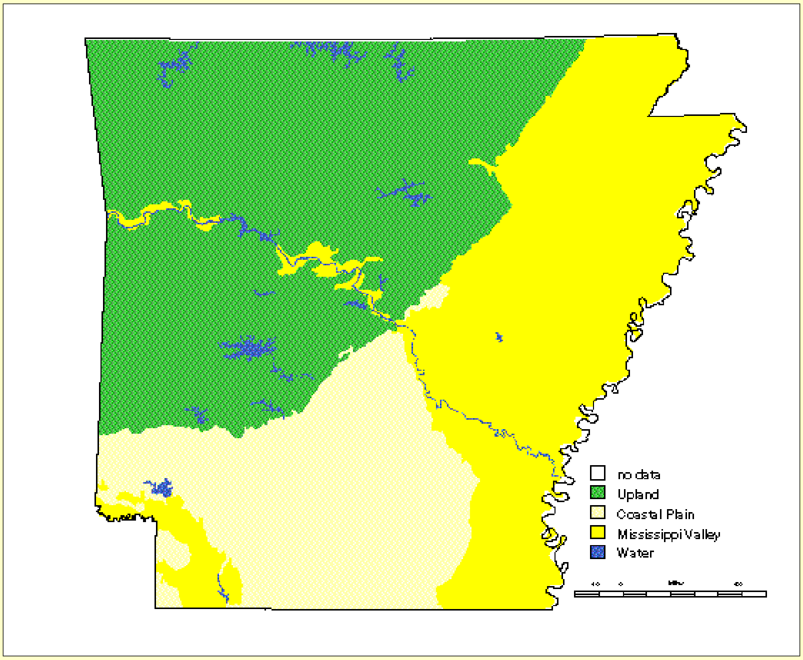
Agricultural Water Management in the Mississippi Delta Region of Arkansas



H. Don Scott, James A. Ferguson, Linda Hanson, Todd Fugitt and Earl Smith

ARKANSAS AGRICULTURAL EXPERIMENT STATION

Division of Agriculture | University of Arkansas

August 1998 | Research Bulletin 959

IMPACT STATEMENT

Agriculture is the largest use of soil and water resources in eastern Arkansas. This bulletin summarized the recent historical use of soil and water by agriculture and the impact of irrigation on yields of rice, soybeans and cotton. The experiments conducted in the field to quantitatively schedule irrigations of crops are summarized. The results show the close relationship between the irrigation of crops and the extraction of water from the Alluvial Aquifer. The implications of this relationship for the future are discussed.

Key words: ground water, soils, crops, landuses, irrigation.

ACKNOWLEDGMENTS

Appreciation is expressed to several individuals who greatly assisted the authors in writing this document. Marty McKimmey and Barnali Mitra of the Department of Agronomy, University of Arkansas, Division of Agriculture helped with the development of the digital databases and maps of the various parameters and relationships. Larry Ward and Rick Fielder of the Natural Resources Conservation Service in Little Rock provided helpful information on the soils in eastern Arkansas and the Mid-South region. Thanks are also given to the graduate students in the Departments of Agronomy and Biological and Agricultural Engineering who conducted many of the research studies as a portion of their graduate degree program at the University of Arkansas, Fayetteville. Dr. Nancy Wyatt served as the editor. The Arkansas Agricultural Experiment Station and the Arkansas Soil and Water Conservation Commission provided the publication costs, and the Arkansas Soybean Promotion Board and the Arkansas Rice Research and Promotion Board funded much of the research.

Editing and cover design by Nancy G. Wyatt

Agricultural Experiment Station, University of Arkansas Division of Agriculture, Fayetteville. Milo J. Shult, Vice President for Agriculture and Director. Charles J. Scifres, Associate Vice President for Agriculture. PS1.2M798PM.

The Arkansas Agricultural Experiment Station follows a nondiscriminatory policy in programs and employments. ISSN:0099-3491 CODEN: AKABA7

Agricultural Water Management in the Mississippi Delta Region of Arkansas

H. Don Scott
University Professor
Department of Agronomy
University of Arkansas
Fayetteville, Arkansas

James A. Ferguson
Professor
Department of Agricultural and Extension Education
University of Arkansas
Fayetteville, Arkansas

Linda Hanson
Arkansas Soil and Water Conservation Commission
Little Rock, Arkansas

Todd Fugitt
Arkansas Soil and Water Conservation Commission
Little Rock, Arkansas

Earl Smith
Arkansas Soil and Water Conservation Commission
Little Rock, Arkansas

Arkansas Agricultural Experiment Station
Fayetteville, Arkansas 72701

ABBREVIATIONS USED IN THIS PUBLICATION

AAES	-	Arkansas Agricultural Experiment Station
ASWCC	-	Arkansas Soil and Water Conservation Commission
CS	-	crop susceptibility
CV	-	coefficient of variation
DBES	-	Delta Branch Experiment Station
DC	-	double cropping
DM	-	dry matter
DSEEP	-	deep seepage or internal drainage
E	-	evaporation
Eh	-	redox potential
ESPS	-	early-soybean production systems
ET	-	evapotranspiration
g	-	stomatal conductance
gal/min	-	gallons per minute
ha	-	hectares
I	-	irrigated
J	-	joules
LAI	-	leaf area index
LAR	-	leaf area ratio
LSEEP	-	lateral seepage
LWR	-	leaf weight ratio
m/d	-	meters per day
Mgal/d	-	million gallons per day
Mha	-	million hectares
MJ	-	mega joules
MLRA	-	Major Land Resource Area
mV	-	millivolts
NEREC	-	Northeast Research and Extension Center
NI	-	nonirrigated
NRCS	-	Natural Resources Conservation Service
ODR	-	oxygen diffusion rate
RREC	-	Rice Research and Extension Center
SDRAIN	-	surface drainage
SLA	-	specific leaf area
SSURGO	-	Soil Survey Geographic Database
STATSGO	-	State Soil Geographic Database
SY	-	seed yield
T	-	transpiration
Tgal	-	trillion gallons
USGS	-	U.S. Geological Survey
WUE	-	water use efficiency

