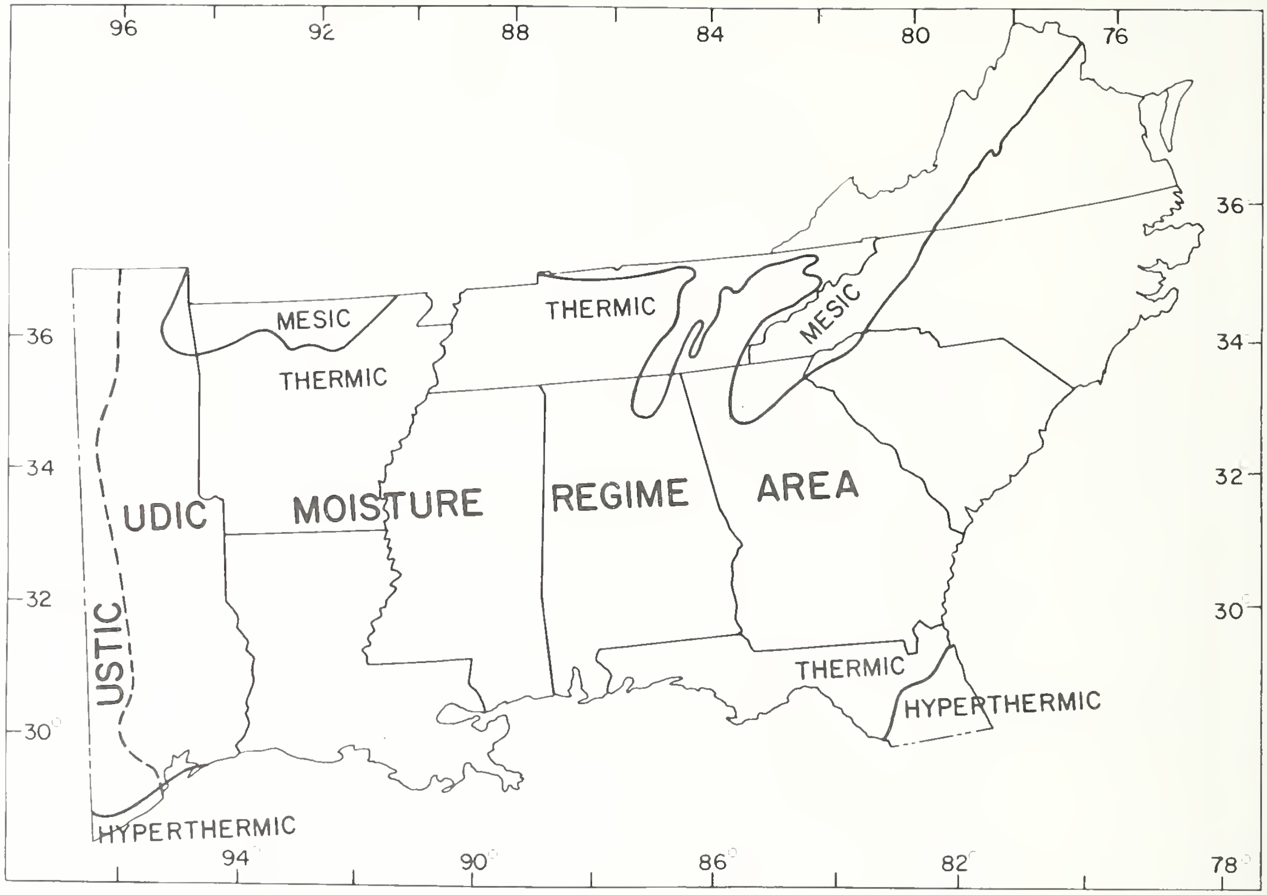


FIGURE 2.—Soil-moisture regime and soil-temperature regime of 11 Southeastern States. (Source: U.S. Soil Conservation Service 1975a.)

either well-distributed rainfall throughout the year or enough summer rain that stored soil water plus rainfall approximates evapotranspiration (U.S. Soil Conservation Service 1975). The udic moisture regime corresponds to more than 40 inches (102 cm) of mean annual precipitation and less than 5 inches (12.7 cm) of absolute water deficit (fig. 3).

CLIMATE

Although everyone is aware of climate and weather variations, weather and climate data often are not fully used in crop production. If irrigation is to be intelligently applied, climate and weather information must be examined simultaneously with plant, soil, and water information. The following look at rainfall and temperature at two sites in Georgia represents a sample treatment. Useful climatic data have been logged, compiled, and reported for each State. These data are available from the State agricultural experiment stations, from the Environmental Studies Service Center, Leach Nuclear Science Center, Auburn University, Auburn, Ala. 36830, or from the National Climatic Center, Federal Building, Asheville, N.C. 28801.

PRECIPITATION

Much of the South, certainly Georgia, is well supplied with water. For example, most of Georgia's water comes from rainfall, which averages about 50 inches (127 cm) a year. Most of Georgia's rainfall comes from warm air masses that form over the Gulf of Mexico; lesser amounts come from the Atlantic Ocean. Average annual rainfall decreases with distance from the Gulf of Mexico and the Atlantic Ocean toward the southern

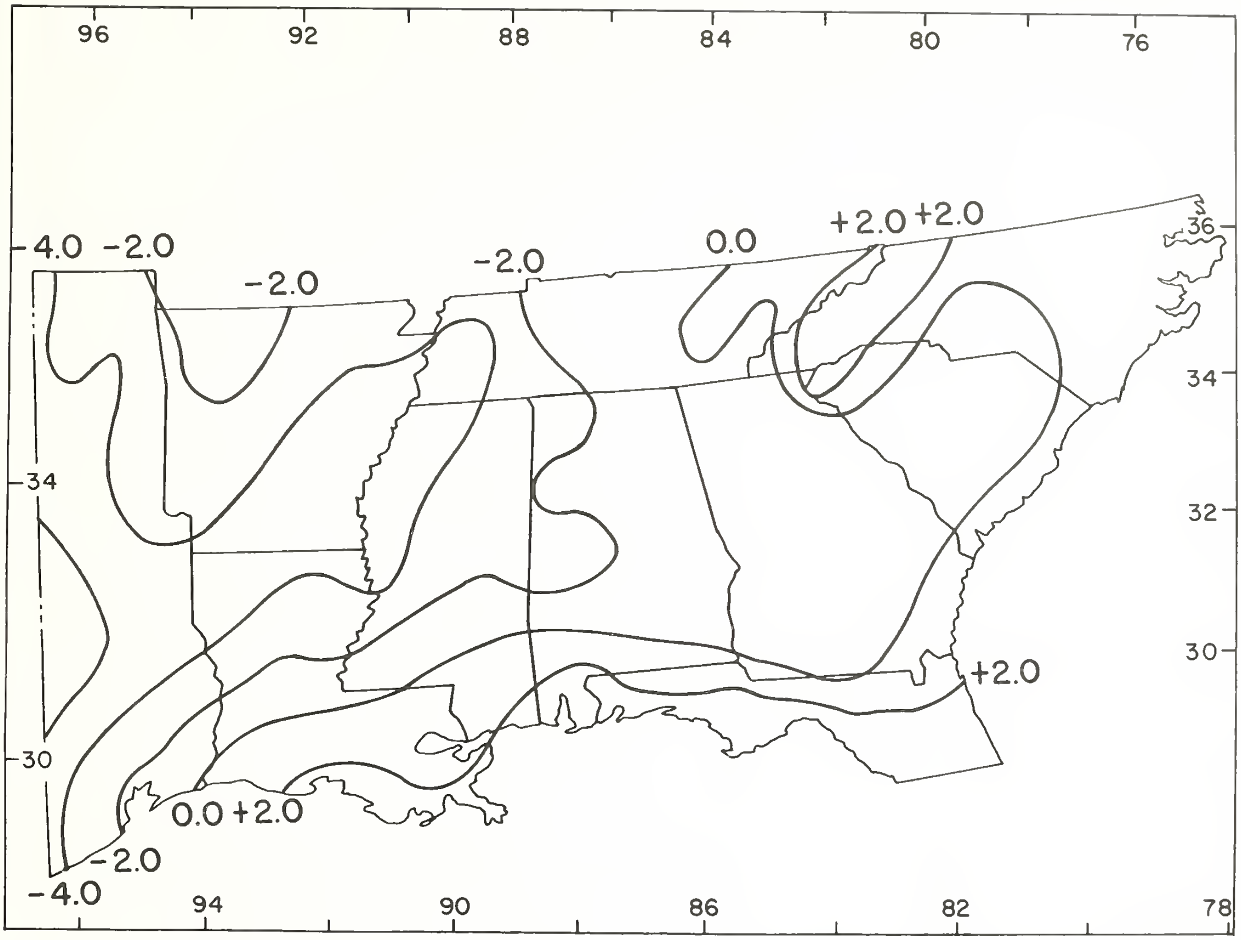


FIGURE 3.—Average absolute moisture deficit or surplus (inches) during June-August for 10 Southeastern States. To convert inches to centimeters, multiply by 2.54. (Source: Palmer 1964; personal correspondence 1971.)

boundary of the Southern Piedmont. Average annual rainfall increases north of this line because the moist air is forced to rise, and it precipitates as it passes over the higher land.

Figure 4 gives the average annual rainfall distribution for Georgia. This map does not show the variation in rainfall that occurs from year to year at all locations. For example, during the 1954 drought, generally considered the most severe in recent history, the rainfall deficiency over the State was about 15 inches (38 cm). There are also seasonal variations, which vary in character across the State. For example, more rain generally falls in winter and early spring than in May, June, and fall.

The tremendous variation of rainfall over time and area and the uncertainty of its occurrence make application of plant- and soil-water principles difficult. Regulating water in the root environment is much easier when there is low probability of rainfall, as in the arid West. Unexpected rain after a heavy irrigation can cause excess-water problems and severe plant damage, especially in somewhat poorly and poorly drained soils. Other potential problems that can occur from excess water (irrigation plus rain) are leaching and washoff of plant nutrients and pesticides, erosion, and reduction of soil stability, thus delaying needed equipment operations.

Proper water management requires an understanding of the general character of rainfall in a given area and its impact on plants in terms of water deficits and excesses. An analysis of the rainfall character in concert with plant, soil, and other climatic information can help a farm manager decide whether supplemental water is needed, as well as the type of application system and system operation needed. Athens and Tifton,

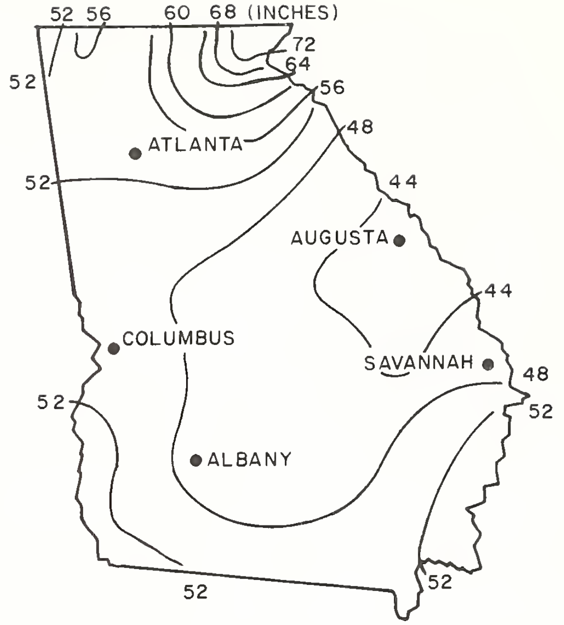


Figure 4.—Average annual precipitation in Georgia. To convert inches to centimeters, multiply by 2.54. (Source: Callahan et al. 1965.)

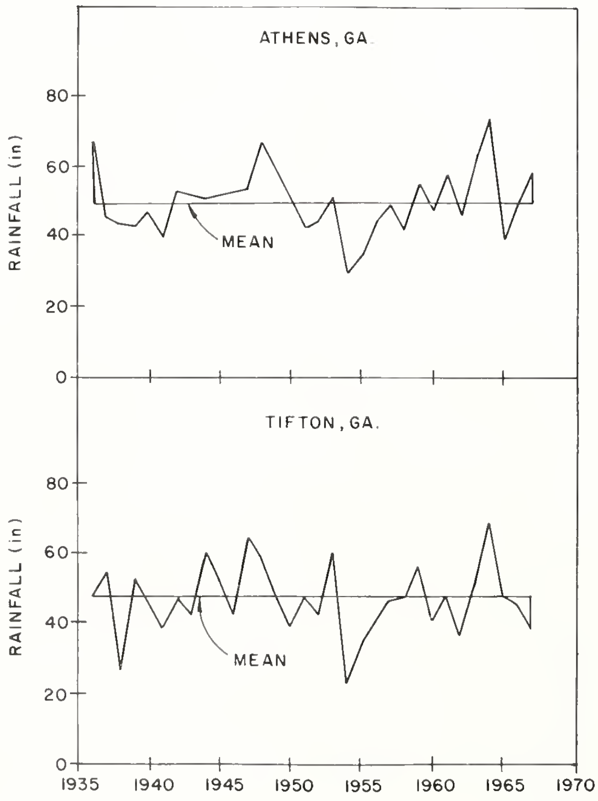


Figure 5.—Annual rainfall distribution for Athens and Tifton, Ga., from 1936 to 1967. To convert inches to centimeters, multiply by 2.54. (Source: Crosby et al. 1970.)

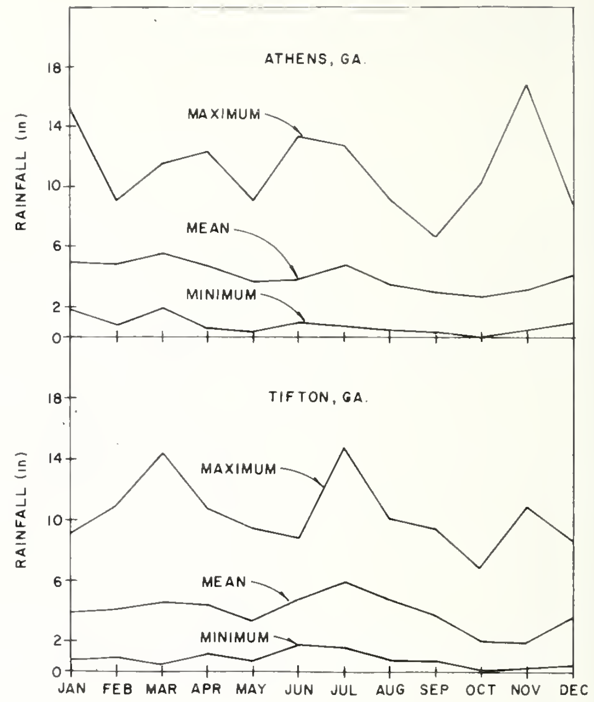


Figure 6.—Monthly rainfall distribution for Athens and Tifton, Ga., from 1936 to 1967. To convert inches to centimeters, multiply by 2.54. (Source: Crosby et al. 1970.)

Ga., were selected as sample sites where important rainfall characteristics are examined. These sites are in the Southern Piedmont and the Southern Coastal Plain, respectively, and are generally characteristic of their climates.

Figure 5 gives the annual rainfall distribution for Athens and Tifton from 1936 to 1967. Although the means were almost equal, the rainfall at the two sites for any given year varied as much as 40%. The main point, however, is not the between-year variation at the two sites but the within-year variation at each site. Consequently, such gross information is of limited value in making plant-water management decisions and more detailed analysis is required.

Figure 6 gives the monthly rainfall distributions for Athens and Tifton from 1936 to 1967. The maximum and minimum curves for each location indicate that extreme variations occurred within months. Again, average values do not mean much, but some useful information exists in the trends. For example, at Tifton, May is normally drier than other spring months; June, July, and August are considerably wetter; and October and November are very dry.

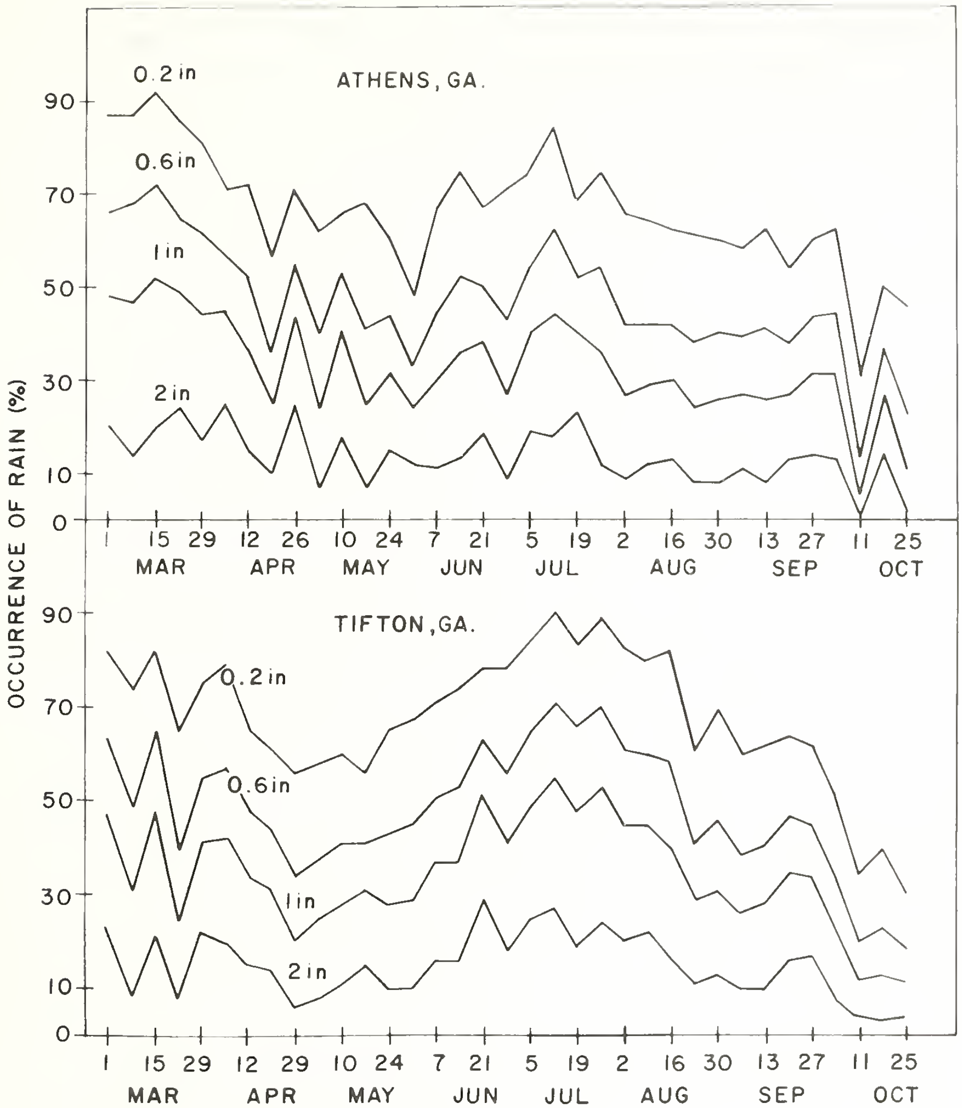


FIGURE 7.—Occurrence of indicated amount of precipitation in a 1-week period, Athens and Tifton, Ga. To convert inches to centimeters, multiply by 2.54. (Source: Crosby et al. 1970.)

Figure 7 shows the occurrence of indicated rain in 1-week periods for Athens and Tifton, based on the number of rainfall observations in the total population. Figure 8 gives the occurrence of indicated rain in a 24-hour period by months. Although such statistics do not predict future rainfall, this type of information accompanying plant and soil data allow one to plan a certain amount of water management. When utilizing such rainfall information for plant use, one must be sure to account for losses such as runoff and leaching below the root zone.

Excesses as well as deficits of rain can occur and cause problems. Consequently, any well-planned water-management system and its operation will include drainage considerations. Since plants and soils vary considerably in susceptibility to excess water, interpretation of the information in figure 8 is specific for each plant-soil system.

In addition to rainfall, evapotranspiration data are useful in planning water-management systems. Since information on evapotranspiration is often difficult to obtain, pan evaporation is used as a potential index of atmospheric water losses. Figure 9 gives the monthly evaporation and rainfall distribution for Athens and Tifton. In addition, the percentage of years that evaporation

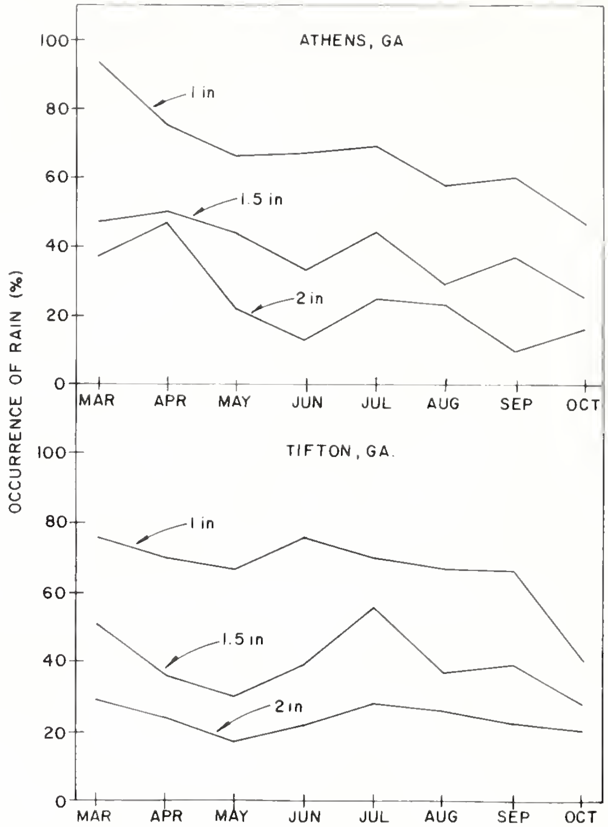


Figure 8.—Occurrence of indicated amount of precipitation in a 24-hour period, Athens and Tifton, Ga. To convert inches to centimeters, multiply by 2.54. (Source: Crosby et al. 1970.)