CONTENTS

AGRICULTURAL WATER MANAGEMENT IN THE MISSISSIPPI DELTA REGION OF ARKANSAS

H. Don Scott, James A. Ferguson, Todd Fugitt, Linda Hanson and Earl Smith

INTRODUCTION

For much of the Mississippi Delta Region of Arkansas, agriculture is a major economic factor. The predominant crops of soybeans, rice and cotton are produced during the hot summer months. Water management is of primary importance in producing high yields of those crops. Water management encompasses many facets, but the emphasis in this report is on irrigation, use and conservation of water, crop response to water management and improved drainage.

Soybeans have been grown for 168 years in the U.S., probably originally coming from China. They have been used as a coffee substitute, as livestock forage and currently as a valuable protein and oil crop. Researchers over the past decades have sought methods for producing greater crop yields and/or reducing use of inputs. Typical production practices have incorporated the use of cultural, fertilizer and pesticide programs to effectively manage and control a broad range of pests. In recent years, greater emphasis has been directed to research on the detrimental effects of drought and standing water on yields and the development of effective water management strategies to overcome those undesirable water effects.

In much of the U.S., soybeans historically have not been irrigated. This is due to a combination of factors including climate, soil characteristics, water availability, land tenure and economic investments associated with irrigation. The availability of water is essential to a high level of production. The evapotranspiration process provides some level of temperature control and water movement and is the primary medium of transport of nutrients and other inorganic and organic chemicals within the soil and in the plant.

In Arkansas, irrigation of soybeans has been expanded considerably in the past 25 years. This expansion has been driven by availability of considerable quantities of water and the combination of soils and climate that create a situation in which irrigation significantly increases crop yields in most years.

Rice was first grown extensively in Arkansas in 1904 on 186 ha (Huey, 1977). The crop historically has been irrigated with flood irrigation, which tends to remove drought stress as a limiting factor in production. The presence of a flood is not a prerequisite to high rice yields, but it is the simplest and most effective way to assure high availability of water to the rice crop. A flood also functions to control many weeds. Inadequate surface drainage can be a detriment at planting and germination as well as at harvest time.

In Arkansas, irrigation of cropland has been extensively developed in the past 25 years. This is primarily due to the combination of natural resources, such as climate, soils and availability of an abundant supply of water, and to the water requirements of the crops grown in the state. As a result, the use and management practices of water have become important components in production agriculture.

The purpose of this report is to summarize the primary factors affecting the historical, spatial and temporal use of water in agriculture in eastern Arkansas and the research conducted to quantify the impact of water management on crop growth and development. Emphasis is given to the region in Arkansas with the most intensive use of water (i.e., the 27 counties of eastern Arkansas) on soybeans and rice, the most extensively grown crops in eastern Arkansas, and to the research conducted in the field over the years by the senior authors.

PHYSIOGRAPHIC REGIONS

Arkansas has an area of about 13,753,177 ha[1] and ranks 27th in area of the 50 United States. The 1990 population of 2.351 million ranked Arkansas 33rd among all the states. The state is divided into 75 counties.

Three major landforms occur in Arkansas (Fig. 1). The northwestern area is a physiographic region known as the Uplands or Interior Highlands, which consists of mountains and plateaus of the Ozark and Ouachita Mountains and Arkansas Valley and Ridges. This region occupies about 44% of the land area of Arkansas. The altitude in this region ranges from about 76 to 853 m above sea level, averaging about 427 m. The bedrock of the Interior Highlands consists of interbedded shale, sandstone and limestone. The rocks are relatively old geologically and have been compacted and cemented. To the south is the Western Gulf Coastal Plain, which consists of gently to steeply sloping dissected rolling hills. This region occupies about 21% of the state. The altitude of this region ranges from about 30 to 200 m above sea level. The soils in the Coastal Plains tend to be deep, moderately coarse to coarse textured with moderately coarse-textured to fine-textured subsoils. To the east is the Mississippi Alluvial Plain, which consists of level to gently sloping broad flood plains and low

[1]For conversion to English units, please see the conversion table inside the back cover of this publication

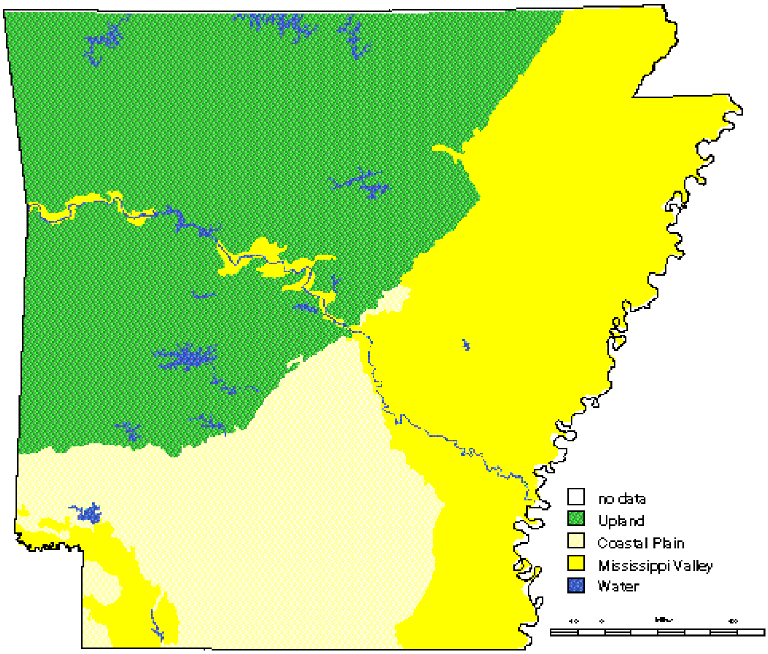


Fig. 1. Major physiographic regions of Arkansas.