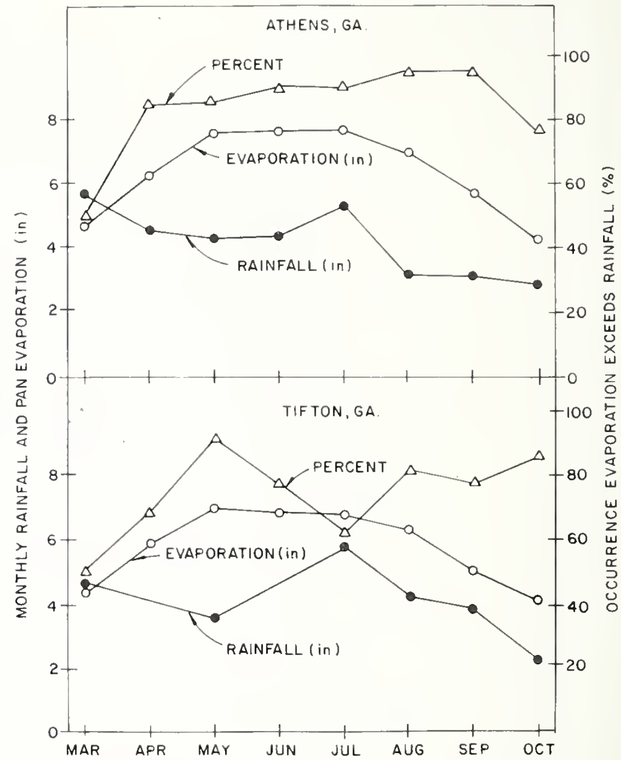


Figure 9.—Monthly rainfall, pan evaporation, and percentage of years that evaporation exceeded rainfall in Athens and Tifton, Ga., from 1946 to 1967. To convert inches to centimeters, multiply by 2.54. (Source: Crosby et al. 1970.)

exceeded rainfall is given. Clearly, the potential for atmospheric water loss exceeds rainfall during most of the year.

Temperature

Temperature is one of the most important climatological elements affecting agriculture. The temperature regime depends primarily on incident solar radiation, which is a function of latitude and time of year. However, other factors such as distribution of land and water surfaces, prevailing winds, ocean currents, and topography significantly influence temperature regimes. The warm waters in the Atlantic Ocean and the Gulf of Mexico and the mountains in the northern part of the State modify the latitudinal influence over Georgia temperatures considerably. The net result is short mild winters in the south and much colder winters in the north. The average annual temperature ranges from 56° F (13° C) in the northeast to 69° F (21° C) near the coast in the southeast.

Temperatures, like rainfall, vary tremendously from year to year and within years. Except for concern about late-spring frost, temperature has not been used very much in agricultural planning. With use of intensive agricultural systems, more attention will probably be given to the temperature regimes in the aerial and root zones of the plants. Recognition of temperature, especially late-spring and early-fall frosts, will allow better planned multiple-cropping systems, and such systems will be more common as better water-management practices are accepted.

Figure 10 gives the maximum, mean, and minimum monthly temperature distribution for Athens and Tifton, Ga., from 1936 to 1967. One factor the locations have in common is the small variation in maximum and minimum temperatures in the summer as compared to the winter months. The winter months can be rather mild or quite cold. In general, the winters are

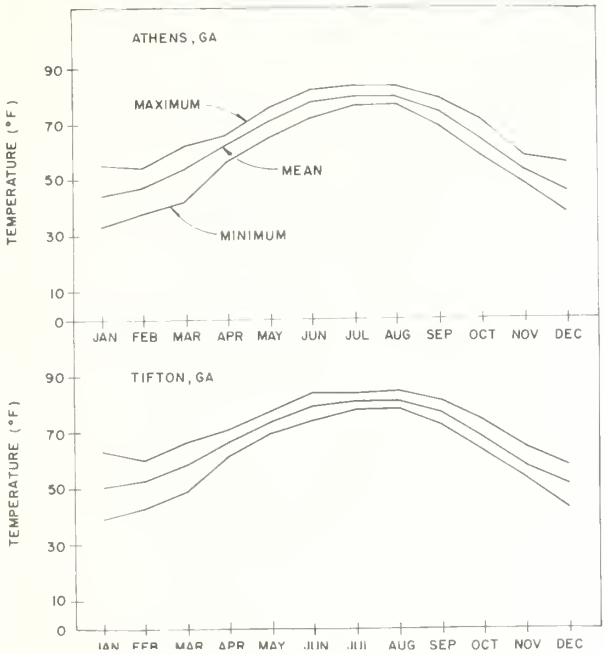


FIGURE 10.—Monthly temperature distribution for Athens and Tifton, Ga., from 1936 to 1967. To convert degrees Fahrenheit to degrees Celsius, subtract 32 and multiply by 5/9. (Source: Crosby et al. 1970.)

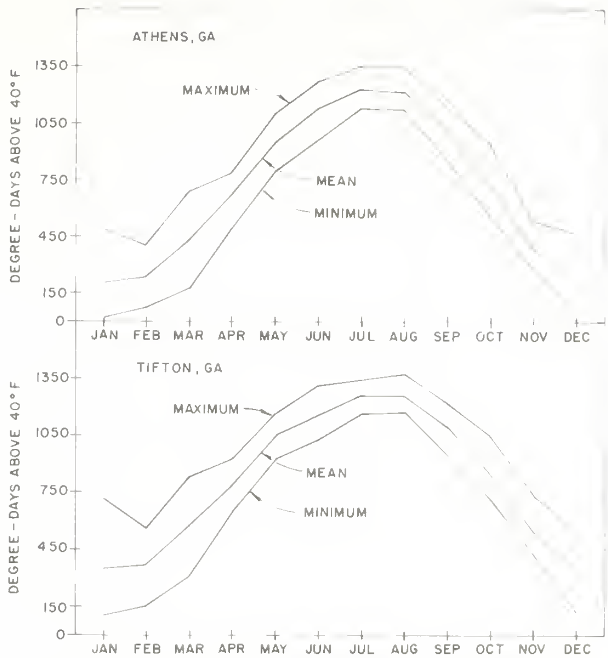


FIGURE 11.—Monthly distribution of growing degree-days above a base of 40° F (4° C), Athens and Tifton, Ga. (Source: Crosby et al. 1970.)

milder at Tifton, but there is very little difference in the summer temperatures. Figure 11 gives the annual distribution of monthly growing degree-days above 40° F (determined by subtracting 40 from mean monthly temperature (° F) and multiply by number of days in the month). The growing degree-day is an index of potential plant activity.

A farmer's main concern about temperature is the potential for frost damage. Several climatological conditions can cause frost damage to plants. Hoarfrost is the deposit of feathery ice crystals on surfaces near the ground. The frost is formed by water vapor changing directly into ice crystals without going through the liquid state. Hoarfrost forms when the air with a dew point below freezing is brought to the saturation point by radiant cooling. The observed temperature may be above 32° F (0° C) during these frost conditions. Black frost (a dry freeze) occurs when the temperature drops below 32° F. The damaged plant tissue turns black from the freezing, but there are no visible ice crystals since the temperature does not reach the dew point. Figure 12 gives the dates of the last time in spring and first time in fall that temperatures are equal to or less than 32° F for Athens and Tifton, Ga. Tremendous variation exists around the mean dates.

Susceptibility to freeze damage varies greatly with plant species as well as with different stages of development of the same plant. Other factors that tend to influence freeze damage are duration of freezing temperatures, temperatures before the freeze, suddeness of the temperature drop, and wind (dessicating wind contributes enormously to damage). In general, plants are classified as tender, semihardy, and hardy according to their ability to survive low temperatures.

To categorize degrees of freezing, three temperature classes have been used—light, moderate, and severe (Carter 1957). In a light freeze [32° to 29° F (0° to -2° C)] tender plants are killed. In a moderate freeze [28° to 25° F (-2° to -4° C)] there is some damage to most plants, with heavy damage to fruit blossoms and semihardy plants. A severe freeze [24° F (-4° C) and lower] heavily damages most plants. Adopting these temperature classes, the chance of such occurrences in the spring and fall were developed for Athens and Tifton. Figure 13 gives the occurrence of a spring temperature equal to or less than 32°, 28°, or 24° F on a given date or

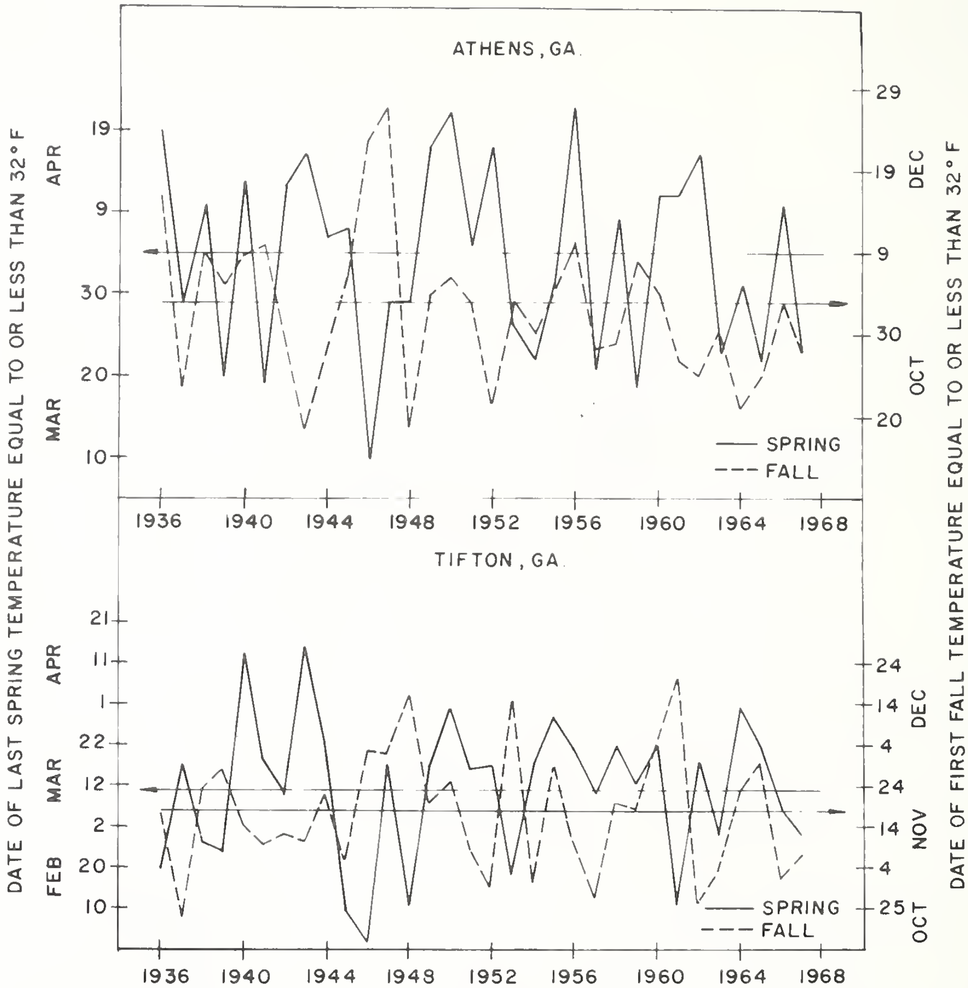


Figure 12.—Last date in spring and first in fall that temperatures are equal to or less than 32° F (0° C), Athens and Tifton, Ga., from 1936 to 1967. The straight lines are the mean dates. (Source: Crosby et al. 1970.)

later. Figure 14 gives the occurrence of the first fall temperature equal to or less than 32°, 28°, or 24° F on a given date or earlier. These figures should help farm managers schedule planting and harvesting of temperature-sensitive crops.

WATER

Although the Southeast generally has an abundant supply of high-quality water, the quantity of water required for large irrigation systems is not uniformly available at acceptable cost. The type and quantity of water supplies are strongly influenced by topography, soils, and geology. In Georgia, for example, the average annual precipitation is 50 inches (127 cm) and the average annual runoff ranges from 8 to 40 inches (20 to 102 cm), which is considerably more variable than the rainfall. Thus, the amount of water that actually infiltrates the soil is quite different in different areas.

Georgia can be divided into two major geographic areas, north and south of the Fall Line. This geologic divide, running through Columbus, Macon, Milledgeville, and Augusta, separates two areas that can be described in general terms of water availability. North of the Fall Line, the major source of irrigation water is small farm ponds. With high runoff and desirable topographic features in this area, farm ponds offer excellent holding reservoirs. However, farm ponds are not generally large enough to hold sufficient water for large irrigation systems. Consequently,

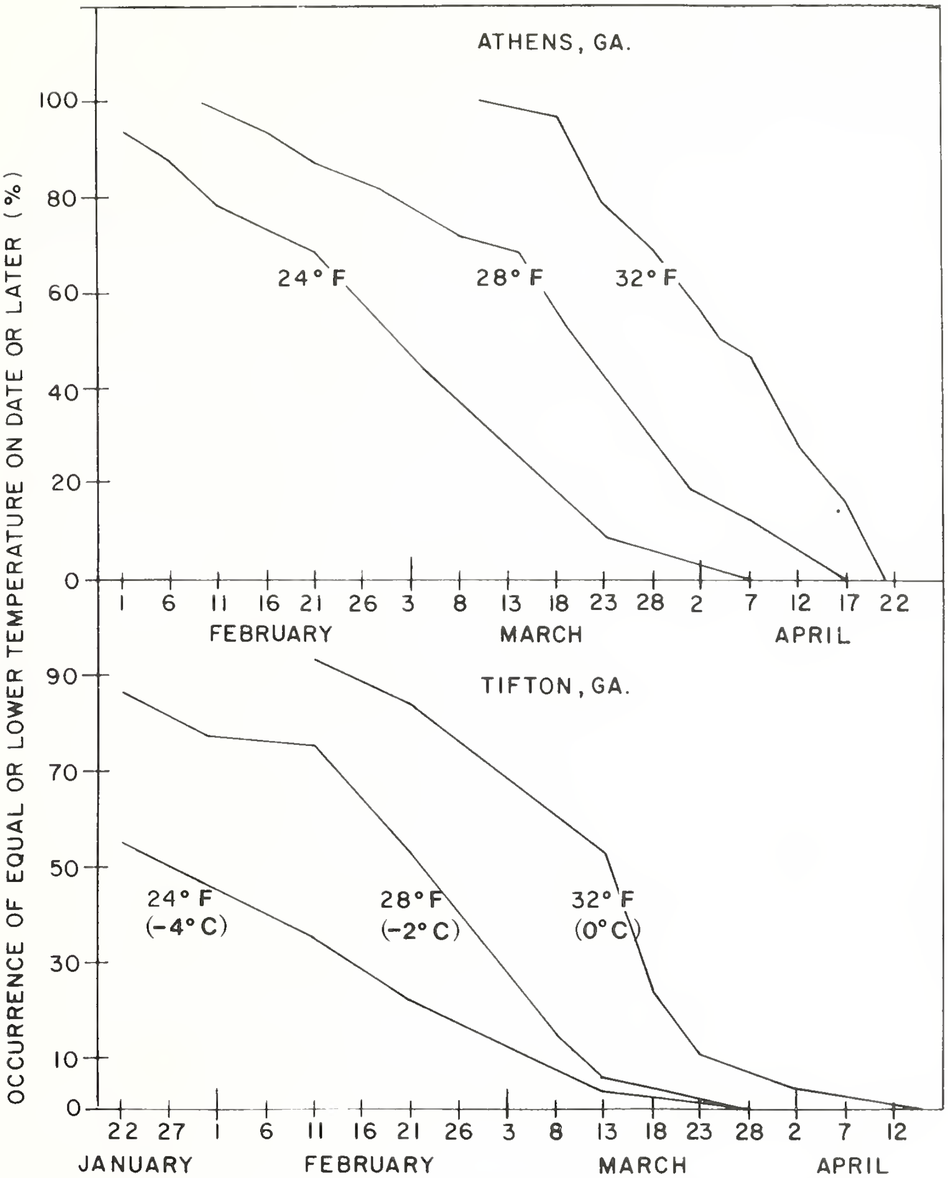


FIGURE 13.—Occurrence of a spring temperature equal to or less than the indicated temperature on a given date or later, Athens and Tifton, Ga. (Source: Crosby et al. 1970.)

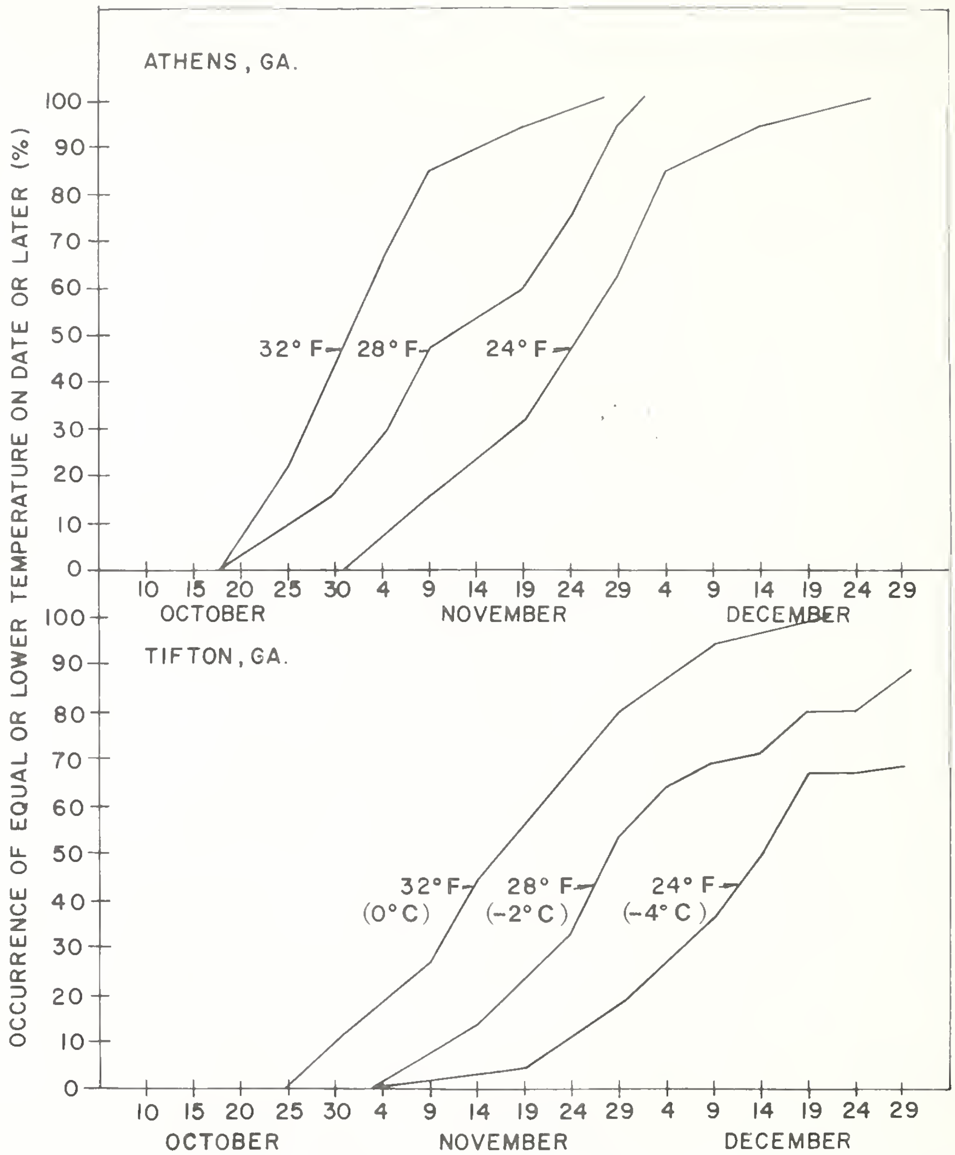


FIGURE 14.—Occurrence of a fall temperature equal to or less than indicated temperature on a given date or earlier, Athens and Tifton, Ga. (Source: Crosby et al. 1970.)

these ponds are used primarily to supplement the water needs of small acreages of high-value crops. The Piedmont and Blue Ridge provinces are underlain by metamorphic and igneous rocks (crystalline rocks) where ground-water yields are low. Generally, wells in this region are not adequate for sprinkler irrigation supply since yields range from less than 30 gal/min (114 l/min) to a maximum of 500 gal/min (32 l/s). There is one unique area north of the Fall Line, however; in northwestern Georgia Paleozoic formations (fig. 15) can produce between 600 and 3,500 gal/min (38 to 221 l/s).

Farm ponds are not only used north of the Fall Line, they are also plentiful in the Southern Coastal Plain. In addition, irrigation pits, which tap shallow ground-water aquifers, are common in the lower Southern Coastal Plain and the Atlantic Coast Flatwoods. Again, these water resources are used to supplement the water needs of small acreages of high-value crops. However, ground water has been the water source for many of the large irrigation systems in southern Georgia.

The artesian aquifers found in the Southern Coastal Plain are some of the most prolific aquifers in the world. These aquifers provide high-yielding wells if proper construction techniques are used. Many of these aquifers are sand, and well construction requires well screens and gravel packing. In the Southern Coastal Plain, the sedimentary rocks can be thought of as a series of inclined wedges that become thicker and become buried by younger sediments towards the south or southeast. Consequently, at some locations one can drill a well that would penetrate successively older rocks and possibly tap two, three, or four major aquifers. For example, in Dougherty County, Ga., it is possible to tap the Ocala Limestone and the Tallahatta Formation, which form part of the principal artesian aquifer, and still deeper tap the Clayton aquifer and Upper Cretaceous sand aquifers.

The legend of figure 15 gives the sequence of water-bearing formations in Southern Georgia from the youngest to the oldest. As the map shows, some areas of Georgia have ground-water supplies that have the potential for supporting large irrigation systems.

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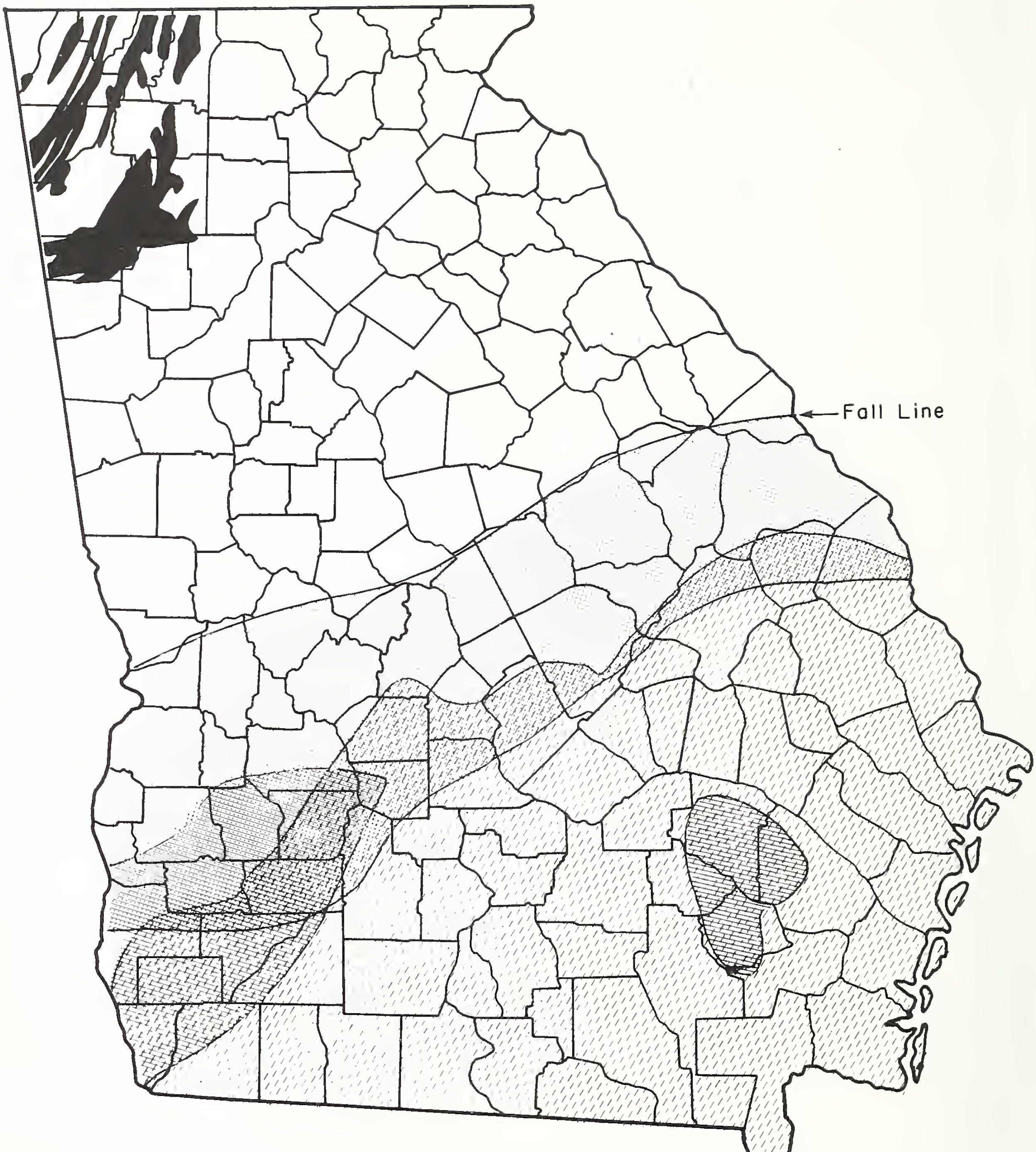
Fall Line

FIGURE 15.—Major aquifers in Georgia and their geologic system, principal stratigraphy, and lithology. (Compiled by David E. Swanson, Georgia Department of Natural Resources, Atlanta.)

Aquifer symbol	System or series	Principal stratigraphic unit	Primary lithology	Remarks
		Northern Georgia (North of Fall Line)		
	Pennsylvanian through Cambrian.	Undiff	Limestone, dolomite.	Well yields average from 5 to 200 gal/min (19 to 757 l/min); however, favorable well sites can yield from 600 to 3,500 gal/min (38 to 221 l/s).
	Pennsylvanian through Cambrian.	Undiff	Limestone, chert, sandstone, shale.	Poor (0-30 gal/min or 0-114 l/min) to intermediate (up to 500 gal/min or 32 l/s) yields are possible. Water quality is often poor, especially because of excessive iron.
		Southern Georgia (South of Fall Line)		
	Miocene	Tampa Ls	Limestone	Forms upper part of principal artesian aquifer. Yields 300 gal/min (19 l/s) in Glynn County.
	Oligocene	Suwannee Ls	Limestone	Forms part of the principal artesian aquifer. This unit yields 1,400 gal/min (88 l/s) in Screven County. May be capable of 1,000 gal/min (63 l/s) in Thomas County.
	Upper Eocene	Ocala Ls	Limestone	Major unit in the principal artesian aquifer. Capable of yielding as much as 11,000 gal/min (694 l/s) in Glynn County area. Often used in conjunction with other limestone units. Several thousand gallons per minute is generally available throughout area shown.
	Middle Eocene	McBean Fm, Lisbon Fm, Avon Park Fm, Tallahatta Fm, Lake City Fm.	Sand, clay, marl, limestone.	Forms part of lower confining bed for the principal artesian aquifer in southeast Georgia. Yields well in southwest portion of State—1,400 gal/min (88 l/s) in Dougherty County. Often used with younger or older units. Saline water present along coast and along portions of south border.
	Paleocene	Clayton Ls	Limestone	Important aquifer in southwest Georgia. Yields as much as 1,700 gal/min (107 l/s) in Dougherty County. Often yields several hundred gallons per minute in area shown.
	Upper Cretaceous	Providence Sd, Ripley Fm, Cusseta Sd, Blufftown Fm, Eutaw Fm, Tuscaloosa Fm.	Sand, clay, gravel, marl.	Sands and gravel of the Providence, Cusseta, and Tuscaloosa yield large quantity of water. 1,000 gal/min (63 l/s) obtained in Sumter County. Very productive aquifer throughout area shown.

Abbreviations: Fm, Formation. Ls, Limestone. Sd, Sand. Undiff, Undifferentiated.

Plant- and Soil-Water Principles

Plants live with roots in one environment, the soil, and shoots in another, the air, and their growth reflects the integration of the variations in each. Knowledge of the effects of both environments upon plant growth is therefore required before crops can be intelligently managed. A crop is an association of plants that compete for space and vital elements of the environment, such as light, carbon dioxide, water, and nutrients, and so interactions related to cultural patterns must also be understood. Only a brief discussion of topics most relevant to irrigation practice will follow. An extended discussion may be found in reviews by Slatyer (1960, 1967) and Kozlowski (1968).

SOIL

The characteristic response of soils in the Southern Coastal Plain, Southern Piedmont, and similar climatic regions to tillage, other cropping operations, rainfall patterns, and irrigation is affected to a large degree by the texture of the surface and upper subsoil layers or horizons. In managing or regulating water in these soils it is important to specify the depth of soil available for root proliferation, the soil-water retention characteristics of this zone, and the waterflow characteristics. Thus, in tables 4 and 5 soil groupings based on the texture of the surface and subsurface layers have been specified and designated by letter. Although the effect of texture on soil response may be modified by amount and kind of organic matter and mineralogy, the response of major areas of cropped soils of the Southeastern U.S.A. is closely related to texture. When making irrigation recommendations or prescriptions, texture is therefore the first soil information needed.

In that part of the Southeast unaffected by wind-blown deposits from the Mississippi flood plain, only sand, loamy sand, sandy loam, sandy clay loam, sandy clay, clay, and sometimes loam and clay loam textures occur. It is important to specify the sand-size distribution, for example, coarse, medium, or fine sandy loam. Root proliferation, water retention, and soil-water flow characteristics of the region are associated with soil texture or particle-size distribution of soil layers or horizons in the potential rooting depth.

Rooting Volume

The soil volume that plant roots enter and from which the plant obtains nutrients and water is often referred to as the rooting volume. The size

(Continued on page 20.)

Table 3.—Effect of soil compaction on yield of irrigated sweet corn, cucumber, and southern pea, Tifton, Ga., 1975[1]

	Crop yield		
	Sweet corn (crates/acre)[2]	Cucumber (dollars/acre)[2]	Southern pea (pounds/acre)[3]
Noncompacted	228	317	2,409
Compacted	200	244	1,873

[1] Irrigation applied to both treatments when soil-water suction of noncompacted treatments at 6-inch (15-cm) depth reached 0.4 bar.

[2] To convert to per-hectare values, multiply by 2.471.

[3] To convert pounds per acre to kilograms per hectare, multiply by 1.12.

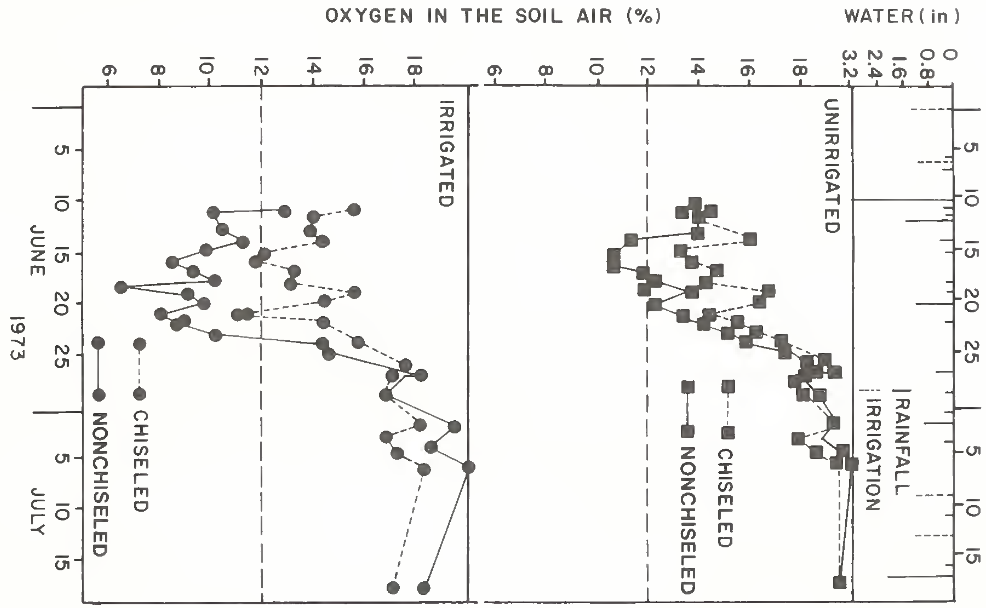

FIGURE 16.—Oxygen in soil air at 10-inch (25-cm) depth in Varina sandy loam during June and July 1973. Chisel depth was 15 inches (38 cm). To convert inches to centimers, multiply by 2.54. (Source: Doty et al. 1975.)

Table 4.—Characteristics of soil-texture groupings for Southern Piedmont soils

Soil-texture grouping	Layer	Soil texture	Maximum depth available for water regulation (inches)[1]	Water retention, inch/inch, at suction of—						Maximum water application rate (inch/hour)[2]
				0.03 bar	0.06 bar	0.25 bar	0.50 bar	0.75 bar	1.0 bar	
A	Surface	Loamy sand or coarse sandy loam.	7	0.22	0.17	0.125	0.11	0.105	0.10	0.5
	Subsoil	Sandy clay loam, clay loam, or clay.	11	.36	.34	.32	.30	....	.29	
B	Surface	Sandy loam	6	.28	.23	.17	.165	.155	.15	.5
	Subsoil	Sandy clay loam, clay loam, or clay.	12	.36	.34	.32	.30	....	.29	
C	Surface	Loam to clay loam	6	.35	.34	.32	.31	.30	.295	.3
	Subsoil	Sandy clay loam, clay loam, or clay.	12	.36	.34	.32	.30	....	.29	

[1] To convert inches to centimeters, multiply by 2.54.
[2] To convert inches per hour to centimeters per hour, multiply by 2.54.

Table 5.—Characteristics of soil-texture groupings for Southern Coastal Plain soils

Soil-texture grouping	Layer[1]	Soil texture	Water retention, inch/inch, at suction of— 0.025 bar	0.05 bar	0.10 bar	0.25 bar	0.50 bar	1.0 bar	Maximum water application rate (inch/hour)[2]
A	Surface	Sand and loamy sand	0.29	0.20	0.13	0.10	0.08	0.07	0.7
	Subsoil	Sand and loamy sand	.29	.20	.13	.10	.08	.07	
B	Surface	Sand and loamy sand	.29	.20	.13	.10	.08	.07	.7
	Subsoil	Sandy loam and fine sandy loam.	.31	.26	.20	.17	.15	.13	
C	Surface	Sand and loamy sand	.29	.20	.13	.10	.08	.07	.5
	Subsoil	Sandy clay loam and sandy clay.	...	.30	.27	.25	.23	.22	
D	Surface	Loamy fine sand	.29	.25	.18	.13	.11	.09	.5
	Subsoil	Sandy clay loam and sandy clay.	...	.30	.27	.25	.23	.22	
E	Surface	Loamy fine sand	.29	.25	.18	.13	.11	.09	.5
	Subsoil	Sandy loam and fine sandy loam.	.31	.26	.20	.17	.15	.13	
F	Surface	Sandy loam and fine sandy loam.	.31	.26	.20	.17	.15	.13	.5
	Subsoil	Sandy clay loam and sandy clay.	...	.30	.27	.25	.23	.22	

[1] Maximum layer thickness available for water regulation is 10 inches (25 cm)
[2] To convert inches per hour to centimeters per hour, multiply by 2.54.

and shape of the rooting volume are not static but depend upon crop species, stage of growth, crop culture, tillage, and several physically, chemically, or biologically limiting soil conditions. Important as soil characteristics may be, it is important to maintain focus on the crop and satisfying its requirements for a desired level of performance. This statement may appear self-evident and trite unless the distinction between irrigated and unirrigated culture in the Southeastern U.S.A. is made. In unirrigated culture, the capacity of a soil to retain water and the proliferation of plant roots into a large soil volume are a primary concern because the crop depends on infiltrated rainfall for water. In irrigated culture, however, the water retention of soils and extent of rooting are much less important in this region because frequent irrigation with smaller quantities of water is necessary to maintain an adequate supply of mobile nutrients (for example, nitrogen) to the crop. It is extremely important that the distinction be made between irrigated culture and unirrigated culture in defining the plant-soil-water system.

The primary function of tillage is to modify either the dimensions of the rooting volume—for example, depth—or the environment for root growth and function — for example, aeration conditions. Preplant tillage must provide a desirable condition for seed germination and seedling emergence as well as assure a satisfactory depth of soil for ready root penetration. Certainly, deep rooting of crop plants provides a measure of insurance against drought. However, the benefit derived from tillage that may allow deeper rooting is difficult to predict since it depends not only upon crop species and variety but also on the imposed culture and the weather patterns. If a crop is not irrigated and depends upon the vagaries of the weather, deep rooting is very important.

Plowing and subsoiling operations usually produce a loose soil (large pore space, low bulk density) that allows plant roots to penetrate easily. Most tillage practices imposed after plowing and subsoiling compact the soil and either restrict root penetration or increase the energy expended by the plant in penetrating the soil. Therefore, tillage after subsoiling and plowing should be minimized (Reicosky et al. 1977). In fact, a minimum of tillage is always desirable. The effect of soil compaction that may result from multiple-disk harrowing operations on yield of sweet corn, cucumber, and southern pea (table 3) indicates the detrimental effect of unnecessary field traffic. Root growth and soil-water measurements showed that the 12% to 24% yield reduction with compaction was due to restricted root growth and inefficient utilization of soil water and nutrients.

A few realities must be accepted: the soils in the Southeast characteristically do not permit crops to root deeply; many soils, because of their particle-size distribution, become increasingly restrictive to rooting when they receive implement traffic and excess tillage in seed-bed preparation; rooting may be further restricted by chemical characteristics of the soil; and less rooting volume is necessary when proper water regulation is done by irrigation. For proper irrigation, the farmer must know the effective rooting volume and be certain that soil-water-measuring equipment is sensing the actual rooting volume.

Tables 4 and 5 specify the maximum zone available for water regulation, not the actual depth of surface and subsoil encountered. For example, the thickness of surface soil in a particular area of interest may be 8 inches and not the maximum thickness of 10 inches specified in table 5. The actual depth of the subsurface layer that is readily proliferated by roots and therefore available for water regulation must be specified in each cropping situation. If rooting is restricted by a compacted zone from implement traffic, deep chiseling may be necessary to obtain sufficient depth for water regulation. A minimum rooting depth probably exists which makes water regulation practically impossible and which increases the hazard of excess water during periods of frequent rainfall. Application of the data in tables 4 and 5 presumes the use of actual depth of surface soil and subsoil appropriate for each soil and crop situation.

Data in figure 16 from experiments at Florence, S.C., support the need for increased rooting depth by deep chiseling if crops are not irrigated. In this experiment on a soil with a sandy loam surface layer and a sandy clay subsoil (Varina sandy loam), evidence of poor aeration occurred for a longer period on nonchiseled, irrigated plots. In table 6 annual dry-matter yields of millet in 1969, a wet year, are compared with yields in 1970, a dry year. Irrigation without chiseling in 1969 was not productive. So in this case, where rooting was restricted to the plow layer, deep chiseling was required to reduce the effect of drought and provide a rooting volume for more ready water regulation by irrigation. In this situation, chiseling was done to a depth of 15 inches (38 cm) on a 10-inch (25-cm) interval to eliminate the root restriction between 7 and 12 inches (18 and 30 cm).

The extent of rooting may be restricted by excess manganese and aluminum or by soil pH. If these conditions exist in the surface soil, lime, fertilizer, and other amendments may be incorporated to obtain a suitable environment for root growth. However, modifying subsoil chemical environment is very difficult and expensive (Lund and Elkins 1978). To circumvent chemical modification of the soil, select crop species and varieties that tolerate the soil condition.

Water Retention

Tables 4 and 5 give water-retention data for the surface and subsurface layer of each soil-texture grouping. The values in these tables give the depth of water per unit depth of soil at six soil-water suctions ranging from 0.025 or 0.03 to 1 bar.

Table 6.—Annual dry-matter yields of millet from chiseled and nonchiseled treatments with and without irrigation, Florence, S.C., 1969 and 1970[1]

Treatment	Tons per acre[2]	
	1969	1970
Nonchiseled	3.67a	4.54a
Nonchiseled + irrigation[3]	4.17ab	6.18c
Chiseled	4.24ab	5.24b
Chiseled + irrigation[3]	4.91b	6.33c

[1] Rainfall during the growth period was 20 inches (50.9 cm) in 1969 and 14 inches (35.0 cm) in 1970. Yields followed by a common letter within each year are not significantly different at the 5% level.

[2] To convert tons per acre to metric tons per hectare, multiply by 2.24.

[3] 5.1 inches (13 cm) of water applied in 1969 and 15 inches (38 cm) applied in 1970.

Source: Doty et al. 1975.

This is a selected range in a continuous relationship between soil-water content and soil-water suction that starts at zero soil-water suc-

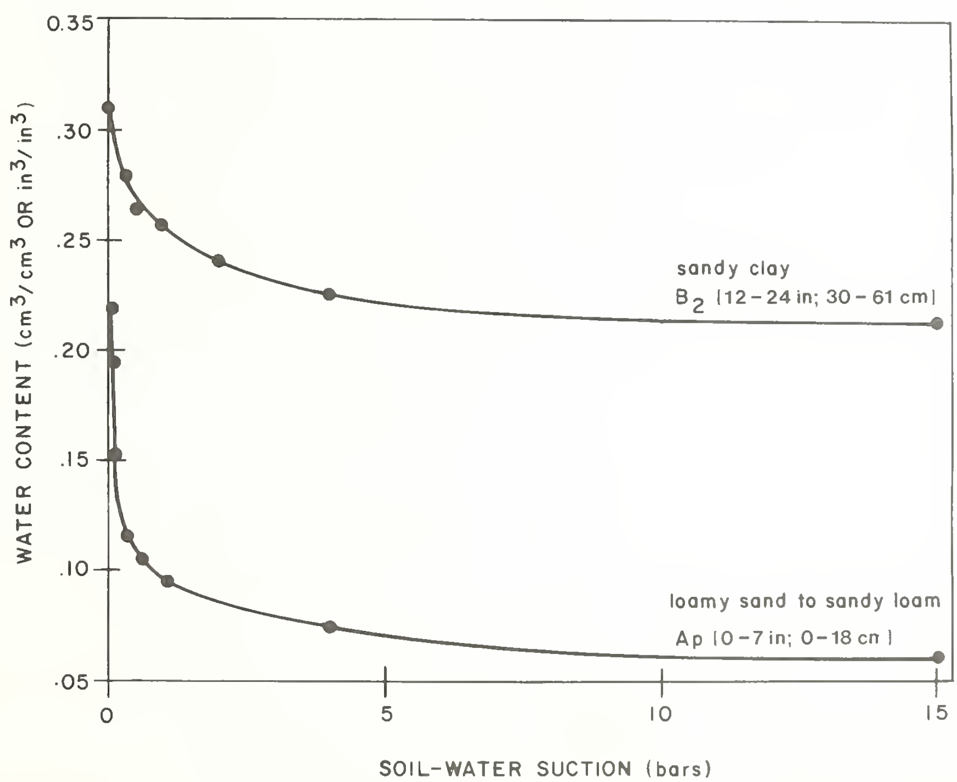

FIGURE 17.—Water retention for Ap and B_2 horizons of a Faceville loamy sand to sandy loam.

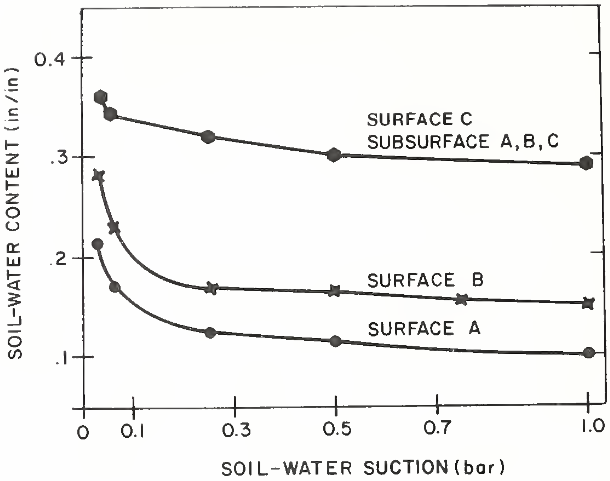

FIGURE 18.—Soil-water retention for surface and subsurface layers of Southern Piedmont soils. A, B, and C refer to texture groupings in table 4.