terraces with deposits of sand, silt and clay. This region, sometimes called the Mississippi Delta or Delta, occupies about 33.4% of the land area of Arkansas. The altitude ranges from 30 to 90 m above sea level. The most prominent feature of the landscape in the Alluvial Plain (Delta) is Crowleys Ridge, an erosional remnant, which rises above the Delta and reaches a maximum elevation of 168 m in Clay County and varies in width from 0.8 to 19 km. The deposits of the two plains are relatively young geologically and have been compacted and cemented only slightly.

NATURAL RESOURCES

Effective water resource management in the agricultural sector of the Mississippi Delta region of Arkansas requires a working knowledge of the climatic, water and soil resources and their interactions and effect on agricultural production. The region has the preponderance of irrigation as well as extensive drainage problems. It is the dominant rice, soybean and cotton producing region of the state. This section will present an overview of the climate, water and soil resources in the region.

Climate

The climate is a natural resource of Arkansas that has a fundamental impact on the agricultural economy and, therefore, on water management. Climate is the average of weather events over many years. Effective water management is driven by the daily weather occurrences within the climatic regime of the region. Since the practice of agriculture is the business of converting solar energy, water and other substances into usable biological materials, climatic extremes are frequently the difference between good and poor crop production years. The impact of a drought or flood can cost literally billions of dollars. As a result, agriculture is closely tied to the effects of weather in many direct, as well as numerous subtle, ways. Great economic and environmental benefits can be obtained by directing timely weather-related information to the agricultural sector of the economy. The aspects of weather to be dealt with here include precipitation, pan evaporation, potential evapotranspiration, air temperature and water deficit.

Precipitation

Long-term average annual rainfall in the Mississippi Delta region of Arkansas ranges from 1180 mm/year at Saint Francis in the northern end of the Delta region to 1340 mm/year at Monticello in the southern part of the Delta region with most weather stations indicating about 1250 mm/year.

Mean monthly rainfall is distributed throughout the year as shown in Fig. 2 for three stations. Note that there is a distinct spring maximum at all stations with significantly lower monthly precipitation in the summer months of June, July and August. September shows a secondary maximum at all three stations. The maximums generally correspond to the passage of the mean polar front location. Cumulative summer crop season rainfall for the months of June, July, August and September is about 350 mm for most stations.

Significant variation in the rainfall among years is common. Monthly rainfall for any given month may vary from near zero to as much as several times the mean monthly rainfall.

Evaporation

The process of water moving from the liquid state in the plant or soil to the atmosphere in the gaseous state is evaporation (from soil surfaces) and transpiration (from plant surfaces). These are physically similar processes and are frequently combined and called evapotranspiration. These processes are predominantly energy driven, controlled to a great extent by solar radiation with humidity and wind being less-dominant factors.

Potential evapotranspiration, often called reference crop evapotranspiration, is a meteorological parameter that expresses the rate at which water, if readily available at the soil and plant surfaces, would be moved to the vapor state in the atmosphere. Actual crop evapotranspiration can be less than poten-

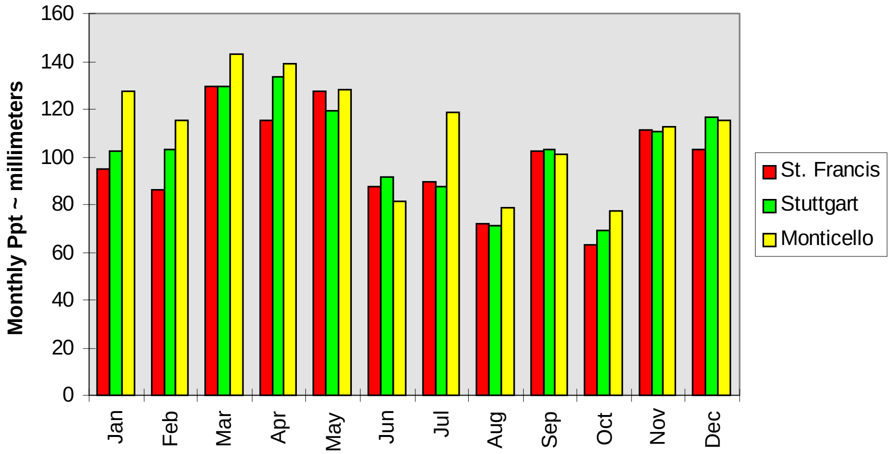


Fig. 2. Mean monthly precipitation at three stations ranged across the Delta region from north to south, 1960-1989.

tial evapotranspiration due to limited availability of water, insufficient crop leaf area or crop senescence, but it will never be greater. The ratio of actual crop evapotranspiration to potential evapotranspiration (under well-watered conditions) is called the crop coefficient and typically varies from about 0.25 with emerging plants to 1.0 after plants have reached a leaf area index of about 3.0. Workable estimations of potential evapotranspiration are essential to effective water management.

Pan evaporation is a meteorological measurement that is taken at selected weather stations. It is the rate of evaporation from a free water surface in a specified pan situated in specified conditions. Pan evaporation is a good index of the potential evaporativity of the atmosphere, particularly in humid and subhumid regions such as the Delta region of Arkansas. For this region, the ratio of potential evapotranspiration to pan evaporation, called the pan coefficient, can normally be taken as 0.85 (Doorenbos and Pruitt, 1977).

Mean monthly pan evaporation and potential evapotranspiration typical of the entire Delta region are given in Table 1. These data are for the weather station located at the Rice Research and Extension Center near Stuttgart, Arkansas (Stuttgart 9 east southeast, ESE) but are typical of the entire Delta region. It is important to note that both the spatial and year-to-year variation in observed values of evaporation will be much less than the variation in rainfall.

Table 1: Long-term (1960-1989) mean monthly pan evaporation (Pan Evap.) for Stuttgart 9 East Southeast taken from NOAA climatic data for Arkansas and potential evapotranspiration (Pot. ET) calculated as 0.85 x pan evaporation.

Month	Pan Evap.	Pan Evap.	Pot. ET	Pot. ET
	mm	in.	mm	in.
Jan	27	1.05	23	0.89
Feb	43	1.70	37	1.45
Mar	92	3.63	78	3.09
Apr	137	5.38	116	4.58
May	166	6.52	141	5.54
Jun	191	7.51	162	6.38
Jul	194	7.64	165	6.49
Aug	173	6.81	147	5.79
Sep	132	5.19	112	4.42
Oct	100	3.92	85	3.33
Nov	57	2.26	49	1.92
Dec	31	1.22	26	1.04
Total	1342	52.83	1141	44.91

Air Temperature

Long-term monthly mean maximum and minimum air temperature for Stuttgart 9 ESE is presented in Fig. 3, showing a mean maximum above 32 C in July and a mean minimum daily temperature below 1 C during January. The normal daily range (maximum daily temperature minus minimum daily temperature) is about 6.7 C throughout the year, indicating relatively high humidity conditions. In the climate of the Delta where dew forms almost every morning, the minimum daily temperature is normally a good approximation of the daily-mean dew point temperature. The dew point temperature is a direct measure of the vapor pressure (within normal variations in atmospheric pressure), and the vapor pressure is a relatively conservative property of an air mass. Thus, for a day when the temperature ranges from 22 C in the morning to 32 C in the mid-afternoon, the relative humidity will range from near 100% in the early morning to about 60% at the time of maximum temperature.

Crop Water Supply

Differences between rainfall and potential evaporation must be supplied by stored soil water and/or irrigation. Figure 4 presents the long-term normal rainfall and potential evapotranspiration for Stuttgart 9 ESE. It is apparent from this figure that the months of crop production of June, July and August have a relatively large deficit in terms of normal amounts, with lesser deficits during May and September. The average cumulative deficit for June through August is 221 mm. In any given month, the actual precipitation may range from near zero to several times the average monthly precipitation, yet Bruce et al. (1985) found that there is a 50% probability of rainfall being deficit in nine years out of 10 near Stuttgart. In June and August, there was a 50% probability of rainfall being deficit in eight years out of 10. Thus, there is a strong deficit in average

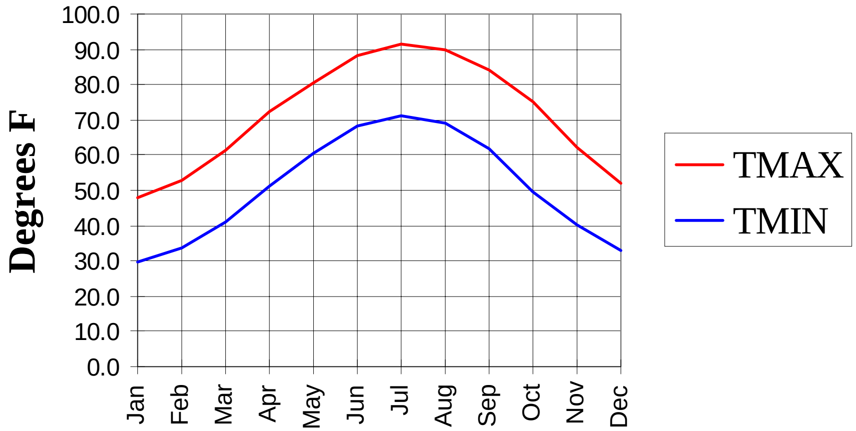


Fig. 3. Mean daily maximum and minimum temperatures for the Rice Research and Extension Center (Stuttgart 9ESE) taken from NOAA Climatological Data for Arkansas, 1960-1989.

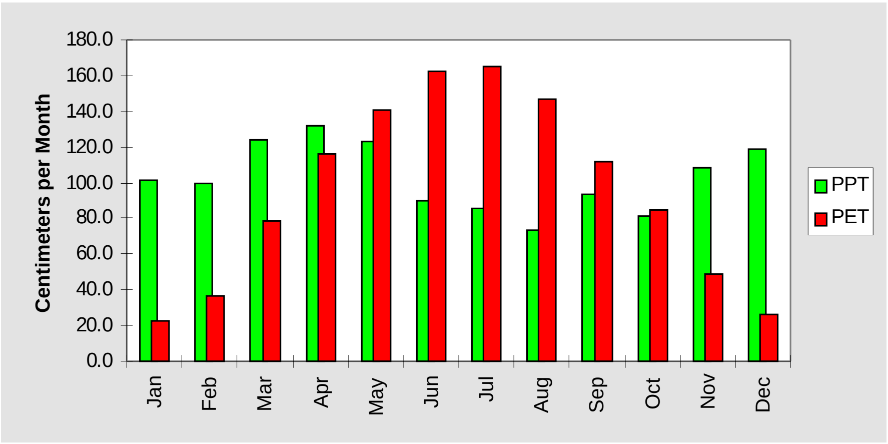


Fig. 4. Long-term monthly rainfall (PPT) and potential evapotranspiration (PET) at Stuttgart 9ESE. From NOAA Climatological Data for Arkansas.

years and a high probable deficit even in years of above-normal rainfall. This water deficit has to be made up from soil water storage or from irrigation in order to achieve maximum crop yields.