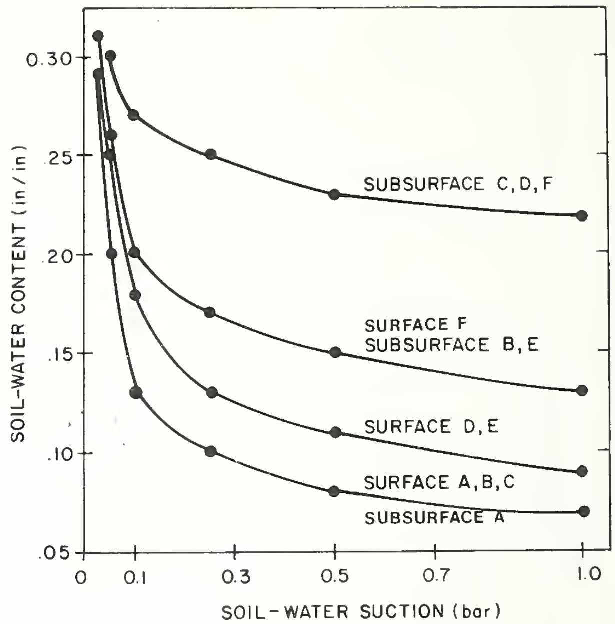

FIGURE 19.—Soil-water retention for surface and subsurface layers of Southern Coastal Plain soils. A, B, C, D, E, and F refer to texture groupings in table 5.

tion, which is soil saturation, and is commonly determined to a maximum soil-water suction of 15 or 20 bars. Such a relationship is shown in figure 17 for the surface and subsoil horizons of a Faceville loamy sand to sandy loam.

An interpretation of the soil-water retention curve and its implications in plant-soil-water relationships is basic to soil-water regulation for crop production. Since modes of expression vary, some definitions seem in order. In figure 17 water content is plotted on the vertical axis in cubic centimeters per cubic centimeter, which can be changed to cubic inches per cubic inch without changing the numbers on the axis. Since volume is the product of area and depth, cubic inches per cubic inch equals inch per inch if the area of soil and water are common. So the values in tables 4 and 5 for soil-water retention can be read off the vertical axis of a graph like figure 17 for a selected soil-water suction. In figure 17 soil-water suction is plotted on the horizontal axis in bars from zero to 15. A bar is a unit of pressure compatible with the centimeter unit of length and is equal to about 14.5 lb/in^2. Since suction implies negative pressure, soil-water suction expresses the energy of water retention by the soil or, conversely, the energy required to remove water from the soil.

The curves in figure 17 show the range of soil-water suction where the major volume of water is retained, i.e., less than 1 bar. Campbell et al. (1974) found that the Ap horizon, or surface layer, of typical Paleudults of the South Carolina Coastal Plain drains 42% of its pore volume between 1 and 10 centibars. That is why tables 4 and 5 provide data only for suctions in the range of less than 1 bar. The soil-water retention data in tables 4 and 5 are plotted in figures 18 and 19 for easier use and examination. Soil water retained at suctions greater than 1 bar may be used by plants. However, it is less available not only because of its retention energy but also because it is relatively immobile, and availability would depend upon a great amount of root-absorption surface permeating the whole soil volume. Therefore, focus should be upon the soil-water-suction range less than 1 bar, where most of the plant-available water-retention capacity exists. Although the B_2 subsoil horizon contains more water than the Ap or surface soil horizon, its available water capacity may be the same as that of the Ap horizon because much of the water is not available to plants.

WATERFLOW CHARACTERISTICS

In the last column of tables 4 and 5 a maximum water application rate is given for each soil-texture grouping. These values represent the water intake or infiltration rate of these soils in a commonly tilled condition after about an hour of infiltration. They represent differences in the flow

Table 7.—Increases in dry matter and uptake of nitrogen, potassium, and magnesium by irrigated sweet corn and snap beans, Tifton, Ga., 1975-76[1]

Week from planting	Pounds per acre per week[2]							
	Sweet corn				Snap bean			
	Dry matter	N	K	Mg	Dry matter	N	K	Mg
1	0	0.0	0.0	0.0	30	1.0	0.5	0.1
2	5	.5	.5	.0	100	2.0	2.5	.3
3	15	1.0	1.0	.5	180	6.0	5.0	1.0
4	130	2.5	3.5	.5	600	17.0	17.0	2.5
5	200	4.0	6.0	.5	1,100	27.0	27.0	3.5
6	350	8.5	17.5	1.0	800	10.0	16.0	3.0
7	1,000	14.5	21.5	2.0	550	6.0	13.0	2.0
8	1,100	25.5	31.0	4.0	250	4.0	12.0	1.5
9	2,450	14.5	26.5	3.5	....	....	....	....
10	2,100	7.0	22.0	3.5	....	....	....	....

[1]Irrigation applied at 0.4 bar for sweet corn and 0.25 bar for snap beans at 6-inch (15-cm) depth.
[2]To convert pounds per acre per week to kilograms per hectare per week, multiply by 1.12.

characteristics of soil horizons, but in many cases they may represent the flow characteristics of the surface 1 inch (2.5 cm) of soil. When wetted by flooding or impacting drops of water from rainfall or sprinklers, soil surfaces develop a denser, more impermeable surface zone that may ultimately limit water infiltration (surface crusting). Thus, the data for application rate in tables 4 and 5 reflect these processes.

When soils are wetted from the surface, a "wetting front" is observable, particularly if water is infiltrating a dry soil. Therefore, as water continues to be supplied at the surface, the wetting front moves deeper, and, in the process, water moves through the pores behind the wetting front. As long as water is supplied to the surface at a rate near the maximum infiltration rate, the soil behind the wetting front is very near saturation, and dissolvable chemicals are in solution and moving, or being leached. When the water supply to the surface stops, water that cannot be retained by the soil against the downward force of gravity drains into the drier soil below. Knowledge of waterflow and drainage must be applied if irrigation water and readily movable plant nutrients like nitrate nitrogen are to be effectively used by the crop. Applying excess water tends to move nitrate out of the zone of major root concentration. Rainfall after irrigation increases the depth of nutrient movement and must be provided for. The expected quantity and pattern of rainfall must, therefore, affect plans for water regulation by irrigation. This is why irrigation strategies in more arid regions cannot be used in this humid region. Application of soil-water-retention and flow principles is discussed in the section entitled "Irrigation Practice: When and How Much."

Nutrient Management

If the crop is to respond to irrigation, sufficient nutrients must be available. Nutrient availability is greatly modified by soil pH. A soil pH near 7.0 (neutral) is desirable for most crops. Calcium, magnesium, molybdenum, phosphorus, and sulfur rapidly become unavailable for plant use when the soil pH is below 6.0. High availability of aluminum and manganese may result in toxic conditions that restrict root growth. High soil-water suctions, which reduce water uptake by the plant, may also reduce nutrient uptake. The effect of soil-water status on nutrient availability varies considerably with the different nutrients. For extended treatises on these and other plant nutrient supply topics, consult Tisdale and Nelson (1966), and Black (1968).

Nutrients such as nitrate nitrogen, ammoniacal nitrogen, potassium, and magnesium are subject to leaching below the root depth in the sandy soils of the Southern Coastal Plain (Rhoads 1970, Terry and McCants 1973). Deficiencies of these nutrients may occur even with relatively heavy preplant applications unless additional applications are made as the crop develops. The

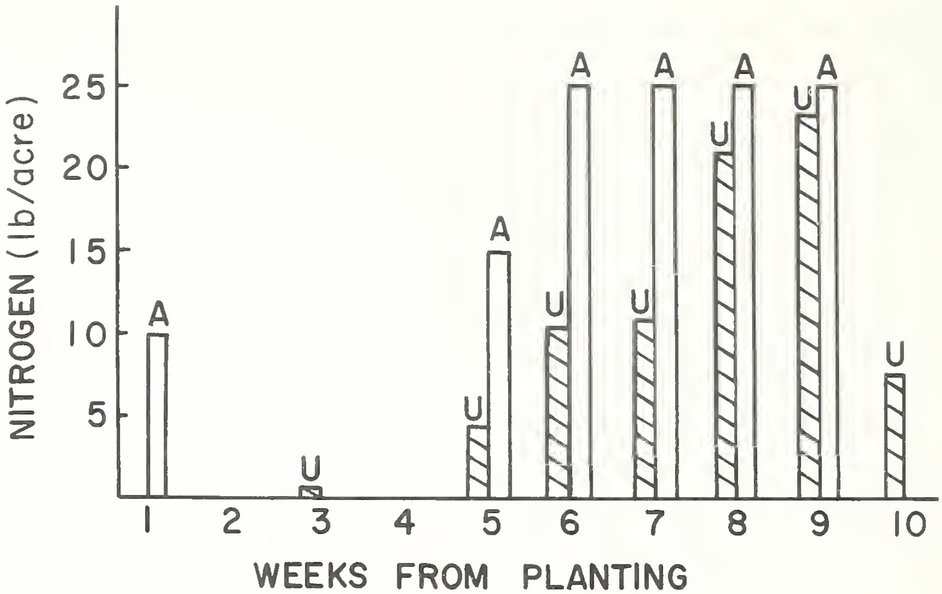

FIGURE 20.— Nitrogen application (A) and uptake (U) by irrigated sweet corn (average of plow-plant, subsoil-bed, and disk tillage systems). To convert pounds per acre to kilograms per hectare, multiply by 1.12.

use of nutrients by the plant is about proportional to the rate of growth by the crop (table 7). Therefore, only small amounts are needed during early plant development. Use of these nutrients can be more efficient if applications are scheduled, either through the irrigation system or by other means, to meet the crop needs for short periods of time.

Nutrient application may be scheduled by coordinating applications with nutrient uptake by the crop (Phene and Beale 1976, Smittle and Threadgill 1977) or by frequent soil or tissue analyses (Smittle 1976, Smittle and Williamson 1977a, 1977b). Results of using nutrient uptake to schedule nitrogen applications are shown in figure 20. Applications of 10 lb N/acre (11.2 kg N/ha) during the first week represents 100 lb/acre (112 kg/ha) 10-34-0 banded at planting of the sweet corn. Assuming the nitrogen applied was mostly used or leached during the week after application, a relatively high (66% to 93%) efficiency was obtained from applications during the fifth, seventh, and eighth weeks. Application rates were excessive during the sixth and ninth weeks. An analysis of the effect of tillage treatments on nitrogen use efficiency (N uptake/applied N) showed 70% for the plow-plant, 62% for the subsoiled, and 40% for the disk tillage systems (Smittle and Threadgill 1977).

Erosion and Drainage

Erosion (water and wind) and drainage problems will become more serious as large areas are developed for row-crop production, and they should be considered when designing an irrigation system. Much of the water erosion presently occurring could be eliminated by good cultural practices including installation of permanent sod waterways. Wind erosion and the associated "sand blasting" of seedlings may be severe in large fields with poor ground cover during high winds that occur each spring. This type of erosion can be reduced by light water applications or by producing a rough soil surface with a rotary hoe or similar equipment. Drainage of low or wet areas should be considered when installing an irrigation system. The type of drainage system required depends on the type of drainage problem. Both a surface and an underground drainage system may be needed.

PLANTS

Crop performance, or the quantity and quality of plant growth, depends on the rates of several physiological processes that are closely related to the internal water balance or turgidity of the plant. The internal water balance is determined by the relative rates of water absorption and water loss. Therefore, all conditions influencing these processes will modify the plant's response to soil-water conditions (Hagan et al. 1967).

Water and Plant Processes

Through photosynthesis, plants capture energy from the sun and combine the carbon and oxygen from carbon dioxide in the air with the hydrogen in water to produce sugar. The sugar is further transformed within the plant into harvestable products that normally contain high amounts of starch, oils or proteins or both, and vitamins and minerals. For the myriads of chemical reactions to occur, however, the plant must have adequate water. When plant water becomes scarce, the rate of at least some of the chemical reactions, including those in photosynthesis, decreases, and growth slows down and may eventually stop.

Under normal conditions, about 80% or more of a plant's weight is water. Reduction of the amount of water in the plant below this level normally causes wilting, although a plant may be under water stress and not wilt. The water balance or status of a plant is described by plant-water potential, which is measured in pressure units, for example, bars. Plant-water potential is the difference in free energy, or chemical potential, per unit of molal volume between pure water and water in the plant's cells at the same temperature, elevation, and pressure. The potential of pure water has arbitrarily been set at zero; therefore, the potential of water in all plant cells and solutions is less than zero, or negative. The water in the plant is seldom in equilibrium with the water in the soil. For the plant to extract water from the soil, the potential energy of the water in the plant must be lower than that of the water in the soil. For water to move through the plant, there must be a water-potential gradient extending from the soil through the plant to the atmosphere. The difference in energy between plant water and soil water depends upon the rate of water uptake from the soil, the water-conducting properties of the soil and plant, and environmental conditions.

Water absorption by roots depends on the water supply at the root surface; therefore, total water available to the plant is determined by water movement to the root surface and growth of roots into the soil. Entry of water into roots is affected by the absorbing area of the roots, the permeability of the root cortex, and the water potential at the root surface. Movement of water vapor through and out of the leaves is determined primarily by atmospheric conditions surrounding the leaf. For most crops more than 95% of the water absorbed from the soil by roots is lost to the atmosphere, and thus only a very small proportion of that taken up remains as a part of any plant tissue. The loss of water from vegetation to the atmosphere is called transpiration. Daily variations in transpiration are due largely to changes in sunshine intensity and duration, wind, vapor pressure deficit of air, and temperature of air and soil. The most important of these factors is the intensity and duration of sunshine. Transpiration keeps the plant cool and provides the capillary movement that transmits nutrients from the root structure to the upper parts of the plant. In some plants, especially warm-season crops, transpiration is partially controlled by the biological properties of the plant (plant factors) as influenced by the environment. In other plants, especially cool-season plants, biological properties seem to have little if any control over transpiration. Most of the water is lost through microscopic pores, called stomata, in the leaf surface.

When young roots and shoots grow, most of the added volume is water, which becomes part of the large central vacuole of plant cells. Water enters the vacuole from regions with a water potential higher than that in the cell vacuole and pushes the cell walls outward. This is called turgor pressure and causes the tissue (such as leaf) both to expand and to stay rigid. If the plant obtains soil water only with difficulty, not enough water will enter the elongation zone of roots and shoots to provide for cell expansion, and growth stops. Further decreases in soil water or in some instances increases in environmental demand for water may reduce turgor pressure to the point where the cells become flaccid, and the leaf or shoot wilts. When such water loss from plants exceeds water absorption, drought occurs. In roots, a prolonged plant-water deficit will shorten those regions of the root with surfaces most permeable to water and minerals. Roots growing in dry soil, therefore, have less fresh tissue in contact with newly explored areas of soil. Such reduction in root growth further reduces the water- and nutrient-supplying power of the root system and subsequently reduces shoot growth. In general, plants subject to drought produce less above-ground dry matter and have smaller, thicker leaves, more packed stomata per unit surface, and smaller cells that conduct less water. Mineral deficiency symptoms also frequently appear because of poor plant-water relations.

Although inadequate water may increase rooting depth slightly, it generally reduces the radius of the root distribution. Many soils of the region have physical and chemical characteristics that frequently restrict root growth to the uppermost part of the soil profile, and this limitation causes frequent periods of drought.

In some instances the soil characteristics that restrict root growth also restrict water movement, causing the soil to become saturated. Too much water causes an oxygen deficiency, which damages root systems and decreases crop yields. Oxygen-stressed plants show some of the same symptoms associated with drought attributable to other causes. These symptoms include stunting, wilting, and abnormal leaf coloration, indicating possible mineral deficiencies. For instance, leaves may yellow, which could indicate nitrogen deficiency. Biochemically, oxygen deficiency is a condition where not enough oxygen is diffused into the plant's roots to satisfy its respiratory needs. When a soil is waterlogged, oxygen diffusion is impeded. Without oxygen, large amounts of toxic substances are produced, and these build up and eventually kill plant-root cells. Lack of hormone synthesis in the roots may also occur. Root-synthesized hormones are needed in the leaves to maintain normal protein synthesis.

Susceptibility to Water Deficit

Variations in drought tolerance among crop species and among cultivars within a crop species may determine the water regime required for acceptable crop performance. Plant characteristics that tend to allow for drought tolerance include both foliage and root characteristics. A small leaf area (transpiring surface) in relation to a large root area (water-absorbing surface) tends to increase drought tolerance. Since the water loss from plants occurs through stomata, the number and location of the stomata on the leaves can greatly modify the water loss per unit of leaf area. A waxy cuticle on the leaf reduces water evaporation from the leaf surface. The extent and character of the crop canopy, which modifies air movement near the canopy (crop aerodynamic roughness), modifies the rate of water-vapor diffusion from the leaf, especially when air currents develop. Other factors aside, crops that produce a compact canopy are more drought tolerant. Water-absorbing surface is a function of rooting depth, the density of roots within the rooting depth, and the rate of root growth. Water absorption occurs primarily near the tip of the plant roots; therefore, many roots in the soil volume do not necessarily mean that water is being effectively extracted. Drought tolerance is also influenced by a plant's ability to survive desiccation of its tissues and, in many cases, drought tolerance may be due to desiccation resistance of the plant part by which crop performance is measured.

In addition to variations in drought tolerance among species, varieties, and cultivars, the sensitivity of many crops to drought varies greatly with physiological growth stage (Salter and Goode 1967). The relative drought sensitivity of crops at different growth stages shown in table 8 reflects primarily a summation of the Salter and Goode report. The influence of physiological growth stage on drought sensitivity has been better established for annuals than for perennial crops because age of perennials is superimposed on physiological growth stages. Age of perennials may have a greater effect on crop response to water than physiological growth stage, mostly because the plant-root system may already be established.

The physiological growth stage of maximum sensitivity to drought conditions is determined largely by the type of harvested product. When crop performance is measured as seed, fruit, or fiber production, formation of reproductive organs, flowering, and seed development are the most sensitive stages of annual crops. When vegetative growth is the measure of performance, crops are about equally sensitive to drought conditions throughout growth. The period of growth of storage organs is the most sensitive stage when tuber, bulb, or corm production is the measure of crop performance. In general, the stage of fruit set and enlargement are the most sensitive stages for perennial crops. The period of seed germination and seedling establishment of all plants is particularly sensitive to drought con-

Table 8.—Relative drought sensitivity of crops at different growth stages[1]

Crop	Germination and seedling	Pre-blossom	Blossom	Development of marketable product	Maturation of marketable product
Vegetative crops (leaves, stems, bulbs, or flowers are marketable product):					
Broccoli	5	5	...	5	...
Cabbage	5	3	...	4	...
Cauliflower	5	5	...	5	...
Celery	5	5	...	5	...
Grass	5	3	...	3	...
Greens	5	4	...	4	...
Lettuce	5	4	...	4	...
Onion	5	3	...	3	...
Silage corn	3	4	...	4	...
Tobacco	5	4	...	4	...
Root crops (roots or tubers are marketable product):					
Beet	5	3	...	3	...
Carrot	5	3	...	3	...
Potato	3	5	...	5	...
Radish	5	4	...	4	...
Turnip	5	4	...	4	...
Fruit and nut crops (fleshy fruit or nuts are marketable product):					
Apple	...	3	4	4	3
Cantaloup	3	4	3	3	2
Cucumber	3	4	3	5	...
Grape	...	2	3	3	2
Peach	...	3	3	4	3
Pecan	...	2	3	4	3
Pepper	5	3	5	4	4
Snap bean	3	4	5	5	...
Squash	3	3	4	4	...
Strawberry	...	3	4	4	3
Tomato	5	3	4	4	4
Watermelon	3	3	3	3	2
Immature seed crops (immature seeds are marketable product):					
Garden pea	3	3	4	3	2
Lima bean	3	3	4	4	2
Southern pea	3	2	3	3	2
Sweet corn	3	5	5	5	...
Mature seed crops (mature seeds are marketable product):					
Corn	3	5	5	5	1
Peanut	3	3	4	4	1
Small grain	2	2	3	3	1
Soybean	2	3	4	3	1

[1]Relative drought sensitivity: 5, very sensitive; 1, relatively dry conditions desirable.

ditions because of their very small rooting volume.

Extreme sensitivity of most economic crops during the physiological growth stages of formation of reproductive organs through fruit or seed development usually results from a combination of internal and external factors. The tissues of reproductive organs are particularly susceptible to damage from water shortage. Water shortage during these periods is exhibited as a reduced number of grains per ear in cereal crops, and as flower and fruit abortion and misshapen fruit in many agronomic and horticultural crops. Root growth of many of these crops is greatly reduced and may even cease when flowers begin to develop. A reduction in root activity may occur from flowering or early fruiting until death of such crops as cucumbers, tomatoes, and some legumes that fruit throughout their life. The reduction in root activity at this critical developmental stage can result in a serious reduction in water absorption by the plant unless the soil-water content is high enough to permit rapid water movement to the root surface. In addition to a reduction of water absorption, a reduction in root growth could also affect nutrient uptake at this particularly important time in the growth of the crop.

Susceptibility to drought at the reproductive stage of development is magnified by changes in climatic conditions that increase evapotranspiration (transpiration plus evaporation from soil or other surface) and water demand by the crop. Most long-season crops are planted early in spring, when solar radiation and temperature are low and humidity and rainfall are high. These factors, together with a small transpiring area of low aerodynamic roughness, result in a low water demand by the crop. As the season progresses, net radiation, temperature, and plant aerodynamic roughness increase, and humidity and rainfall decrease, resulting in maximum evapotranspiration during flowering and fruit or seed development. Drought susceptibility of a crop may change dramatically within a climatic region because of variations in soil characteristics that may vary widely within a small geographic area, possibly within a single field.

Increased populations of root diseases, root-feeding insects, and nematodes occurring during the reproductive stage may reduce water-absorption capacity of the crop plant; high weed populations usually increase the rate of soil-water depletion. Maintaining soil water will not always supply a crop's water demand if severe root diseases or high populations of root-feeding insects or nematodes are present. Conversely, a high incidence of foliage disease and insect damage may temporarily reduce a crop's water demand.