Surface Water

The quantity, quality and management of water are major concerns of production agriculture (Arkansas Farm Bureau Federation, 1982; Shulstad et al., 1978). One area of the land surface where the flow of water is relatively easy to recognize is a watershed. A watershed is defined as an area that topographically appears to contribute all the water that passes through a given cross-section of a stream or lake, i.e., a drainage area. The delineation of watersheds is important because the characteristics of the drainage basin control the paths and rates of movement of water to the outlet and the magnitude and timing of outputs through streamflow, ground water flow and evapotranspiration. The location of each watershed is designated by a hydrologic unit code.

The Water Resources Council developed a hydrologic unit system for watersheds in the U.S. in the mid-1970s. This hierarchical code system divided the country into 21 hydrologic regions, 222 subregions, 352 accounting units and 2,149 cataloging units based on surface hydraulic features. Designation of hydrologic regions enables more effective water and land resource planning by consideration of the land resources within an area and determination of how such resources affect or may be affected by resource development.

Arkansas is almost equally divided by two hydrologic regions. The Lower Mississippi (Region 08) covers about 49.9% of the state, and the Arkansas-Red-White (Region 11) covers about 50.1% of the state. The two hydrologic regions in Arkansas are subdivided into five and four hydrologic subregions, respectively. The nine hydrologic subregions have been further divided into 16 accounting units.

The locations and approximate areal extent of the 23 eight-digit watersheds found in eastern Arkansas are shown in Fig. 5 and in Table 2, respectively. A total of 16 of these watersheds belong to the Lower Mississippi hydrologic region, and seven watersheds belong in the Arkansas-Red-White River hydrologic region, along the White River. The two largest watersheds are the Lower St. Francis and the Cache watersheds, which occupy 18.6 and 12.1% of the land area in the Delta, respectively.

Ground Water

Ground water is another of Arkansas' most valuable natural resources. Ground water use data for several categories are collected and compiled annually by the Arkansas Soil and Water Conservation Commission (ASWCC) in cooperation with the U.S. Geological Survey (USGS) and by the Arkansas Agricultural Statistical Reporting Service. Ground water and the issues surrounding the quantity, quality and right to use water are important to every citizen in Arkansas.

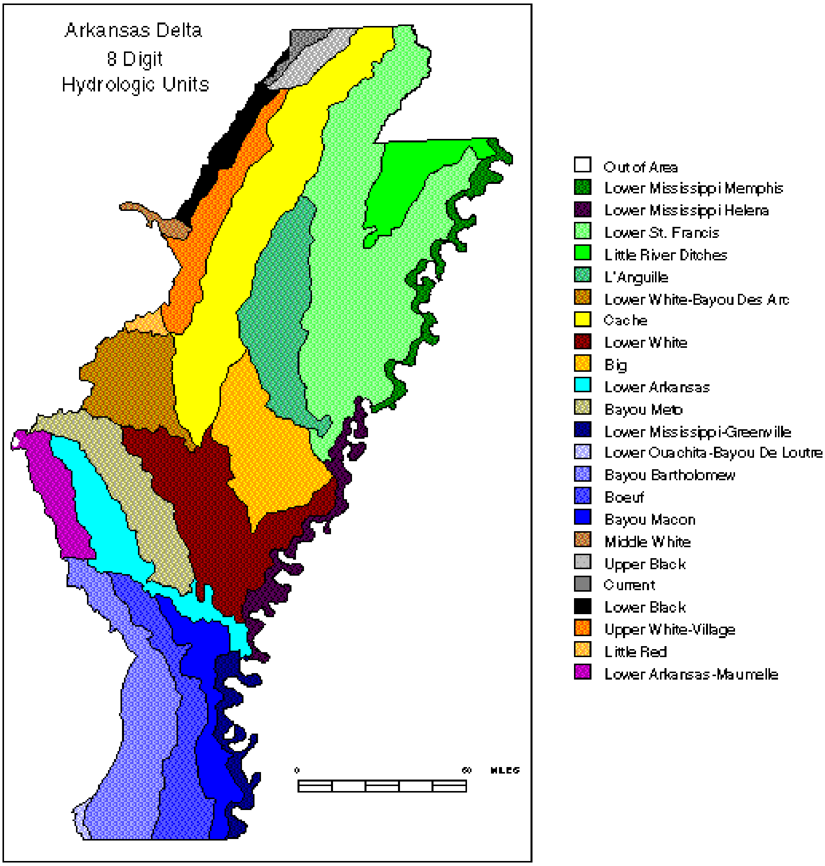


Fig. 5. Locations of the eight-digit watersheds in eastern Arkansas.

Ground Water Use

Ground water plays a major role in supplying the domestic and agricultural needs of water in Arkansas. Almost half of all Arkansans depend on ground water for their drinking water (League of Women Voters of Arkansas, 1984). This ground water is used principally for public supply, industry, rural domestic, irrigation and fish or minnow farming. A small amount is used for wildlife impoundments and thermoelectric energy plants using fossil fuels. Arkansas has an estimated 200 trillion gal (600 million acre-ft) of available ground water storage, with an estimated 6 million acre-ft of transient storage (Jackson and Mack, 1982). According to the USGS, in 1990 Arkansas was tied with Ne-

Table 2. Areal extent of the eight-digit watersheds in eastern Arkansas.

Category	Name	----------Areal extent----------	
		acres	ha
08010100	Lower Mississippi-Memphis	218,387	88,380
08020100	Lower Mississippi-Helena	243,278	98,453
08030100	Lower Mississippi-Greenville	184,483	74,659
08020203	Lower St. Francis	1,914,004	774,587
08020204	Little River Ditches	316,701	128,167
08020205	L'Anguille	621,050	251,336
08020301	Lower White-Bayou Des Arc	453,484	183,523
08020302	Cache	1,239,993	501,818
08020303	Lower White	881,178	356,608
08020304	Big	606,137	245,300
08020401	Lower Arkansas	452,728	183,217
08020402	Bayou Meto	502,151	203,218
08040202	Lower Ouachita-Bayou de Loutre	21,712	8,787
08040205	Bayou Bartholomew	762,311	308,503
08050001	Boeuf	482,154	195,125
08050002	Bayou Macon	357,900	144,840
11010003	Middle White	47,312	19,147
11010007	Upper Black	114,066	46,162
11010008	Current	52,290	21,162
11010009	Lower Black	164,973	66,764
11010013	Upper White-Village	371,245	150,241
11010014	Little Red	39,405	14,947
11110207	Lower Arkansas-Maumelle	238,965	96,708

Source: 1990 TIGER census.

braska for using the fourth most ground water in the U.S. Approximately two-thirds of the 4.1 billion gallons of fresh water used in Arkansas in 1990 originated from ground water sources.

Arkansas has recognized the common and collective right to use ground water. With the passage of Act 1051 in 1985, the Arkansas General Assembly required ground water users with a potential capacity of 50,000 gal/day or greater to report their annual ground water use. In 1989, the ASWCC was given the authority to impose up to $500 late registration fee for late water use reports for both ground and surface water. The Arkansas Ground Water Protection and Management Act 154, passed in 1991, requires a $10 fee per diversion or withdrawal point to be collected at the time of water use reporting. The annual use for the prior water year (1 October to 30 September) is to be reported no later than 1 March on forms provided by ASWCC. There are approximately 37,877 registered wells in Arkansas, nearly 37,322 of which are irrigation wells (ASWCC, 1997).

The use of ground water in Arkansas has increased steadily in recent years (Table 3). In 1965, the state's average ground water use was about 1,335 million gallons per day (Mgal/d) or a total of nearly 1.5 million acre-ft for the year. By 1980, average ground water use had increased to 4,052 Mgal/d or over 4.5 million acre-ft for the year. By 1994, average ground water withdrawal

Table 3. Historical summary of water use (in Mgal/d) by aquifer in Arkansas.

Aquifer	1965	1970	1975	1980	1985	1990	1994
Quaternary-alluvial	1066.7	1307.1	2227.6	3716.9	3559.4	4375.8	4220.7
Sparta/Memphis sand	192.1	141.5	144.5	185.5	157.0	222.5	192.1
Wilcox	38.6	22.5	24.3	50.7	20.8	30.9	38.6
Paleozoic	26.6	42.0	69.4	73.9	63.7	63.1	19.6
Cockfield	4.0	5.3	5.2	7.2	3.8	8.1 8.7	
Cane River	0.8	3.4	3.5	5.3	4.1	2.2	3.9
Nacatoch	2.4	3.5	3.6	6.5	3.4	3.1	1.1
Tokio	2.0	2.4	4.5	6.0	3.9	2.3	1.0
Trinity	1.1	0.0	0.0	0.0	0.0	0.2	0.0
Clayton	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Total	1334.5	1528.6	2478.8	4051.8	3816.0	4708.2	4485.8
%Quaternary-alluvial	79.9	85.5	89.9	91.7	93.3	92.9	94.1

Source: ASWCC.

had increased to 4,486 Mgal/d (ASWCC, 1995). These data show that the use of ground water in Arkansas in 1994 was 3.36 times greater than that in 1965.

A summary of the water withdrawals by use category in 1993 is presented in Table 4. About 5,130 Mgal/d were withdrawn from ground water sources with 4,741 Mgal/d obtained for irrigation purposes (ASWCC, 1995). By far most of the ground water withdrawals (92.5%) were for irrigation of agronomic crops such as rice, soybeans and cotton. Other aspects of agriculture, including aquaculture, account for about 4.3% of the ground water use. Thus, agricultural operations accounted for 96.8% of the ground water used in Arkansas in 1993.

A historical summary of withdrawals of water from the Alluvial Aquifer by county in eastern Arkansas since 1965 is presented in Table 5. Use of ground

Table 4. Use of ground water by category in 1993.

	Use		Percent
Category	(Mgal/d)	Acre-ft/year	of total
		(x1000)	
Agriculture	221.3	249.9	4.32
Commercial	1.6	1.8	0.03
Industrial	65.8	73.7	1.28
Irrigation	4741.1	5311.5	92.46
Fossil	18.6	20.8	0.36
Hydro electric and nuclear	0.0	0.0	0.0
Public supply	79.2	88.7	1.54
Total	5127.6	5744.5	100.0

Source: ASWCC (1995).

water increased in all but one county but not always consistently in all counties over the years. In 1994, the greatest ground water withdrawals were in Poinsett, Arkansas, Craighead, Jackson, Lonoke, Cross and Lawrence Counties. Growth in magnitude of ground water use between 1965 and 1994 varied by county with the greatest expansion in Poinsett, Craighead, Lawrence, Jackson and Arkansas Counties. Water use in these counties expanded by greater than 200 Mgal/d over this period. However, when expressed as the ratio of water used in 1994 to that used in 1965, Mississippi, Lawrence, White, Chicot and Greene Counties increased water use by greater than 10-fold during the 30-year time period. On the average across counties, water use in the Alluvial Aquifer of eastern Arkansas increased by 3.36 times between 1965 and 1994.