Crop Management

Since crop performance is the product of climate, soil, plant, and water interactions, all practices must be considered as a unit in a crop management or farming operation. Several aspects, either singly or in combination, modify the water management program that is required. Keisling et al. (1975) have discussed the ingredients for maximum yields through irrigation in the Southern Coastal Plain of Georgia.

It is generally accepted that man has little control over the climate. However, climate can be managed to some degree by scheduling planting dates and by frequent, light irrigation. Normal variations in climatic conditions during a growing season can be utilized in scheduling planting of a crop to obtain maximum benefit from normal weather conditions (see "Introduction: Resource Characteristics"). This can be done with crops that have a particular developmental stage of maximum drought sensitivity by scheduling planting so that this period occurs during a period of adequate rainfall or lower evaporation demand. Planning a planting program using this type of information will be extremely important when

Table 9.—Effect of plant spacing on yield of irrigated snap beans and lima beans, Tifton, Ga., 1973-74[1]

Plant spacing (inches)[2] Between rows	Plant spacing (inches)[2] In row	Snap bean pod yield (tons/acre)[3]	Lima bean seed yield (lb/acre)[4]
36	1.5	3.0	2,147
18	3	4.2	2,629
12	3	5.2	3,030
6	6	6.1	3,553

[1] Irrigation applied at soil-water tension of 0.3 bar for snap beans and 0.4 bar for lima beans at 6-inch (15-cm) depth.

[2] To convert inches to centimeters, multiply by 2.54.

[3] To convert tons per acre to metric tons per hectare, multiply by 2.24.

[4] To convert pounds per acre to kilograms per hectare, multiply by 1.12.

irrigation is not available or when access to irrigation equipment is limited.

Another aspect of using normal weather patterns by scheduling planting would be to avoid excess water or poor drying conditions at particular stages of plant growth. As an example, poor drying conditions (high humidity and rainfall) are undesirable near harvest of many seed crops that are harvested in the mature or semimature stage; therefore, scheduling of planting to result in harvest during dry periods would be beneficial whether or not irrigation is available.

The transpiration demand of a crop can be reduced by frequent, light irrigations. The lower transpiration is due to both a higher humidity resulting from water evaporating from the soil and plant surfaces and a lower temperature from application of cool water and from evaporative cooling. The use of frequent, light irrigation as a method of reducing transpiration demand would most likely be of benefit during emergence and growth of seedlings of small-seeded vegetable crops.

Some drought tolerance within a crop can be obtained by variety selection. Usually varieties that have a smaller leaf surface or a more rapid and more extensive root development are more drought tolerant. Selection of varieties having a shorter or possibly longer growing season may increase apparent drought tolerance because planting can be scheduled so that drought-sensitive growth stages coincide with normal periods of frequent rainfall or low evaporation demand.

In the past, some drought tolerance has been achieved by using lower plant populations. This method of inducing drought tolerance has worked relatively well when drought conditions were not severe. In many cases, plant populations have not been increased enough to take advantage of the yield potential provided by irrigation. Examples of yield increases with greater plant populations and modification of plant spacing of snap bean, lima bean, and corn with irrigation are shown in tables 9 and 10.

Soil management practices can greatly modify the type of root system a crop develops and thereby modify the frequency of application and amount of water needed in an irrigation program. Important aspects of soil management are tillage, fertility and liming, and erosion control and drainage practices. Since water used by a crop under the same climatic conditions is similar, soil management practices that increase the rooting depth or volume decrease the apparent drought susceptibility of the crop.

Pests can greatly modify a crop's response to irrigation or soil-water status. A high weed population usually increases the rate of soil-water depletion, and the weeds compete with the crop for light and nutrients as well. Diseases, insects, or nematodes that attack a plant's root system reduce the effective water-absorbing area. Severe infestations may result in crop failure. Less severe infestations increase the frequency of irrigation needed to compensate for the reduced soil-water-extracting volume resulting from root damage. Diseases such as Fusarium wilt, which interferes with water transport, result in a physiological drought condition and usually cannot be corrected

Table 10.—Effect of row and drill spacing on yield of two irrigated corn varieties, Quincy, Fla., 1971[1]

Row spacing (inches)[2]	Drill spacing (inches)[2]	Plants per acre[3]	Grain yield (bu/acre at 15.5% H_2O)[4]	
			'Pioneer 3369A'	'McNair 440V'
18	6	58,000	199	200
18	9	38,600	212	197
18	12	29,000	203	194
36	6	29,000	181	174
36	9	19,300	163	175
36	12	14,500	134	157

[1] Irrigation applied 0.3 bar at 6-inch (15-cm) depth.
[2] To convert inches to centimeters, multiply by 2.54.
[3] To convert plants per acre to plants per hectare, multiply by 2.471.
[4] To convert bushels per acre to metric tons per hectare, multiply by 0.0627.

Source: Stanley and Rhoads 1971.

Table 11.—Effect of irrigation regime on snap bean yield, Tifton, Ga., 1974 and 1976

Treat-ment	Soil-water suction at irrigation (bar)	Pod yield (tons/acre)[1]	
		Spring 1974	Fall 1976
1	0.25	3.45	3.61
2	.50	1.30	1.65
3	.75	.70	1.43
4	.75 (preblossom)[2]	2.57	1.61
5	.75 (blossom)[2]	2.35	2.68
6	.75 (postblossom)[2]	2.35	4.24

[1] To convert tons per acre to metric tons per hectare, multiply by 2.24.

[2] Irrigation applied at 0.25 bar during remainder of season.

Source: J. R. Stansell and D. A. Smittle, unpublished data.

by more frequent irrigation. Foliage disease or insect damage reduce carbohydrate production by the plant, thereby reducing the yield potential of the crop. Good pest control practices are essential to obtain maximum benefit from irrigation.

Irrigation Response Data for Selected Crops

The response of selected crops to imposed water regimes and other variables support the principles that have been discussed.

Snap beans

The yield response of snap beans to irrigation on Tifton loamy sand (Plinthic Paleudult) shows how sensitive some crops are to soil-water deficits, both throughout growth and at different stages of growth (table 11). When the soil-water suction was allowed to reach 0.50 and 0.75 bar (treatments 2 and 3) before irrigation of sheltered plots, the pod yields of the spring and fall crops added together were about 58% and 70% lower than plots irrigated at 0.25 bar (treatment 1). Soil-water deficits reduced yields more in the spring crop than in the fall crop.

The interrelation of soil-water deficit and evapotranspiration on crop yield is shown by the differences in response between spring and fall plantings from imposing soil-water deficits during preblossom, blossom, and postblossom growth stages. The spring yield was reduced more by soil-water deficits during blossom and postblossom stages, when evaporative demand was high. However, a soil-water deficit in the fall planting during the postblossom stage, when evaporative demand was low, resulted in a greater pod yield than the continuous 0.25-bar treatment. In the fall planting, the yield was reduced more by pre-blossom water stress, when evaporative demand was high, than by blossom or postblossom stress.

Peanuts

In a 3-year study of peanut irrigation in sheltered plots, the greatest yield was obtained when irrigation was done at 0.2-bar soil-water suction to recharge the soil to a depth of 24 inches (61 cm) (table 12). However, this yield was only 7% greater than that at 0.6-bar soil-water suction and was not statistically different from that produced by the 0.2-bar treatment for any of the cultivars used. Yield was reduced more when irrigation was applied at greater soil-water suctions. Applying irrigation after the foliage had permanently wilted reduced yield 56%.

Irrigation also affected the percentage of sound mature kernels of the harvested pods, magnifying the response to irrigation. Yield from the second 0.2-bar treatment was 9% greater than that from the 0.6-bar treatment (table 13). 'Florigiant' produced a lower percentage of sound mature kernels than the other cultivars in all irrigation regimes. This cultivar seems to be more sensitive to extreme soil-water deficits, as indicated by the 80% reduction in yield of sound mature kernels when irrigation was applied at permanent wilt of the peanut foliage.

The variation in sensitivity of peanuts (6% yield reduction) and snap beans (58% yield reduction) to similar changes in soil-water content reflects differences in plant characteristics. Peanuts have a much longer growing season with a less critical requirement for fruit set during a short period, a more extensive root system, and a smaller leaf area in relation to root area. Snap bean foliage, in contrast, has a greater aerodynamic roughness, and the blossoms are more exposed to the environment.

Corn

Experiments from 1962 through 1964 in Mississippi indicated how different corn cultivars and hybrids respond to soil-water regime and the effect of parental lines upon the response (Bruce et al. 1966, 1969). Two single-cross hybrids planted at 20,000 plants/acre (49,420/ha) yielded 186 bu/acre (11.67 metric tons/ha) when the mean soil-water suction at 12 and 24 inches (30 and 61

Table 12.—Effect of irrigation regime on pod yield of three peanut varieties, Tifton, Ga., 1970-73

Soil-water suction at irrigation[1] (bars)	Recharge depth (inches)[2]	Harvestable pod yield (lb/acre)[3]		
		'Florigiant'	'Florunner'	'Tifspan'
0.2	12	3,654	4,111	3,374
.2	24	3,982	4,531	4,052
.6	24	3,634	4,217	3,931
[4].2	34	3,488	4,085	3,842
([5])	24	1,241	2,119	2,222
15.0	24	2,347	2,988	2,788

[1] Represents mean soil-water suction in surface 12 inches (30 cm) of soil.
[2] To convert inches to centimeters, multiply by 2.54.
[3] To convert pounds per acre to kilograms per hectare, multiply by 1.12.
[4] Irrigation applied at 0.2 bar until 30 days after first bloom, then at 2.0 bars until harvest.
[5] Irrigation applied after foliage had permanently wilted.

Source: Stansell et al. 1976.

Table 13.—Effect of irrigation regime on sound mature kernel yield of three peanut varieties, Tifton, Ga., 1970-73

Soil-water suction at irrigation[1] (bars)	Recharge depth (inches)[2]	Sound mature kernel yield (lb/acre)[3]		
		'Florigiant'	'Florunner'	'Tifspan'
0.2	12	2,477	3,086	2,403
.2	24	2,641	3,421	2,909
.6	24	2,326	3,150	2,744
[4].2	24	2,125	3,028	2,789
([5])	24	534	1,236	1,476
15.0	24	1,292	2,048	1,853

[1] Represents mean soil-water suction in surface 12 inches (30 cm) of soil.
[2] To convert inches to centimeters, multiply by 2.54.
[3] To convert pounds per acre to kilograms per hectare, multiply 1.12.
[4] Irrigation applied at 0.2 bar until 30 days after first bloom, then at 2.0 bars until harvest.
[5] Irrigation applied after foliage had permanently wilted.

Source: Pallas et al. 1977.

cm) was maintained at less than 0.3 bar until 4 weeks past pollination and at less than 0.6 bar until maturity, with 180 lb/acre (202 kg/ha) of nitrogen applied (table 14). In addition to showing a marked difference in hybrid response to treatment, the importance of maintaining a low soil-water suction during the fruiting stage (from 3 weeks before pollination until 4 weeks after) was shown. These hybrids responded to over 200 lb/acre (224 kg/ha) of nitrogen under the low-suction water regimes (Bruce et al. 1966).

In 1973, the results of regulating irrigation of corn by tensiometer readings at a 6-inch (15-cm) depth in Orangeburg loamy fine sand in Florida showed that when soil-water suction was allowed to exceed 0.6 bar, yields were no different from those of unirrigated treatments (Rhoads and Stanley 1973). On the other hand, irrigation when soil water was in the 0.2- to 0.4-bar range significantly increased grain yield. One variety yielded 190 bu/acre (11.92 metric tons/ha) when irrigated at 0.2 bar and 160 bu/acre (10.04 metric tons/ha) at 0.6 bar in a 1971 experiment where 300 lb/acre (336 kg/ha) of nitrogen was applied (table 15). Later experiments (Rhoads and Stanley 1974) in Florida on Lakeland sand and Magnolia sandy loam in addition to Orangeburg loamy fine sand indicated that irrigation when soil-water suction at the 6- to 8-inch (15- to 20-cm) depth reached 0.4 bar resulted in the highest irrigation efficiency for all soils (yield increase divided by amount of water applied). However, the yield was highest on Lakeland sand when irrigation was at 0.2 bar.

With both early- and full-season corn hybrids irrigated when 0.2-bar soil-water suction was reached at the 6-inch (15-cm) depth in Orangeburg loamy fine sand, yields were highest at a spacing of 12 by 18 inches (30 by 45 cm) and about 29,000 plants/acre (71,660 plants/ha) (Stanley and Rhoads 1974). Some Florida on-farm experience supports the results of these experiments (Rhoads and Russell 1977).

At Florence, S.C., water was applied to sweet corn when soil-water suction at the 6-inch depth near the plant was 0.1, 0.2, or 0.4 bar, and yield of marketable ears at these three levels was similar (Phene 1974a, 1974b, Phene and Beale 1976). In plots watered by trickle irrigation, when suction was 0.2 bar at the 6-inch (15-cm) depth, 6.6 tons/acre (14.8 metric tons/ha) and 7.7 tons/acre (17.2 metric tons/ha) of marketable ears were produced with 150 lb/acre (168 kg/ha) of nitrogen and 300 lb/acre (336 kg/ha) of nitrogen, respectively. Potassium was applied in each case at the same rate as nitrogen.

Table 14.—Effect of parentage, nitrogen, and water regulation on yield of corn grain, State College, Miss., 1962

Corn hybrid[1]	N (lb/acre)[2]	Grain yield (bu/acre)[3]			
		M_1	M_2	M_3	Mean[4]
Fertile....	90	105	103	103	104
Sterile....	90	143	132	131	135
Mean	...	124	117	117	119c
Fertile....	180	149	144	128	140
Sterile....	180	186	174	160	173
Mean	...	167	159	144	157d

[1] Fertile = single cross $F_{44} \times F_6$. Sterile = F_{44} cms $\times F_6$. Plant density was 20,000 plants/acre (49,420 plants/ha).

[2] To convert pounds per acre to kilograms per hectare, multiply by 1.12.

[3] Mean soil-water suction at 12- and 24-inch (30- and 61-cm) depth from 3 weeks before pollination to 4 weeks after was maintained at less than 0.3 bar for M_1, less than 0.6 bar for M_2, and less than 2.4 bars for M_3. Mean soil-water suction was maintained at less than 0.6 bar in all treatments from 4 weeks after pollination to maturity. To convert bushels per acre to metric tons per hectare, multiply by 0.0627.

[4] Means not followed by the same letter are significantly different at 0.05 probability level, by Duncan's multiple-range test.

Source: Bruce et al. 1966.

Soybeans

Research has generally emphasized that soybean yield is most sensitive to the plants' water supply after the mid- to full-flowering stage. In experiments in Alabama, yields increased 24% to 55% because of irrigation; varying the row width from 2 to 3 feet (60 to 90 cm) or population from 43,000 plants/acre (106,300 plants/ha) to 131,000 plants/acre (323,700 plants/ha) had little effect (Doss et al. 1974, Doss and Thurlow 1974).

Field experiments at Plains, Ga., on Greenville sandy loam (Rhodic Paleudult) involving three cultivars emphasized the need for adequate water supply from early flowering through pod filling. 'Ransom', a relatively short-statured cultivar, yielded over 53 bu/acre (3,562 kg/ha) when irrigated, but only 30 bu/acre (2,016 kg/ha) unirrigated. The irrigated treatment received water when 60% of the available water in the

Table 15.—Effect of irrigation at specified soil-water suctions on grain yields of two corn varieties, 1971

Soil-water suction at irrigation (bar)[1]	Number of irrigations	Total water applied (inches)[2]	Grain yield (bu/acre)[3]	
			'Coker 71'	'Funks G-4761'
0.2	11	8.7	190	129
.4	6	7.1	175	120
.6	4	4.7	160	111
...	0	0	115	80

[1] Measured at 6-inch (15-cm) depth.

[2] To convert inches to centimeters, multiply by 2.54.

[3] To convert bushels per acre to metric tons per hectare, multiply by 0.0627.

Source: Rhoads and Stanley 1973.

surface 2 ft (61 cm) was depleted as determined by electrical resistance blocks (Ashley and Ethridge 1978).

Cotton

In the Southeastern U.S.A., the culture of irrigated cotton is more complex than that of other crops. The interaction of nitrogen fertilization with irrigation is primary, and there is still not enough experimental data to satisfactorily treat the problem. Studies at Thorsby, Ala. (Scarsbrook et al. 1959, 1961), and State College, Miss. (Bruce and Romkens 1965), are significant, and they form a basis for analysis such as that done by Baker et al. (1973). A few tentative conclusions seem justified:

1. Before flowering and first fruit set, nitrogen supply to the plant must be carefully controlled. If ample nitrogen is available while the plant is well watered and other nutrition is adequate, growth is very rapid, resulting in an excessively large plant that must then be maintained during fruiting. Since water supply from rainfall is uncontrollable, nitrogen must be controlled by multiple small applications made by current irrigation water application. Simultaneous control can be judiciously exercised by irrigation.

2. After first boll set, growth can be more readily controlled, since fruit become a primary sink for photosynthate. Therefore, nitrogen or water stress during fruiting is disastrous and must be avoided by careful regulation of the water and nitrogen supply. The larger the plant, the more important water and nitrogen supply become. In fact, the high yields of seed cotton at Thorsby and State College were only possible under the imposed irrigation treatment because the nitrogen supply was maintained through the critical fruiting period.

3. Application of nitrogen for the entire season at planting is not only wasteful but may cause excessive growth even in unirrigated conditions in some seasons. Leaching of nitrogen may occur, and then nitrogen is not available to support the fruiting process. The result is a large plant with few fruit.

4. Plant-water supply through irrigation can assure high yields if other growth variables are appropriately assessed, particularly nitrogen supply.

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Irrigation Practice: When and How Much

Discussing methods of applying irrigation water is inappropriate until we know where the crop is to be grown and have defined the plant-soil system. To review the principles discussed in the preceding section, the character of the climate must be specified at the outset, and climatic hazards inherent in growing a given crop under a given set of cultural practices or crop plan should be examined and the merits of alternative schemes weighed. The adjustment of planting date, fertilizer application schedule, and harvesting plan depends on climate and weather. Historical records for a location and current weather forecasts provide useful planning information. The crop species immediately imposes the most important characteristics of the system. Rooting, canopy development, fruiting habits, and particular nutritional, pesticide, and water requirements of the crop become criteria for establishing water-regulation plans. To complete the system definition, the soil series or association must be specified. Once the system has been defined and the decision made that irrigation should be part of water-management plans, the two questions remaining are when to apply water and how much water to apply.

In concept, irrigation should add prescribed amounts of water to a specified soil-water control zone at less than a specified soil-water control level as measured at a specified depth. It may seem incongruous that these are apparently soil-related quantities after emphasizing the plant as the focal point. However, in reality, plant characteristics and requirements strongly influence the value assigned to each. Since these two concepts are the keys to setting irrigation practice, a thorough understanding of them is necessary.

The *soil-water control zone* is the soil depth to which prescribed soil-water levels are to be maintained. Both soil and crop characteristics are used in setting this depth. Begin by establishing the rooting extent of the particular crop in the particular soil. When the crop has a naturally shallow or limited root system or when roots are restricted by soil characteristics, then this depth becomes the soil-water control zone. It likely represents 95% to 100% of the root system. In other instances, the crop may naturally have an extensive root system, and it may be distributed to great depths since the roots are not greatly restricted by soil conditions. The depth of the control zone in these situations is determined by the retention and flow characteristics of the soil that affect the leaching of mobile plant nutrients. Tables 4 and 5 give maximum depths available for water regulation in typical soil-texture groups in the Southern Coastal Plain and Southern Piedmont. Table 16 gives data for setting the soil-water control zone for selected crops.

The *soil-water control level* is the prescribed soil-water suction at a point, points, or region in the soil-water control zone at which irrigation is initiated. It is the highest soil-water suction allowable at a specified point, points, or region in the soil-water control zone (table 16). Assignment

Table 16.—Soil-water control zone and maximum soil-water suction for selected crops

Crop	Depth of soil-water control zone: Inches	Depth of soil-water control zone: Centimeters	Maximum soil-water suction in control zone[1] (bar)
Corn	12	30	0.6
Cotton	12	30	.6
Cucumbers	9	23	.5
Peaches	16	41	.6
Peanuts	18	46	.6
Pecans	18	46	.6
Snap beans	9	23	.4
Southern peas	12	30	.6
Soybeans	18	46	.6

[1] This is the maximum mean soil-water suction that should be allowed by the adopted irrigation procedures. In practice, the soil-water suction at which irrigation should begin is less than these values and is affected by the particular soil and water regulation system.

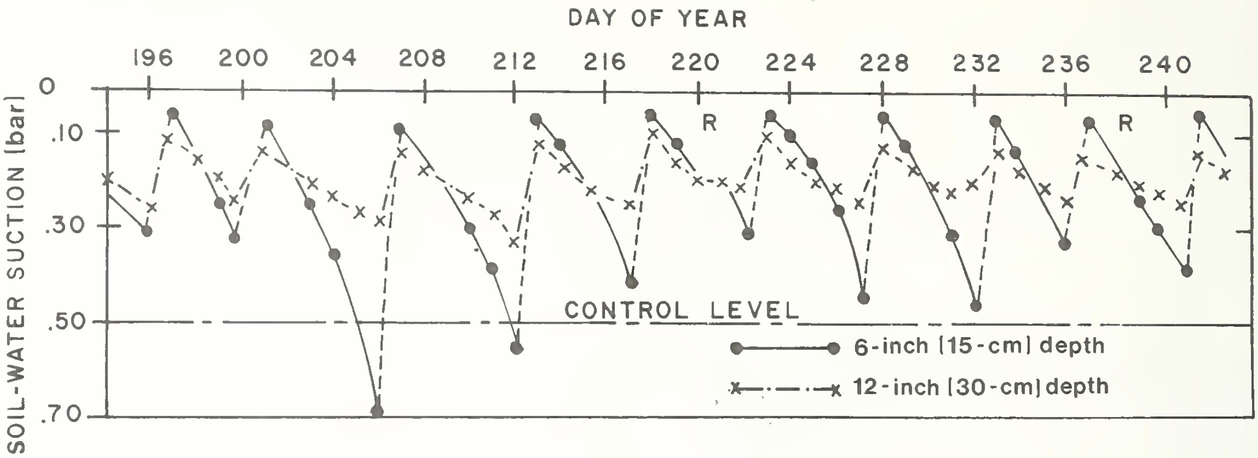

FIGURE 21.—Tensiometer record of soil-water suction in potatoes. Irrigations were scheduled when water suction reached 0.5 bar at the 6-inch (15-cm) depth. R indicates less than 0.18 inch (5 mm) of rainfall. (Source: Taylor and Ashcroft 1972.)

of the soil-water control level depends upon crop species, depth and characteristics of soil-water control zone, fertilization practice, and method of water application. In this climatic region the quantity of mobile nutrients leached out of the root zone can be reduced by scheduling application of fertilizer in relation to crop need and applying only enough irrigation water to recharge the soil-water control zone. Therefore, soil-water control level and the points of measurement must accurately reflect the available water stored in the water-control zone to avoid excessive water application.