The number of ground water wells in each county and the average use of water per well is also presented in Table 5. Counties with more than 2000 wells included Craighead, Lonoke, Jackson, Poinsett, Cross and Arkansas. On the average, the 4.143 Mgal/d of ground water used in eastern Arkansas during 1994 by the 37,768 wells was 0.1097 Mgal/d/well. The six counties with the highest number of wells also had greater-than-average water use per well.

Aquifers in Eastern Arkansas

Most of the ground water supplies in the Delta are obtained from five water-bearing formations called aquifers or aquifer systems (Fig. 6). Movement of ground water through the aquifers is directly related to the product of the hydraulic conductivity and hydraulic gradient. The saturated hydraulic conductivity, which depends on physical properties of the porous medium such as the porosity, permeability and connectivity of the unconsolidated sediment and rock materials, tends to be greater in coarser materials than in the finer materials.

In eastern Arkansas, the aquifers listed according to increasing depth are the Alluvial, Cockfield, Sparta/Memphis Sand, Wilcox and Nacatoch Sand. The withdrawals of ground water from these aquifers in 1990 are listed in Table 6 (ASWCC, 1995). These data indicate that by far most of the ground water in eastern Arkansas is extracted from the relatively shallow Alluvial Aquifer. The second-most-used aquifer is the Sparta/Memphis Sand.

Characteristics of the Aquifers

Alluvial Aquifer. The Mississippi River Valley Alluvial Aquifer, sometimes called the Alluvial Aquifer or the Quaternary Aquifer, underlies nearly all of the Arkansas Delta region, with the exception of Crowleys Ridge, which trends nearly north to south and divides the alluvium north of the Arkansas River into two hydraulically separate flow regimes.

The Alluvial Aquifer is the principal source of water for irrigation (Table 6). Partially because of the Alluvial Aquifer, irrigated agriculture in the Arkansas Delta region has been quite productive for decades and significantly contributes to the economies of Arkansas, Mississippi and Louisiana.

Table 5. Historical summary of the ground water use (Mgal/d) by county in eastern Arkansas.

County	Year 1965	1970	1975	1980	1985	1990	1994	Change in use	Ratio[1]	#wells in 1995	Ave. use per well[2]
Arkansas	113.5	117.4	136.3	209.5	185.1	357.0	318.8	205.3	2.81	2056	0.1551
Ashley	22.8	35.4	53.3	109.6	77.4	74.4	79.8	57.0	3.50	889	0.0898
Chicot	12.2	23.9	46.6	69.2	75.7	116.5	134.7	122.5	11.04	1140	0.1182
Clay	22.1	19.0	60.3	150.5	175.9	196.4	53.0	30.9	2.40	390	0.1359
Craighead	48.8	65.9	145.3	222.6	202.8	237.6	315.9	267.1	6.47	2630	0.1201
Crittenden	26.4	29.7	38.2	79.0	113.7	62.3	96.5	70.1	3.67	829	0.1164
Cross	68.0	81.1	169.6	226.3	261.0	337.4	255.5	187.5	3.76	2190	0.1167
Desha	45.1	85.4	144.0	146.3	128.6	211.7	199.8	154.7	3.43	1552	0.1287
Drew	8.5	22.5	32.1	43.6	41.1	36.0	43.0	34.5	5.06	415	0.1036
Greene	15.8	18.6	67.9	139.0	131.8	188.2	170.0	154.2	10.76	1667	0.1020
Independence	2.2	5.3	7.7	16.9	32.6	7.7	12.5	10.3	5.68	188	0.0665
Jackson	56.9	60.0	164.8	212.9	203.5	269.8	269.8	212.9	4.74	2532	0.1066
Jefferson	42.0	61.6	106.8	141.1	134.0	174.7	148.8	106.8	3.54	1638	0.0908
Lawrence	17.7	24.5	77.0	154.1	153.7	212.4	253.4	235.7	14.32	1621	0.1563
Lee	25.4	21.8	40.3	166.7	96.6	162.5	136.6	112.2	5.38	1632	0.0837
Lincoln	25.9	69.2	83.9	88.7	86.0	110.4	97.9	72.0	3.78	944	0.1037
Lonoke	155.5	177.0	257.2	374.1	293.8	263.7	261.8	106.3	1.68	2565	0.1021
Mississippi	5.2	7.5	8.5	19.4	50.4	93.7	119.9	114.7	23.06	1245	0.0963
Monroe	56.1	46.0	81.8	165.2	124.1	178.6	173.9	117.7	3.10	1762	0.0987
Phillips	14.4	14.2	16.9	78.0	71.7	110.9	103.4	89.0	7.18	1237	0.0836
Poinsett	86.2	100.5	177.7	308.9	299.8	403.2	370.6	284.4	4.30	2166	0.1711
Prairie	69.9	70.8	125.8	166.5	169.6	185.0	166.2	96.3	2.38	1812	0.0917
Pulaski	12.8	16.8	21.7	33.5	29.5	28.7	6.6	- 6.2	0.52	182	0.0363
St. Francis	32.8	52.3	104.3	140.7	110.9	159.7	169.3	136.5	5.16	1439	0.1177
White	3.6	5.4	14.4	47.2	50.5	41.4	44.9	41.3	12.47	1190	0.0377
Woodruff	58.0	49.5	22.4	167.0	142.4	140.8	140.8	82.8	2.43	1857	0.0758