The depth of soil-water control zone and the soil-water control level are interdependent—one must be adjusted in relation to the other to achieve the desired pattern of soil-water suction from irrigation practice. The relationship is illustrated by data from a potato irrigation experiment (fig. 21). In this case it seems that 12 inches (30 cm) can be considered the soil-water control zone, and the soil-water control level is 0.5-bar soil-water suction at 6 inches (15 cm). Each time the 6-inch depth approached 0.5 bar, enough water was applied to wet the 6-inch depth to near 0.05 bar and the 12-inch depth to near 0.1 bar. Since the 12-inch depth was never wetted to the same level as the 6-inch depth, very little drainage occurred below 12 inches. In this case, suction very seldom exceeded 0.5 bar in the 6-inch depth and did not exceed about 0.3 bar in the 12-inch depth. Nearly the same soil-water suction ranges could have been realized by irrigating when the 12-inch depth reached about 0.25 bar, although it is clearly a less sensitive indicator point than at 6 inches, and it would be more difficult to maintain the 6-inch depth at 0.5 bar or less. This is due to the greater rates of water uptake at the 6-inch depth because of root concentration. The mean of the readings at the two depths might have been used to signal the start of irrigation. However, a value of the mean must be selected to assure that excessively high soil-water suctions do not occur in the zone of major root concentration and rapid water extraction.

In a study of water management for corn on Troup loamy sand (Grossarenic Paleudult) by Rhoads et al. (1978), three treatments were employed: natural rainfall only, daily trickle irrigation of 0.25 inch (0.64 cm), and trickle irrigation of 0.5 inch (1.3 cm) when tensiometer readings at the 6-inch (15-cm) depth in the row were 0.1 bar. The pattern of soil-water suction at several depths for each treatment was recorded, and plots of these data depicted the actual soil-water regime in the rooting volume. The unirrigated-plot data showed that the major water withdrawal occurred in the surface 24 inches (61 cm). Irrigation maintained soil-water suction at less than 0.1 bar at 12 inches (30 cm) and greater depths throughout the season. Overirrigation occurred under the daily irrigation treatment since drainage continued at all depths throughout the season. Tensiometer-controlled irrigation most effectively used applied water, as measured by yield per inch of water. Only under irrigation did programed fertilizer management (applied in increments) produce significant yield increases. A

Table 17.—Liquid fertilizers for application through irrigation systems

Fertilizer	Formula	Total nitrogen (% N)	Available phosphoric acid (% P)	Water-soluble potash (% K)	Approximate pounds of product for 1 lb of nutrient[1]		
					N	P	K
Ammonium nitrate	NH_4NO_3	20	...	...	5	...	...
Ammonium phosphate	$NH_4H_2PO_4$	8	24	...	12	4	...
Potassium ammonium	KNH_4HPO_4	15	15	10	7	7	10
phosphate (N-P-K		10	10	10	10	10	10
liquid mixes).		15	8	4	7	12.5	25
Urea (low biuret)	$CO(NH_2)_2$	23	...	...	4.4	...	...
Urea-ammonium nitrate.	35.4% $CO(NH_2)_2$ + 44.3% NH_4NO_3	32	...	...	3.1	...	...
Phosphoric acid (green)	H_3PO_4	...	52-54	...	...	1.9-1.8	...
Calcium ammonium nitrate.	11.6% $Ca(NO_3)_2$ + 5.4% NH_4NO_3	17	...	...	6	...	...

[1]To convert pounds to kilograms, multiply by 0.454.

Source: Western Fertilizer Handbook (1961).

similar study by Stansell et al. (1976) depicts the major water removal zone by irrigated peanuts.

In summary, the frequency of application depends upon the depth of the control zone, the specified soil-water suction limit, and the current water demands of the crop. In cases of shallow control zones maintained at low soil-water suctions on sandy soils, frequent small applications are required to adequately meet crop water requirements without risking excessive leaching of the more mobile nutrients. In other cases, water-control zones of greater depth and higher soil-water suctions may be satisfactory; therefore, larger water applications are made less frequently.

FERTILIZATION THROUGH IRRIGATION SYSTEMS

Satisfying a crop's nutrient requirements cannot be separated from satisfying its water requirements. Inadequate fertilization of irrigated crops in the Southeast has seriously limited yields and lowered return on investment. By regulating water supply to plants, all cultural practices become more critical, and more attention must be paid to adequate fertilization. This may even include attention to some essential nutrients for crop growth that were adequate in unirrigated culture. Therefore, the best information possible must be obtained in meeting plant nutrient needs.

In this region, the managing of mobile nutrients deserves particular attention. Since nutrients can easily be applied through the commonly used irrigation systems, crop requirements can be programed and met simultaneously with water requirements. By such a procedure, nutrient losses by leaching should be minimized and effectiveness of applied materials increased. Nitrogen fertilization by this means is particularly attractive. The main advantages of applying nutrients with water are savings in labor and equipment, better timing and utilization of the nutrient application, ease of split and multiple applications, and larger yields of better quality crops.

With the great variety of fertilizer products available, there are several choices to be considered. Liquid fertilizers are convenient to handle with pumps and gravity flow. They may contain a single nutrient or combinations of nitrogen (N), phosphorus (P), and potassium (K). Liquid fertilizers commonly applied through irrigation systems are listed in table 17. There is a wide variety of soluble dry fertilizers containing nitrogen, phosphorus, and potassium singly or in combination. Dry fertilizer can be dissolved by mixing with water in a separate, open tank and then pumped into the irrigation stream, or it can be placed in a pressurized container through which part of the sprinkler stream passes; the bypass water dissolves the fertilizer and carries it into the main stream. Typical dry fertilizers that may be applied through irrigation systems are listed in table 18.

The common methods of injecting fertilizers into an irrigation system are as follows:

Gravity mixing and injection on suction side

Table 18.—Dry fertilizers for application through irrigation systems[1]

Fertilizer	Formula	Total nitrogen (% N)	Available phosphoric acid (% P_2O_5)	Water-soluble potash (% K_2O)	Total sulfur (% S)	Approximate pounds of product for 1 lb of nutrient[2]			
						N	P_2O_5	K_2O	S
Ammonium nitrate	NH_4NO_3	33.5	...	...	...	3	...	...	...
Calcium ammonium nitrate.	$CaNH_4(NO_3)_3$	26	...	...	...	4	...	...	...
(Mono)ammonium phosphate.	$NH_4H_2PO_4$	11	48	...	2.6	9	2	...	40
Ammonium phosphate sulfate.	$NH_4H_2PO_4 + (NH_4)_2SO_4$	13	39	...	7	8	2.5	...	14
Ammonium phosphate sulfate.	40% $NH_4H_2PO_4$ + 60% $(NH_4)_2SO_4$	16	20	...	15.4	6	5	...	7
Ammonium phosphate nitrate.	$NH_4H_2PO_4 + NH_4NO_3$	24	20	...	...	4	5	...	...
Ammonium phosphate nitrate.	$NH_4H_2PO_4 + NH_4NO_3$	27	14	...	...	4	7	...	...
Diammonium phosphate	$(NH_4)_2HPO_4$	21	53	...	...	5	2	...	...
Ammonium chloride	NH_4Cl	25	...	...	...	4	...	...	...
Ammonium sulfate	$(NH_4)_2SO_4$	20-21	...	...	24	5	...	...	4
Calcium nitrate	$Ca(NO_3)_2$	15.5	...	...	...	6	...	...	...
Sodium nitrate	$NaNO_3$	16	...	...	...	6	...	...	...
Potassium nitrate	KNO_3	13	...	44	...	8	...	2.3	...
Urea	$CO(NH_2)_2$	45-46	...	...	...	2.2	...	...	...
Double or treble superphosphate.	$Ca(H_2PO_4)_2 \cdot H_2O$	...	42-46	...	10	...	2.3	...	10
Potassium chloride	KCl	...	...	60-62	...	...	...	1.7	...
Potassium sulfate	K_2SO_4	...	...	50-53	18	...	...	2	5.5
Sulfate potash magnesia	$K_2SO_4 \cdot 2MgSO_4$	...	...	26	15	...	...	4	7
Nitrate soda potash	$NaNO_3 \cdot KNO_3$	15	...	14	...	7	...	7	...

[1] Check with governmental chemical regulatory agencies for approval before use.
[2] To convert pounds to kilograms, multiply by 0.454.

Source: Western Fertilizer Handbook (1961).

of pump.—A centrifugal pump obtaining water from a free water surface, such as a ditch or pond, develops a negative pressure in its suction pipe. This reduced pressure can be used to draw fertilizer solutions into the pump. A hose or pipe delivers the fertilizer from an open supply tank to the suction pipe. The rate of delivery is controlled by a valve. This connection must be tight to keep air from entering the pump.

Pressure pump injection.—When turbine pumps with submerged impellers are used, the fertilizer (or other chemical) solution may be injected into the sprinkler line under pressure. A small separate rotary, gear, diaphragm, or piston pump can be used to force the chemical solution from the supply tank into the pressure line. This pump must develop a greater pressure than that delivered by the irrigation pump. The internal parts of the pump should be noncorrosive. An external source of power for the injector pump must be provided.

Venturi principle of injection.—A tapered constriction known as a Venturi unit can be used to inject chemicals into a pipeline under pressure. A pressure drop accompanies the change in velocity of the water as it passes through the constriction. The difference in pressure between a connection above and one within the constriction is enough to cause a flow of water through a supply tank containing the chemicals. Since the water flowing through the tank is under pressure, a sealed airtight pressure supply tank constructed to withstand the maximum operating pressure is required.

Pitot tube injection.—One open-ended pipe is faced into the stream of water, and another is faced opposite in the direction of the waterflow. This arrangement establishes a flow of water between the pipe ends. The water is circulated through an airtight pressure supply tank containing fertilizer or other chemicals, similar to the Venturi unit.

MEASUREMENT OF SOIL-WATER SUCTION

Day-to-day scheduling of water application depends upon measurements of soil-water suction. This is an intrinsic property of the system by which plants are directly influenced. Plants are only influenced indirectly by soil-water content. Measurement of soil-water suction removes much of the subjectivity common in irrigation practice. When plants show visible signs of water deficit, plant growth has already been retarded. In some instances it may be practical to automatically switch the irrigation system on and off from a soil-water suction measuring device. Otherwise, instrument readings must be recorded daily during periods of no rainfall. Daily readings allow one to project initiation of irrigation.

Soil-water suction is considered an equivalent pressure in the soil solution. Three instruments to measure soil-water suction are on the market: tensiometers, electrical resistance blocks, and matric potential sensors (soil-water suction is sometimes called matric potential).

Tensiometers.—These instruments may be called irrometers, soil-moisture gages, or soil-moisture indicators. To be classified as tensiometers, they must directly measure equivalent hydrostatic pressure in unsaturated soil. They have two major components: a porous ceramic cup that allows water to pass but when wet prevents air passage, and a gage that measures tension (vacuum or negative pressure) with respect to barometric pressure. The porous cup

FIGURE 22.—Commercial tensiometer.

and gage are connected by tubing. Figure 22 shows a commercially available tensiometer.

For pressure in the soil water to be adequately measured, the installation of the porous cup in the soil must insure contact between the water in the soil pores and the water in the pores of the ceramic cup. Water moves in and out of the tensiometer through the cup wall as hydraulic equilibrium is maintained between the water in the soil and in the tensiometer. The soil-water suction or tension can be read on the gage hydraulically connected to the cup. For a tensiometer to work, the pores of the ceramic cup must remain filled with water, and the tube between cup and gage remain free of air. The measurement range of the tensiometer is limited to less than 1 bar (in practice, less than about 0.85 bar), a range that is adequate for most irrigation practice. Gages on most commercially made tensiometers read from 0 to 100 centibars (1 bar=100 centibars).

If tensiometers are properly installed and used in their functional range, relatively little maintenance is required. However, each time they are read, the need for servicing should be determined. Tensiometers may be purchased with an electrical switching device that automatically turns an electrical system on and off at preset suctions. Alternately, electrical switching tensiometers may be used to turn a system on which may then be turned off by an interval timer.

Electrical resistance blocks.—These devices consist of two electrodes embedded in a porous material such as gypsum, nylon, or fiberglass. When the porous material is placed in contact with the soil, water moves from soil to block or block to soil until the water in block and soil are in equilibrium. The electrical resistance measured between the electrodes is a function of the amount of water in the porous material. Since the nature of the pore system in the block material affects the quantity of water in the block at a given suction, the relation between electrical resistance and soil-water suction will be different for each type of porous material and porous block preparation. Assuming that blocks have been uniformly fabricated from a given material and electrodes embedded in a uniform geometry, the relation of block resistance to soil-water suction will be constant for a large variety of soils. The nature of this relation is shown in figure 23.

To eliminate the effect of the soil characteristics upon the measured electrical resistance, block design is very important. The use of

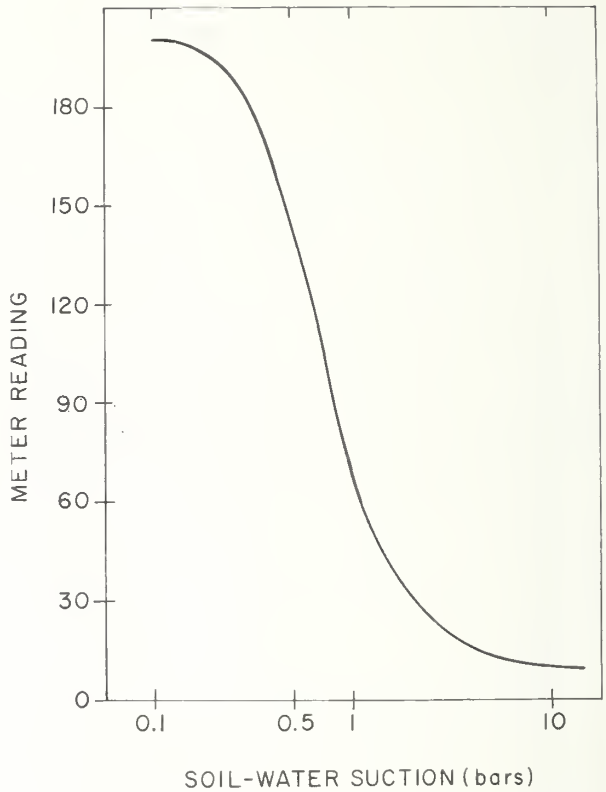

FIGURE 23.—Calibration of gypsum electrical resistance block (Delmhorst).

cylindrical electrodes in cylindrical blocks and screen electrodes in rectangular blocks has eliminated this problem. Embedded electrodes in gypsum are most commonly used. Two or three manufacturers market resistance units and meters for quickly reading electrical resistance.

To insure ready water transfer, contact between block and soil must be satisfactory. The soil must be carefully tamped back in the installation hole to a density slightly higher than natural density to prevent excess water at the surface from freely running down the hole to the blocks. A slight mounding at the surface is a further precaution. Installation instructions are available from manufacturers.

Electrical resistance blocks will not measure soil-water suction reliably at less than 0.25 bar. However, they may be used in many situations. They can be read quickly and do not require much maintenance. Gypsum blocks will slowly dissolve and must be replaced every 1 or 2 years in the Southeast, but they are inexpensive.

Matric potential sensors.—These devices also include a porous ceramic material in their construction. They must be installed at prescribed depths so that water readily moves between them and the soil to achieve equilibrium. Matric potential sensors measure the change in soil-water content of the porous block by determining the effect upon thermal conductivity. Devices in the block measure temperature change in the block resulting from an imposed heat pulse from a very small electrical heater.

Currently available sensors measure most reliably in the range of 0.1 to 1 bar, but they may be constructed to measure at higher soil-water suctions. Maintenance is fairly low, and the ceramic lasts for several years. They cost more than electrical resistance blocks and tensiometers. The manufacturer offers a variety of meter types and controls for irrigation equipment.

SIZING AND OPERATING IRRIGATION SYSTEMS

Two types of water application systems, sprinkler and drip systems, are particularly well suited to the climate, soils, and topography of the Southeast. Before equipment is purchased, the system capacity required to meet the crop's needs must be determined. After equipment is installed, it must be operated appropriately to meet the crop water requirements.

Sprinkler Systems

Sprinkler systems, either center-pivot or cable-tow, apply water as droplets that range in diameter from 0.04 to 0.28 inch (0.10 to 0.71 cm), depending on nozzle design and operating pressure. Larger droplets are less subject to being haphazardly dispersed by wind and to evaporative losses, but they can injure small or delicate plants more and can accelerate surface crusting in certain soils. Once droplets reach the soil surface, they either infiltrate and move downward by gravity and capillary forces, or produce runoff. While some lateral movement occurs, most of the movement is downward. To avoid runoff, a sprinkler system should apply water uniformly over the surface of the entire field at a rate less than the infiltration rate. Uneven water distribution results in too little water being applied in some areas, reducing crop yield, and too much in other areas, resulting in deep percolation losses, runoff and perhaps erosion, higher energy costs, and reduced yields. The coefficient of uniformity (C_u) is the most commonly used measure of application uniformity. It compares application depths at selected locations to the mean value. Absolute uniformity is represented by a C_u of 100%. Systems with C_u values of 80% or higher are generally acceptable.

Application efficiency (E_a) is defined as the ratio of water retained in the water-regulation zone to the total water applied. It depends upon the losses from evaporation, runoff, and deep percolation. Since these losses generally represent water that is unavailable to the plants, the flow capacity of the system must be increased by the amount of these losses. Application efficiencies range from a low of 70% for high-volume traveling sprinklers under windy conditions to a high of 85% for low-pressure center-pivot systems under low-wind conditions.

A system's delivery capacity must be large enough to meet maximum daily potential evapotranspiration. Determining this capacity requires a knowledge of the area to be irrigated (A, in acres or hectares), the maximum evapotranspiration rate of the crop to be grown (ET, in inches or centimeters per day—see table 19), the application efficiency of the system (E_a, as a decimal fraction), and the hours of operation per day (h). The required capacity, Q_s, in gallons per minute or liters per second is

$$Q_s = (K \times ET \times A)/(E_a \times h), \qquad (1)$$

where $K = 453$ for U.S. customary units and 27.8 for metric units.

The soil-water recharge (SWR, in inches or centimeters) of the root zone depends upon the soil depth to which water is regulated (D, in inches or centimeters), and the water retention of the

Table 19.—Maximum evapotranspiration rates for selected crops

Crop	Evapotranspiration rate: Inch per day	Evapotranspiration rate: Centimeter per day
Corn, cotton, peanuts, soybeans	0.3	0.76
Cucumbers, southern peas, snap beans	[1]0.2-0.3	[1]0.51-0.76
Peaches, pecans	[2]0.2-0.3	[2]0.51-0.76

[1]Value depends on completeness of canopy.

[2]Value depends on type and amount of ground cover and on tree canopy.

Table 20.—Maximum water application rates for three different sprinkler arrangements along a center-pivot lateral

Sprinkler arrangement	Maximum wetted diameter per sprinkler		Maximum application rate[1]	
	Feet	Meters	Inches per hour	Centimeters per hour
Variable-size sprinklers	175	53.3	1.3	3.3
All medium-size sprinklers	90	27.4	2.0	5.1
Spray-jet sprinklers	20	6.1	6.0	15.2

[1]Measured at a distance of 1,200 ft (366 m) from the pivot.

Source: Hagan et al. 1967.

regulated zone at the low (WR_l, in inches per inch or centimeters per centimeter) and high (WR_h, in inches per inch or centimeters per centimeter) water-suction values selected. The equation expressing this relationship is

$$SWR = (WR_l - WR_h)(D). \quad (2)$$

If the soil in the zone of regulation is layered, equation 2 should be applied to each layer and the results summed.

The maximum irrigation interval (I, in days) is calculated from the soil-water recharge (SWR, in inches or centimeters) and the peak evapotranspiration rate (ET, in inches or centimeters per day):

$$I = SWR/ET. \quad (3)$$

This interval should not be used for scheduling irrigations, however, because of the variability in daily ET values and effective rainfall amounts experienced during the growing season. It serves only as a potential upper limit for estimating the maximum time between irrigations. Actual in-field scheduling should be based on measured soil-water suction within the water-regulation zone.

The power required to pump water for sprinkler systems is a function of the discharge capacity of the system and in turn that of the pump (Q_s, in gallons per minute or liters per second), the total pumping head, including suction lift and friction losses (H_t, in feet or meters), and the efficiency of the pump (E_p, as a decimal fraction). The brake horsepower requirement (BHP) relationship is:

$$BHP = (Q_s \times Ht)/(K \times E_p), \quad (4)$$

where $K = 3{,}960$ for U.S. customary units and 76 for metric units.

Center-pivot systems

The center-pivot arrangement requires that each successive section of main line (moving from the center pivot to the outer end) must irrigate an increasingly larger area. To achieve this, the discharge capacity of the sprinklers (which are usually attached directly to the main line) increases with distance from the pivot point. Sprinkler wetting patterns are also overlapped to obtain the required application rates and uniformity. Generally, those systems with variable sprinkler spacings as opposed to fixed spacings provide a more uniform increase (center pivot to outer end) in application rate.

To achieve a uniform depth of water application from pivot to end point, the applicator must continuously increase the application rate by increasing the number of sprinklers or increase the sprinkling time and rate by increasing the discharge and wetting diameters of the sprinklers. Most systems use a combination of these methods, but several manufacturers have begun offering a "low pressure" system with nonrotating sprinklers that utilize only the first method. As the area irrigated per system increases, so also does the length of the main lines. This increases the possibility that peak application rates near the end of the main line will exceed the soil infiltration rate (see table 20). If this occurs for a long enough time over a large enough area to produce surface runoff, water regulation and crop response can be adversely affected. If excessive application rates cannot be avoided through suitable sprinkler sizing and spacing, the size of the area irrigated per system should be reduced.

The total depth of water applied per irrigation

Table 21.—Performance characteristics of center-pivot systems

Characteristic	Operating range
End sprinkler operating pressure	20-80 lb/in^2 (138-552 kPa).
System size	20-400 acres (8-162 ha).
Application depth	0.1-5.0 inches (0.25-12.7 cm).
Travel time	10-96 hours per revolution.
Type of drive	Electric or hydraulic.

Table 22.—Performance characteristics of cable-tow systems

Characteristic	Operating range	Most common value
Operating pressure	50-130 lb/in^2 (344-896 kPa).	80 lb/in^2.
Flow rate	74-1,210 gal/min (4.7-76.3 l/s).	550 gal/min.
Application rate	0.20-0.50 in/h (0.51-1.27 cm/h).	0.35 in/h.
Application depth	0.1-12.2 inches (0.25-31 cm).	1.5 inches.
Travel speed	0.4-10 ft/min (7.3-183 m/h).	1.8 ft/min.

by a center-pivot system is a function of the application rates along the main line and the travel speed. Since application rates are fixed by system design, the irrigator controls depth of watering by changing the system travel speed. All systems should have a travel speed that allows one full circle (or less if obstructed) in 24 hours and applies enough water to meet the peak *ET* demand of the crop. Applications less than this amount are often desirable for seed germination, seedling emergence, and chemical applications. In this situation, the system must have a full-circle travel time of less than 24 hours, for example, 12 hours if one-half of the peak *ET* amount is to be applied. When the water-regulation plan for a particular crop and soil permit more than one day's *ET* storage in the water-regulation zone, the full-circle travel time can be adjusted to meet this longer time period if desired. Table 21 summarizes the range of operating and performance characteristics of currently available center-pivot systems. Because of the day-to-day variability in *ET* and rainfall experienced in this region, the irrigator must rely on measurements of soil-water suction in determining when and how much to irrigate. Tensiometers are well suited for medium- to coarse-textured soils where suctions are to be maintained at less than 0.8 bar.

We suggest placing two tensiometers at each of several stations: one in the center of the soil-water control zone, but not less than 6 inches (15 cm) deep to determine when to begin irrigation, and a second near the bottom of the soil-water control zone to determine whether or not the water applied per irrigation is recharging the whole zone.

Frequency of tensiometer readings will depend upon climatic conditions and crop growth stage. We suggest reading them a minimum of three times a week at the beginning of the season. As the plants mature and water demands increase, daily readings may be necessary. The rate of change of soil-water suction between readings will dictate the frequency.

The number and location of tensiometer stations should be based on field size and soil variability, planned irrigation schedule, and accessibility. We suggest a minimum of six tensiometer stations for fields of 100 to 200 acres (40 to 81 ha). The irrigation schedule and full-circle travel time must also be considered when deciding where to locate the stations. If possible, there should be one or more stations within each area irrigated during a 24-hour period. Accordingly, if the full-circle travel time is 24 hours, stations can be located to best represent the soil variability in the field. If the full-circle travel time is 72 hours, placing two stations near each of three radii (120° apart) would be advisable. These stations might be located at points one-third and three-fourths radius lengths from the pivot. Allowances should be made, of course, for soil variability and station accessibility. Locating stations next to access roads or near support tower wheel tracks is convenient, although ease of access must not be the principal criteria in determining the number and location of the stations. The main objective is to obtain suction readings that best represent the average conditions throughout the entire field. Flagging and mapping the station locations is advisable.

Cable-tow systems

The cable-tow volume gun utilizes a single large sprinkler mounted on a four-wheel trailer. A

Table 23.—Lane spacings for cable-tow systems

Wind velocity	Lane spacing (% of wetted diam.)
No wind	80
Up to 5 mi/h (2.24 m/s)	70-75
Up to 10 mi/h (4.47 m/s)	60-65
Over 10 mi/h (4.47 m/s)	50-55

Source: Pair et al. 1975.

water-driven turbine powers the cable-winding mechanism. Table 22 summarizes the performance characteristics of the cable-tow systems currently available.

The application rate of the volume gun is not uniform over the entire wetted area. Consequently, the depth of water applied at each application depends on the distance from the sprinkler as well as on the rotation rate and the wind velocity. Wind velocity has the greatest effect upon application uniformity. High winds tend to distort sprinkler coverage into an egg-shaped pattern. Therefore, if possible, direction of travel should be at right angles to the prevailing wind and the lane spacing adjusted (see table 23) to obtain adequate overlap. The average application rate (AR, in inches or centimeters per hour) is a function of the sprinkler discharge (Q_s, in gallons per minute or liters per second), and the area of the wetted circle (A_w, in square feet or square meters) and is calculated by

$$AR=(K \times Q_s)/A_w, \quad (5)$$

where $K=96$ for U.S. customary units and 360 for metric units. AR should always be less than the infiltration rate of the area being irrigated.

The travel speed, which is adjustable, determines the total depth of water applied in one pass of the sprinkler. Travel speed (V_t, in feet or meters per minute) is determined from the sprinkler discharge (Q_s), the lane spacing (S_l, in feet or meters), the net depth of application (D, in inches or centimeters), and the application efficiency (E_a, as a decimal fraction) by the equation

$$V_t=(K \times Q_s \times E_a)/(S_l \times D), \quad (6)$$

where $K=1.605$ for U.S. customary units or 6 for metric units.

The factors affecting the number, location, and management of tensiometer stations in cable-tow irrigated fields are the same as those for center-pivot systems. We suggest establishing one or two stations in each area irrigated in 24 hours. The station within a lane should be placed in the most representative soil and topography and should be physically accessible.

Drip Systems

Drip irrigation is a method of slowly applying water directly onto the soil surface. Water emerges under low pressure from a point or line source. The point-source outlet devices are referred to as emitters, tricklers, or drippers. Emitters dissipate the pipe pressure (10 to 20 lb/in^2 or 69 to 138 kPa) by means of a small orifice, orifice plus vortex, or long flow path. This results in discharges ranging from 0.5 to 2.0 gal/h (1.9 to 7.6 l/h). The line-source outlet is either a porous tube that oozes water along its entire length or a single- or twin-wall tube with regularly spaced emission points. Both types operate under pressure ranging from 3 to 10 lb/in^2 (21 to 69 kPa).

Drip irrigation systems can be used to irrigate all types of crops, but for row crops where the distance between emitter lines is less than 6 feet (1.8 m), the initial cost of the system is high. For widely spaced crops such as orchards, however, the cost of a drip system compares favorably with that of sprinkler systems. In addition, the energy and water savings during operation are significant. The following discussion pertains to widely spaced crops such as fruit trees, vines, and bushes.

In contrast to sprinkler irrigation, drip irrigation does not periodically wet the entire surface of the field. Instead, water is applied at several points or in a line around the plant and flows from these points or lines in response to the water-potential gradients. This provides a means of maintaining a near optimum soil-water suction in the water-regulation or wetted zones beneath the emitters on a continuous (or at least daily) basis. Since the entire root volume occupied by each plant is not irrigated, roots tend to concentrate in the wetted zones. Thus, water is available to a large enough root volume to satisfy the water needs of the plant. Because roots are not evenly distributed, frequent and reliable replacement of water in the wetted zones is extremely important if plant stress is to be avoided during rainfall-deficient periods.

One of the most important considerations in designing a drip irrigation system is to obtain a volume of wetted soil large enough to meet the peak water demands of the plant. The size of the wetted volume beneath an emitter is primarily a function of the soil type and emitter discharge rate. Currently available data (table 24) relate discharge rate and soil texture to wetted surface area rather than to volume. Generally, this correlates reasonably well with an acceptable wetted volume. Exceptions may occur if an impervious subsoil is close to the soil surface. Keller and Karmeli (1975) recommend for humid regions wetting a minimum of 15% to 20% of the gross soil-surface area allocated to each plant. Increasing this value will provide additional water-supplying capacity for extreme dry periods and system downtime. It will, however, add to the system cost by increasing the number of emitters.

To avoid excessive surface ponding and runoff, emitter discharge rates should not exceed the infiltration rate of the soil. A general guideline is to select emitters within the discharge range of 0.5 to 1.0 gal/h (1.9 to 3.8 l/h) for fine-textured soils, 1.0 to 2.0 gal/h (3.8 to 7.6 l/h) for medium-textured soils, and 2.0 to 3.0 gal/h (7.6 to 11.4 l/h) for coarse-textured soils. Actual field trials are desirable when establishing the proper rate.

Under drip irrigation, water losses to evaporation and nonbeneficial plant use are reduced. Transpiration by plants accounts for a particularly high proportion of the consumptive use. Consequently, the evapotranspiration rates used for sprinkler irrigation (table 19) should be reduced. The extent of the reduction has not been firmly established. Keller and Karmeli (1975) suggest basing calculations of the transpirational requirements (T, in inches or centimeters per day) on the percentage of the total area shaded by the crop canopy (P_s):

$$T = (ET)(P_s/85), \qquad (7)$$

where the radio $P_s/85$ is limited to a maximum value of 1. For most row crops the ET adjustment factor will be 1 since the percentage of the total area shaded by the crop canopy (P_s) will be greater than 85.

The peak water requirements per plant (Q_p, in gallons or liters per day) are determined from the transpiration rate (T, calculated by equation 7), gross area (A, in square feet or square meters), the ratio of transpirable water to applied water (TR), and the emission uniformity (EU, a decimal fraction) by

$$Q_p = (K \times T \times A)/(TR \times EU), \qquad (8)$$

Table 24.—Areas wetted by emitters on coarse, medium, and fine soils

Emitter discharge rate		Soil texture[1]											
		Coarse				Medium				Fine			
		Diameter		Area		Diameter		Area		Diameter		Area	
Gallons per hour	Liters per hour	Feet	Meters	Square feet	Square meters	Feet	Meters	Square feet	Square meters	Feet	Meters	Square feet	Square meters
0.5	1.9	1.2	.37	1.2	0.11	2.9	0.88	6.5	0.60	4.1	1.25	13.2	1.23
1.0	3.8	2.5	.76	4.7	.44	4.1	1.25	13.2	1.23	5.4	1.65	22.5	2.09
2.0	7.6	4.1	1.25	13.2	1.23	5.4	1.65	22.5	2.09	7.0	2.13	38.3	3.56

[1]Coarse—sands, loamy sands. Medium—very fine sandy loam, loam, silt loam, silt. Fine—sandy clay, silty clay, clay.

Source: Keller and Karmeli 1975.

where $K=0.623$ for U.S. customary units and 10 for metric units. The emission uniformity is a function of emitter manufacturing tolerances, flow characteristics, and system hydraulics and ranges from 0.85 to 0.95, with 0.90 being an acceptable design value.

The number of emitters required per plant (N_e) is determined by dividing the total wetted area (A_w, in square feet or square meters) by the wetted area per emitter (A_e, in square feet or square meters):

$$N_e = A_w / A_e. \tag{9}$$

The wetted area per emitter is a function of soil type and emitter discharge rate, and values can be obtained from table 24.

The time required to apply the water (I_t, in hours per day) is calculated from the plant's daily water requirements (Q_p, in gallons or liters), number of emitters (N_e), and discharge per emitter (Q_e, in gallons or liters per hour) by

$$I_t = Q_p / (N_e \times Q_e). \tag{10}$$

The tendency in designing a drip irrigation system is to assume continuous system operation during peak transpiration periods in order to reduce pipe and pump sizes and thereby reduce costs. This is possible since drip irrigation does not interfere with cultural activities and little time is lost when irrigation is rotated from area to area. For 24-hour-a-day operation, the number of subunits (N_s) into which the irrigated area can be divided is determined from

$$N_s = 24 / I_t. \tag{11}$$

The system capacity (Q_d, in gallons per minute or liters per second) will depend on the area of the subunit (A_s, in acres or hectares), number of plants per acre or hectare (N_p), the peak water requirement per plant (Q_p, in gallons or liters per day), and the length of water application (I_t, in hours per day). The relationship is

$$Q_d = (N_p \times Q_p \times A_s) / (K \times I_t), \tag{12}$$

where $K=60$ for U.S. customary units and 3,600 for metric units.

In drip irrigation, water is carried in a pipe network to the points where it infiltrates the soil. Therefore, the uniformity of application depends completely on the uniformity of emitter discharge throughout the system. Nonuniform discharge is caused by pressure differences from friction loss and elevation, variations between emitters resulting from different manufacturing tolerances, and clogging. The relationship between the minimum and average emitter discharge within a subunit is a factor utilized to describe the uniformity of application. This relationship is called emission uniformity (EU) and should have a subunit value of 0.90 or greater. This can be obtained by properly sizing lateral and main lines, locating laterals on or near contours, and regulating pressure in each subunit.

The emitting devices must operate at or near their design discharge rates at all times if proper water regulation is to be obtained. Consequently, the importance of matching emitter-flow cross-section size to water-filter size cannot be overemphasized. Flow cross sections range from 0.008 to 0.024 inch (0.2 to 0.6 mm) in orifice emitters to 0.06 to 0.08 inch (1.5 to 2.0 mm) in multiexit long-path emitters. Larger passageways generally reduce the chance of clogging. Emitter selection requires two steps. First, evaluate and choose the general type of emitter that best fits the geometry and distribution of the area to be wetted. Second, according to required discharge, spacing, and other planning considerations, choose an emitter that has the largest cross-sectional flow area and, if possible, can be cleaned.

All the water entering the system must be filtered. The particle size that can be tolerated depends on the flow cross section size of the emitter selected. Typically, the removal of particles 5 to 10 times smaller than the emitter passageway is recommended. Filter types commonly used are screen (or net), gravel, and graded sand. In addition, vortex separators and settling ponds can be used to remove heavy loads of sand.

Ponds are the least suitable water sources for drip irrigation. Algal growth and wind-blown contaminants frequently cause severe clogging that is difficult to correct through filtration. Underground water sources free of organic particulates are much more desirable.

Tensiometers or other suitable soil-water-suction sensors should be installed in several soil-water control zones of each subunit to determine when and how much to irrigate. The actual number of stations per subunit will depend on soil and topographic variability over the area. For subunit areas of 25 acres (10 ha) or less, we suggest a minimum of two stations. Once a base period of soil-water-suction values has been established, variability in readings between stations can be analyzed, and station numbers and locations can be adjusted as needed.

A minimum of two tensiometers should be installed at each station. The shallower tensiometer should be placed at a depth equal to one-half the depth of water regulation and at a distance from the emitter equal to one-fourth the wetted diameter. The mean value of the tensiometer readings at this depth is used to determine when to begin irrigating. The second tensiometer at each station should be located near the bottom of the soil-water control zone and at a horizontal distance from the emitter equal to one-fourth its wetted diameter. The mean suction value at this depth can be used to determine if too little or too much water is reaching the bottom of the soil-water control zone.

All tensiometers should be read and serviced a minimum of three times each week. During periods of high evapotranspiration or minimum rainfall, they will require more frequent reading.

Hand-operated pressure controls and on-off valves at the inlet to each subunit are the "zero level" of automation. Even so, drip irrigation systems require relatively little labor. The main activity of the irrigator, other than scheduling, is to see that the filter is kept clean and that the emitters are flowing freely.

Operation can be automated by using switching tensiometers with a sequential controller. The tensiometer will open the flow valve to a subunit when the soil-water suction reaches a preset level. The sequence controller will not allow flow to other subunits until the tensiometer closes the valve upon sensing a decrease in the suction level.

EXAMPLE PROBLEM SOLUTIONS

Our intention is to illustrate the use of the principles and procedures that have been presented to determine appropriate water-regulation and associated cultural practices for satisfactory crop production in given farm situations. The specific land area and crop are first of all identified. This directs attention to knowledge of a given crop and its culture on a particular soil, in a particular climate, and where availability of quality water can be specified. Included as background information should be projected crop sequence and peculiar soil problems associated with past use, such as hardpans or erosion. Then crop culture and water regulation can be based on the given information and current knowledge of crop-soil-water relations.

Corn in Tift County, Ga.

A farmer in the vicinity of Tifton, Ga., plans to grow irrigated corn in a 160-acre (64.8-ha) field. Corn will be rotated with peanuts, and occasionally snap beans will be grown. The Tift County soil survey map (Jensen et al. 1959) shows that over 80% of the field is a Tifton loamy sand (Plinthic Paleudult) having a 2% to 5% slope. The soil is generally well drained, and where needed, surface drainage has been provided. This site has a potential erosion problem, and suitable control measures must be imposed. The surface soil is about 10 inches (25 cm) deep over about 7 inches (18 cm) of sandy loam to fine sandy loam. There are no pans or impedances to root exploration to the 17-inch (43-cm) depth. Long-term weather records indicate about a 50% chance of receiving 1 inch (2.5 cm) of rainfall per week from June 20 through July, with a much lower chance both before and after this period (fig. 7). In figure 9, we see that there is a 60% to 70% chance that evaporation exceeds rainfall. Tift County is underlain by the Tampa, Suwannee, and Ocala Limestone Formations, which compose the principal artesian aquifer (fig. 15). Consequently, it is feasible to drill a well with the capacity and quality to supply a large sprinkler system.

In the process of procuring a satisfactory irrigation system, careful selection of corn variety, fertilization practices, water procedures, and other cultural aspects must not be deemphasized. In fact, a complete cultural plan becomes more important than in unirrigated culture. In view of the abundant water supply, field geometry, high infiltration capacity of the soil, and the farmer's plans to grow row crops with a minimum of labor, a center-pivot system is recommended.

The capacity of the well should be large enough to meet the peak water demands of the crop with the highest water use. In this example, peanuts, corn, and snap beans all have a peak daily water requirement (table 19) of 0.3 in/day (0.76 cm/day). Assuming an application efficiency of 80% and a full-circle travel time of 24 hours, the required well and irrigation system capacity, according to equation 1, is

$$Q_s = (K \times ET \times A)/(E_a \times h),$$
$$= (453 \times 0.3 \times 160)/(0.8 \times 24),$$
$$= 1{,}132 \text{ gal/min (71 l/s)}.$$

Assuming a 100-foot (30.5-m) lift at the well (located at pivot point) with a pivot-point operating pressure of 60 lb/in^2 (414 kPa) for a total head of 236 feet (72 m) and a pump efficiency of 70%, the brake horsepower requirement is calculated from equation 4 as

$$BHP = (Q_s \times H_t)/(K \times E_p),$$
$$= (1{,}130 \times 236)/(3{,}960 \times 0.7),$$
$$= 96.$$

This horsepower requirement could be met utilizing a direct-drive 100-horsepower electric motor or a 120-horsepower diesel engine.

Water regulation

The depth of water regulation for growing corn on a loamy sand soil is assumed to be 12 inches (30.5 cm) (table 16). Response to water regulation has been good when the water suction at the 6-inch (15-cm) depth has not been allowed to exceed 0.6 bar (table 16). This suction level should not be considered as the starting point for irrigation because of the time required for the system to irrigate the entire field. Therefore, we will plan to irrigate each area in 24 hours or less when the mean soil-water suction at the 6-inch depth reaches 0.40 bar. This value will also be taken as the high suction value for calculating soil-water recharge. A value of 0.05 bar will be taken as the low value. From table 5 and figure 19, soil-texture grouping B, we obtain water-retention values to calculate, using equation 2, the soil-water recharge in the soil-water control zone between the suction limits of 0.05 and 0.40 bar:

$$SWR = (WR_l - WR_h)(D_1) + (WR_l - WR_h)(D_2),$$
$$= (0.20 - 0.09)(10) + (0.26 - 0.16)(2),$$
$$= 1.3 \text{ inches (3.3 cm)}.$$

The time required for the corn plants (plus evaporation) to remove the stored water during periods of maximum evapotranspiration (0.3 in/day or 0.76 cm/day from table 19) is calculated from equation 3 as

$$I = SWR/ET,$$
$$= 1.3/0.3,$$
$$= 4.3 \text{ or about 4 days}.$$

This value can be used to estimate the maximum time between irrigations when peak evapotranspiration requirements must be met (actual scheduling should be based on in-field suction measurements) and to determine the maximum permissible full-circle travel time for the system.

Tensiometers should be installed to determine when to irrigate and how much water to apply. We suggested earlier a minimum of six tensiometer stations located on each of three radii approximately 120° apart. In surveying the field layout (fig. 24) we see that there are two access roads to the pivot point. While these two roads do not exactly fit our 120° criteria, they will provide easy access to four of the six stations. The other two stations could be located along the radius indicated by the dash line. This will place five stations in soil type NbBl (55% of the area) and one station in type Nb (21% of the area). These locations could be altered somewhat to allow for topographic variability. The tensiometers must be serviced and read three times a week early in the season and more often as plant water demand increases.

We stipulated that we would begin irrigating the field when the mean suction (average of all six tensiometer readings) at the center of the water regulation zone—in this case, 6 inches (15 cm)—reached 0.4 bar. We also indicated that no portion of the soil-water control zone should exceed a suction of 0.6 bar. How one operates the system to achieve this level of management will depend upon the portion of the total field area that is irrigated in 1 day.

Consider the case when the full-circle travel time is set at 24 hours (0.3 in/day or 0.76 cm/day net application). If, during peak evapotranspiration periods, irrigation is begun when the mean suction reaches 0.4 bar, by the time the circle is completed (24 hours later) the suction in the area irrigated last could be above 0.6 bar (fig. 25). To avoid this, irrigation should begin at a mean suction value of about 0.20 bar. Consider the other extreme, when the full-circle travel time is set at 96 hours (1.2 inches or 3.0 cm net application). Irrigation would have to begin when the mean suction level in the first quadrant reached 0.08 bar if suctions greater than 0.6 bar were to be avoided in the fourth quadrant. Applying 1.2 inches (3.0 cm) of water to a soil with a suction of 0.08 bar would result in excessively deep percolation below the soil-water control zone, and should be avoided. A system designed for a 4-day full-circle travel time characteristically will

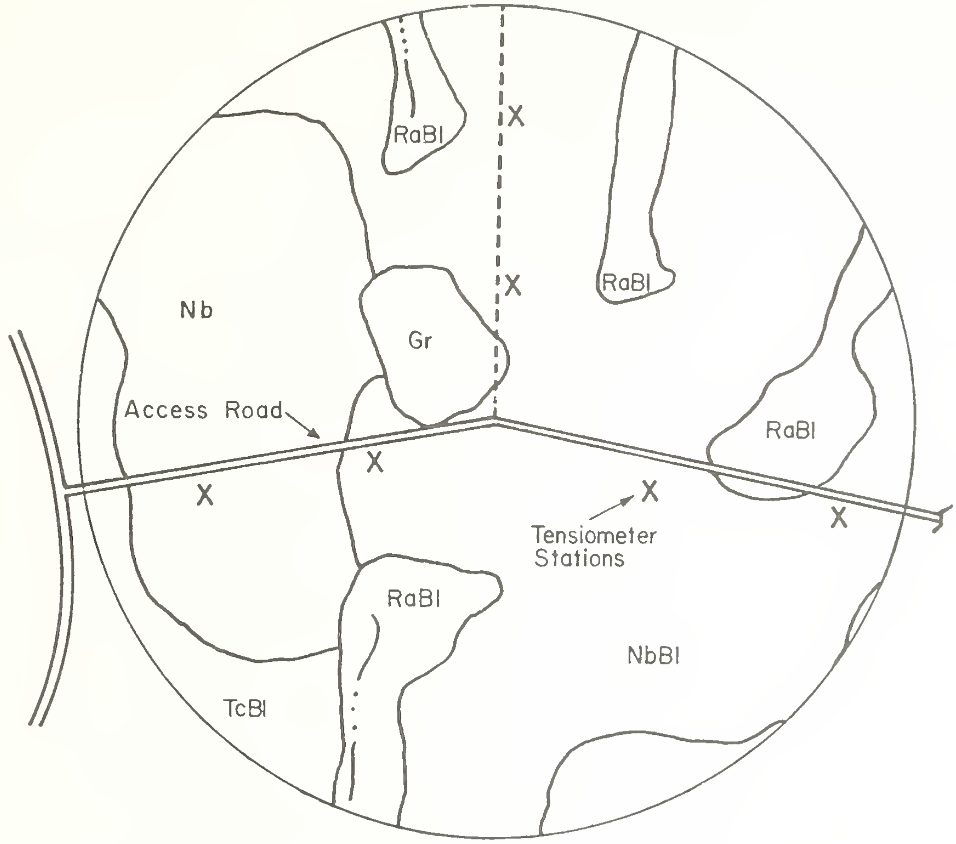

FIGURE 24.—Proposed field site for 160-acre (65-ha) center-pivot irrigation system. Gr, Grady sandy loam. Nb, Norfolk loamy sand, level thick surface phase. NbBl, Norfolk loamy sand, very gently sloping thick surface phase. TcBl, Tifton sandy loam, very gently sloping phase. RaBl, Rains loamy sand, very gently sloping thick surface phase.

either apply water prematurely at the beginning of the cycle or too late at the end. As full-circle travel time is decreased, this problem is diminished. A solution to the problem would be to change the depth of application in each quadrant to that necessary to bring the suction back to 0.05. For example, the first quadrant might receive 0.3 inch (0.76 cm), the second 0.6 inch (1.52 cm), the third 0.9 inch (2.28 cm), and the fourth 1.2 inches (3.0 cm) by adjusting the system full-circle travel times to 6, 12, 18, and 24 hours, respectively. If this is not practical, an alternate approach would be to reduce the full-circle travel time to 2 days (0.6 inch or 1.52 cm, net application) and begin the initial cycle when the suction in the first two quadrants (one-half of the field) reached approximately 0.15 bar. This would result in an acceptable amount of overwatering at the beginning of the cycle and suctions not excessively above 0.6 bar before irrigation near the end of the cycle (end of second day). After the initial cycle had been completed, and if no rainfall occurred, the next cycle would begin when the mean suction value along the nearest radius (in the direction of travel) reached approximately 0.40 bar. During this subsequent "non-start-up cycle," no segment of the circle should exceed 0.4-bar suction before it is irrigated. When significant (more than 0.5 inch or 1.25 cm) rainfall interrupted the cycle, it would then be necessary to return to the "start-up cycle" procedure or a modification thereof.

This "maximum demand" irrigation schedule will only apply during extended rain-free periods that occur at the time of peak evapotranspiration demand. Most of the time during the growing season, the daily water needs of the crop will be less. Consequently, it is extremely important to locate a second tensiometer at the bottom of the soil-water control zone to determine if the proper

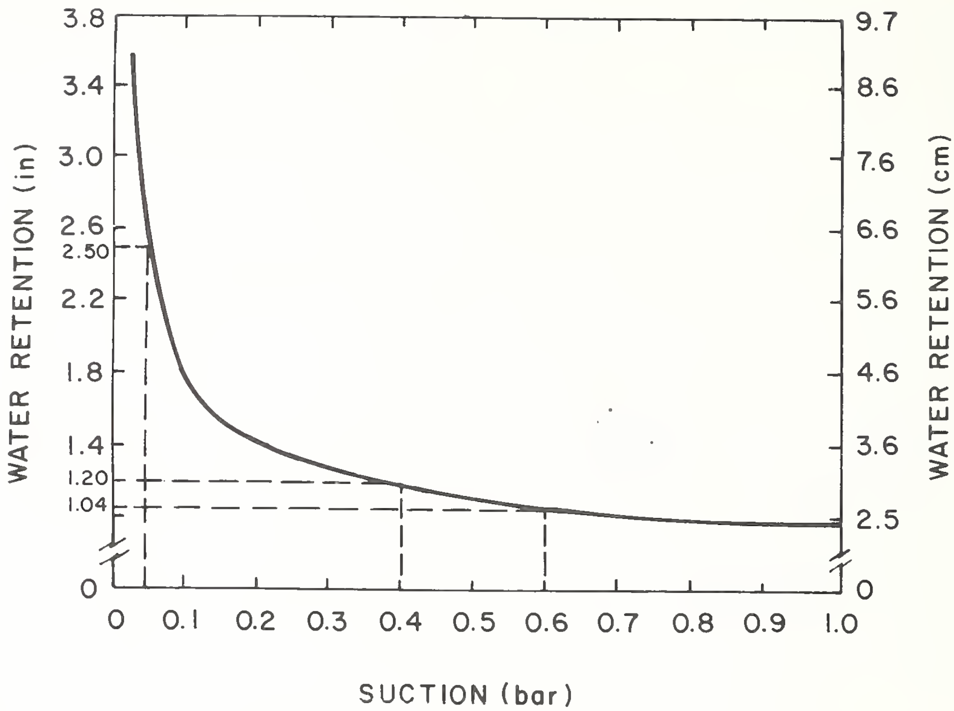

FIGURE 25.—Water retention in the zone of regulation (12 inches or 30 cm) of a Southern Coastal Plain soil with 10 inches (25 cm) of loamy sand over sandy loam or fine sandy loam.

Table 25.—Nitrogen (N) and potassium (K) requirements for corn at various growth stages

Growth stage	Nutrient requirements (% of total)	
	N	K
1. Emergence to 4 fully emerged leaves	2	2
2. 4 to 8 fully emerged leaves	5	5
3. 8 to 12 fully emerged leaves	19	29
4. 12 to 16 fully emerged leaves	26	33
5. 16 fully emerged leaves to silking and pollen shed	12	21
6. Silking to 12 days after silking (blister stage)	12	10
7. 12 to 24 days after silking (dough stage)	10	0
8. 24 to 36 days after silking (early dent)	7	0
9. 36 to 48 days after silking (full dent)	2	0
10. 48 to 60 days after silking (maturity)	5	0

Source: Hanway 1971.

amount of water is being applied at each irrigation. About 6 to 12 hours after an irrigation, the bottom of the control zone should have water-suction values in the range of 0.08 to 0.15 bar. If the suction is less than 0.08 bar, less water should be applied during the next irrigation by reducing the full-circle rotation time (increasing travel speed). If the value is greater than 0.15 bar, more water should be applied by increasing the full-circle rotation time (reducing travel speed). This approach can be used for any full- or part-circle rotation time—12 hours, 1 day, 2 days, and so forth.

Fertilizer applications through the irrigation system can boost yields and lower production costs. This is especially true for those nutrients which are highly leachable, such as nitrogen, and somewhat leachable, such as potassium. Frequent applications quantitatively adjusted to the uptake rate of the corn are very desirable. Table 25 shows the seasonal uptake rate of nitrogen and potassium for corn in relation to growth stage. Assuming that 300 pounds of nitrogen per acre (336 kg/ha) and 200 pounds of potassium per acre (224 kg/ha) are required for a yield of 200 bu/acre (12.54 metric tons/ha) the nitrogen and potassium requirement for each stage can be calculated.

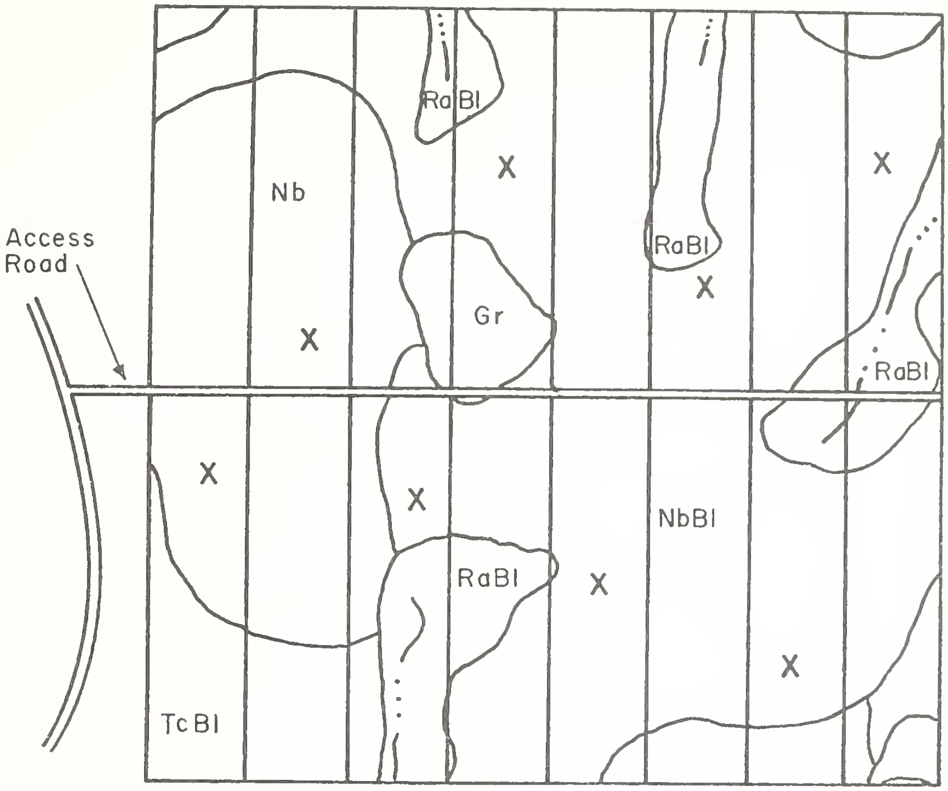

Figure 26.—Proposed field layout for a 160-acre (65-ha) cable-tow volume gun (2 units) irrigation system. X, Tensiometer station. Gr, Grady sandy loam. Nb, Norfolk loamy sand, level thick surface phase. NbBl, Norfolk loamy sand, very gently sloping thick surface phase. TcBl, Tifton sandy loam, very gently sloping phase. RaBl, Rains loamy sand, very gently sloping thick surface phase.

Although the time interval between applications will be partially dependent on weather conditions, a 7- to 14-day interval during rapid uptake periods may be necessary to insure that plant needs are met and serious leaching losses are avoided.

Alternative system

A cable-tow volume-gun system could be utilized as an alternate to the center-pivot sprinkler system. The selection would be predicated upon field shape, initial investment costs, and availability of labor. A typical cable-tow volume gun with a 1.75-inch-diameter (4.4-cm) nozzle at 85 lb/in^2 (586 kPa) will discharge 600 gal/min (37.8 l/s) over a wetted diameter of 460 feet (140 m).

The application rate, according to equation 5, would be

$$
\begin{aligned}
AR &= (K \times Q_s)/A_w, \\
&= (96 \times 600)/(230^2 \times 3.14), \\
&= 0.35 \text{ in/h } (0.9 \text{ cm/h}),
\end{aligned}
$$

which is well below the maximum allowable rate of 0.7 in/h (1.8 cm/h) given in table 5.

Assuming an application efficiency of 75% and a lane spacing of 290 feet (88 m) —63% of the wetted diameter for 10-mi/h (4.5-m/s) winds, the travel speed required to apply 1.2 inches (3.0 cm) of water is calculated from equation 6:

$$
\begin{aligned}
V_t &= (K \times Q_s \times E_a)/(S_l \times D), \\
&= (1.605 \times 600 \times 0.75)/(290 \times 1.2), \\
&= 2.08 \text{ ft/min } (0.63 \text{ m/min}).
\end{aligned}
$$

Utilizing a 660-foot (201-m) flexible hose and irrigating beyond the end of the hose a distance equal to approximately one-third the lane spacing, it is possible to irrigate a strip 1,513 feet (461 m) long (2×660+0.67×290). Traveling at 2.08 ft/min (0.63 m/min), it will require 10.6 hours (2×660/2.08×60) to irrigate one complete strip. To irrigate 80 acres (32.4 ha) with strips 290 feet wide by 1,513 feet long would require eight lanes. Allowing 1.4 hours of moving time between lanes, it would take 4 days (8×12/24) to irrigate the full

80 acres. Consequently, to irrigate 160 acres (64.8 ha) and stay within our maximum irrigation cycle period of 4.3 days would require a two-gun system.

Determining when to irrigate and if the correct amount of water is being applied is carried out in the same manner as for the center-pivot system. The only difference is in selecting the locations for the tensiometer stations. We recommend a minimum of four tensiometer stations per 80-acre (32.4-ha) block. If the stations are in alternate lanes, the volume gun would always be within one day's travel time of a station. Two tensiometers should be installed at each station; one at the midpoint of the soil-water control zone (6 inches or 15 cm) and a second at the bottom of the zone (12 inches or 30 cm). The location of the station within each lane should be based on soil type, topography, and accessibility. One possible field layout for the system including tensiometer stations is shown in figure 26.

The "startup" irrigation cycle should begin when the mean value of the four tensiometers (at the 6-inch depth) in each 80-acre area is approximately 0.15 bar. This will result in over-irrigation of the first three or four strips and suctions greater than 0.6 bar in the final strip prior to irrigation. The other alternative is to reduce the depth of application (by increasing travel speed) to 0.3 inch (0.76 cm) for lanes 1 and 2, 0.6 inch (1.52 cm) for lanes 3 and 4, 0.9 inch (2.29 cm) for 5 and 6, and 1.2 inches (3.0 cm) for lanes 7 and 8. If no significant rainfall occurs, subsequent cycles should begin when the tensiometers in lane number 1 (or 2) approach a mean value of 0.3-bar suction. If a cycle is interrupted by a significant amount of rainfall, the startup procedure can be used when irrigation is called for. In this situation, lane number 1 becomes the next lane to be irrigated.

The amount of water applied should be such that the suction at the bottom of the soil-water control zone is in the 0.08- to 0.15-bar range 6 to 12 hours after an irrigation. If the mean suction consistently falls outside this range, the travel speed of the volume gun should be adjusted accordingly.

Tensiometers should be read and serviced a minimum of three times weekly during the early growing season and mild weather, and more frequently during the mid and late growing season and hot weather.

Peaches in Oconee County, Ga.

In Oconee County, near Watkinsville, Ga., a grower wishes to set out 24 acres (9.7 ha) of peaches on a Cecil sandy loam (Typic Hapludult) with 2% to 4% slope (Robertson 1968). The sandy loam surface soil is about 7 inches (18 cm) deep over about 6 inches (15 cm) of sandy clay loam which classifies it as soil-texture grouping B in table 4. There is a moderate erosion hazard, and control measures must be imposed. Long-term weather records indicate about a 35% chance of receiving 1 inch (2.5 cm) of rainfall per week from early April through July, except from May 15 to June 15, when chances decrease to about 30%. From April through October there is more than a 75% chance that monthly evaporation will exceed rainfall (fig. 9). An adequate supply of water is available in a nearby lake—15 acre-feet (18,505 m^3)—or a well with a 75-gal/min (4.73 l/s) capacity.

Crop culture and water regulation

Sodded middles with vegetation-free strips 5 to 6 feet (1.5 to 1.8 m) wide beneath the trees are recommended for peach culture. The strips should be kept clean with an effective herbicide. The middles should be laid out across the prevailing slope to reduce erosion and vehicular energy requirements. Trees will be planted on a 20- by 20-foot (6.1- by 6.1-m) spacing pattern to allow room for vehicles.

Drip irrigation is well suited to peach trees. Water can be applied daily at low pressures to a small area beneath each tree. This minimizes water and energy requirements while meeting the almost continuous water needs of the tree. A single lateral line will be laid along the clean strip at the base of the trees. One to six emitters, depending on tree size, attached to the lateral line will supply each tree's water requirements. Where surface damage by traffic is a problem, the lateral lines can be buried and a "riser outlet" provided for the emitters at each tree.

Sizing the system

Emitter capacity should be 1.0 gal/h (3.8 l/h). For a medium-textured soil, this flow rate should prevent surface ponding and runoff from the wetted area beneath the emitter.

Under high-level irrigated management, peach trees can be expected to reach full canopy size of 15 to 18 feet (4.6 to 5.5 m) in diameter in 4 years after field transplanting. The peak evapotranspiration demand for a two-thirds sod cover (table 19) should be approximately 0.23 in/day (0.58 cm/day). Utilizing equation 7 the peak transpiration rate for a mature tree with a canopy diameter of 16 feet (4.9 m) is calculated:

$$T=(ET)(P_s/85),$$
$$=0.23(50/85),$$
$$=0.13 \text{ in/day } (0.34 \text{ cm/day}).$$

Assuming a transpiration ratio of 0.95 and an emission uniformity of 0.92, the peak water requirements per tree are calculated from equation 8:

$$Q_p=(K\times T\times A)/(TR\times EU),$$
$$=(0.623\times 0.13\times 400)/(0.95\times 0.92),$$
$$=38 \text{ gal/day } (145 \text{ l/day}).$$

Selecting the total area wetted by the emitters to be 17% of the gross area, the number of emitters per tree is calculated from equation 9 (*Ae* is obtained from table 22):

$$N_e=A_w/A_e,$$
$$=(0.17\times 400)/13.2,$$
$$=5.$$

Spacing the emitters at 4-foot (1.2-m) intervals along the lateral line will allow the wetted areas to just meet (wetted diameter=4.1 ft or 1.25 m from table 24). Emitters *should not* be arranged so that one is right next to the tree trunk. This will reduce soil support for the trunk because of the wetting of the soil. It is preferable to place an emitter 2.0 feet (0.6 m) on either side of the trunk. Because the trees are smaller when planted, no more than two emitters are needed the first year.

The net length of time for applying the peak daily water requirement is calculated from equation 10:

$$I_t=Q_p/(N_e\times Q_e),$$
$$=38/(5\times 1.0),$$
$$=7.6 \text{ hours}.$$

To minimize system flow requirements and pump size, the system should operate continuously during peak demand periods. To achieve this, the field should be divided into subunits according to equation 11:

$$N_s=24/I_t,$$
$$=24/7.6,$$
$$=3.$$

The field layout of the system will then include three independently controlled subunits of 8 acres (3.2 ha) each.

The water requirements to meet the peak daily demand of the 24-acre (9.7-ha) orchard is calculated from equation 12:

$$Q_d=(N_p\times Q_p\times A_s)/(K\times I_t),$$
$$=(109\times 38\times 8)/(60\times 7.6),$$
$$=73 \text{ gal/min } (4.6 \text{ l/s}.$$

Operating the system

Determining when and how much to irrigate is our next consideration. A minimum of two tensiometer stations should be installed in each subunit. These stations should be located at easily accessible sites that represent the predominant soil and topography over the subunit area. Two tensiometers should be utilized to determine when to irrigate the subunit. One tensiometer should be installed at a depth of 8 inches (20 cm) below the emitter, one-half the depth of the soil-water control zone shown in table 16, and 12 inches (30 cm) horizontally (one-fourth the wetted diameter) from the emitter. It is desirable to fix (by pinning) the emitter and lateral line to the soil surface to prevent any accidental change in the configuration. When the mean suction value reaches 0.30 bar, the subunit should be irrigated. This should prevent the suction from exceeding 0.60 bar by the time irrigation is complete, which could be up to 22 hours if all three subunits call for water at the same time during a peak demand period.

The second tensiometer at each station provides a means of determining if too little or too much water is being applied at each irrigation. It should be installed near the bottom of the control zone at a depth of 15 to 16 inches (38 to 41 cm), and located 12 inches (30 cm) horizontally from the emitter (one-fourth the wetted diameter). Twelve to 24 hours after an irrigation, these tensiometers should read between 0.08- and 0.15-bar suction. If the value is consistently less than 0.08 bar, reduce the irrigation time and apply less water. If the value exceeds 0.15-bar suction, the irrigation time should be increased (up to a maximum of 8 hours during peak evapotranspiration demand).

Switching tensiometers could be installed in each subunit to automatically turn the water on when the suction reaches a preset value. These tensiometers should be located in the same position (relative to emitter) as the shallow unit in the manually read tensiometer stations. The tensiometer switch should be set to turn the system on at approximately 0.30-bar suction. The switches will normally close after a 0.04- to 0.06-bar drop. If a switching tensiometer is used, we strongly recommend frequent reading of tensiometers as a further check on the performance of the system.

The importance of regular service and reading of the tensiometers cannot be overemphasized. Three times a week is suggested as a minimum. During high water-demand periods it may be necessary to read the tensiometers daily. Plotting these data will enable the irrigator to trace the history of the suction levels in the soil-water control zone and anticipate when and how much to irrigate. If switching tensiometers are used, the manually read data will help to determine if the switching tensiometer-emitter configuration is adequate.

If possible, a well should be used as a source of water for the drip system. Surface water supplies such as ponds, lakes, and rivers require an intensive filtration system which may not entirely prevent emitter clogging. Filtration requirements for well water can generally be satisfied with a 100-mesh (or smaller) screen-type or equivalent cartridge-type or sand filter.

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