[1]Ratio = water use in 1995/water use in 1965

[2]Water use/well (Mgal/d/well) = water use in 1994/number of wells in 1995

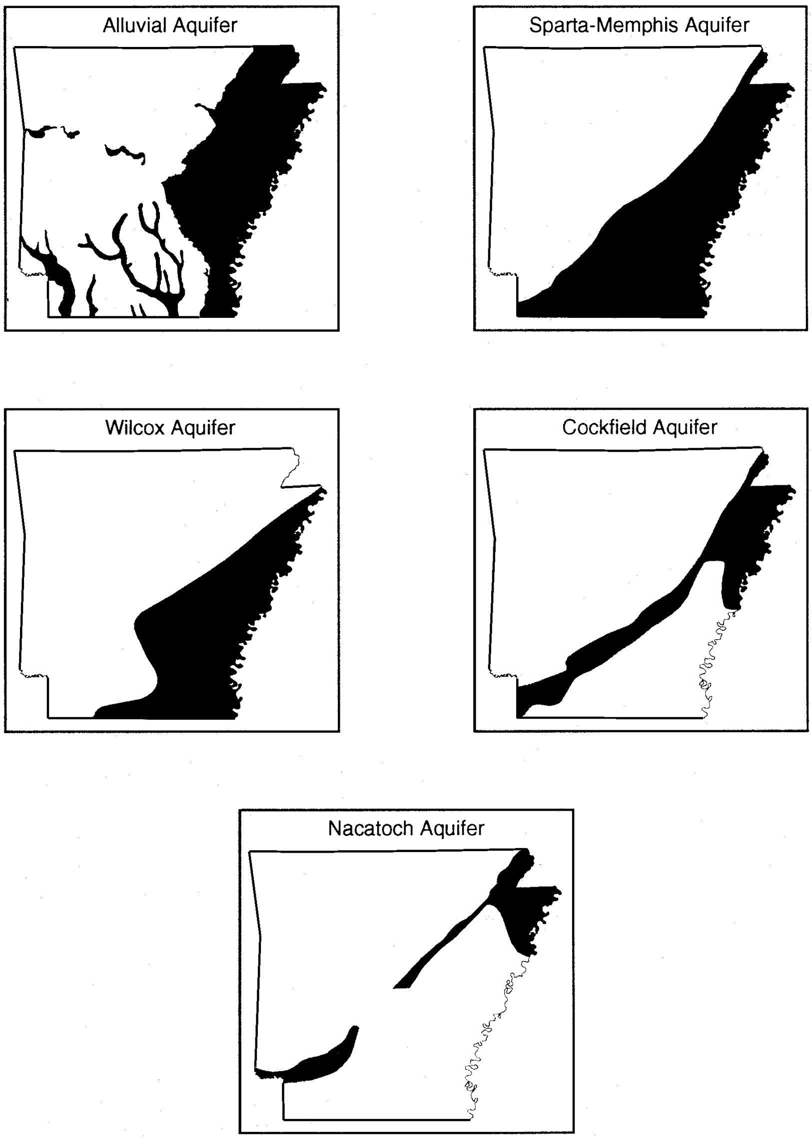


Fig. 6. Areal extent of selected aquifers in Arkansas.

Table 6. Withdrawals of ground water by aquifer in 1990.

Aquifer	Mgal/d	Acre ft/year
		(x 1000)
Alluvial	4,375.8	4,902.3
Cockfield	8.1	9.1
Sparta/Memphis Sand	222.5	249.3
Wilcox	30.9	34.6
Nacatoch Sand	3.1	3.5

These data were obtained from the ASWCC (1995).

The Alluvial Aquifer is the upper aquifer of the Mississippi embayment aquifer system. The Mississippi embayment extends southward in a fan-shaped geosyncline, plunges southward from southern Illinois to the Gulf of Mexico and covers about 414,400 km^2 in parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri and Tennessee (Ackerman, 1996). The ages of the embayment sediments range from Jurassic to Quaternary, but only units of Cretaceous age and younger crop out in Arkansas. The central axis of the Mississippi embayment nearly parallels the Mississippi River, and the embayment surface drainage in Arkansas is ultimately to the Mississippi River.

In Arkansas the Alluvial Aquifer lies from near the land surface in some locations to over 45 m below the surface in northeastern Greene County (Fig. 7). Several relatively large rivers, such as the Mississippi, Arkansas and White, and smaller rivers, such as the Cache and St. Francis, flow across the alluvial plain and exchange water with the aquifer. There are also numerous smaller streams distributed throughout the region. The elevation in the region ranges from near 25 m above sea level in the south to 219 m in the north. This region is generally flat with more than 98% of the area having a slope less than 2%.

Deposition of sediment from the Mississippi and Arkansas Rivers during Pleistocene and Holocene time produced a sequence of sands, silts and clays that constitute the alluvial aquifers and semi-confining units in the Delta. From a regional perspective, this collection of sediment can be divided into three units. The lowest unit is older and consists of eroded bedrock surface having substantially lower hydraulic conductivity. The middle unit is the Alluvial Aquifer, which is composed of coarse sand and gravel at the bottom that grades to fine sand at the top. The thickness of the aquifer materials generally ranges from 20 to 45 m, averages 30 m and decreases to the south (Ackerman, 1996). Lenses of clay and silt occur at numerous locations in the aquifer. Hydraulic conductivity of the aquifer ranges from about 40 to 130 m/d. The hydraulic conductivity is greatest in the coarse sand and gravel near the base of the aquifer. Crowleys Ridge, which averages about 16 km in width, is an erosional remnant of strata of Tertiary age and is capped in places by several meters of loess. It is a substantial barrier to ground water flow in the alluvial aquifer.

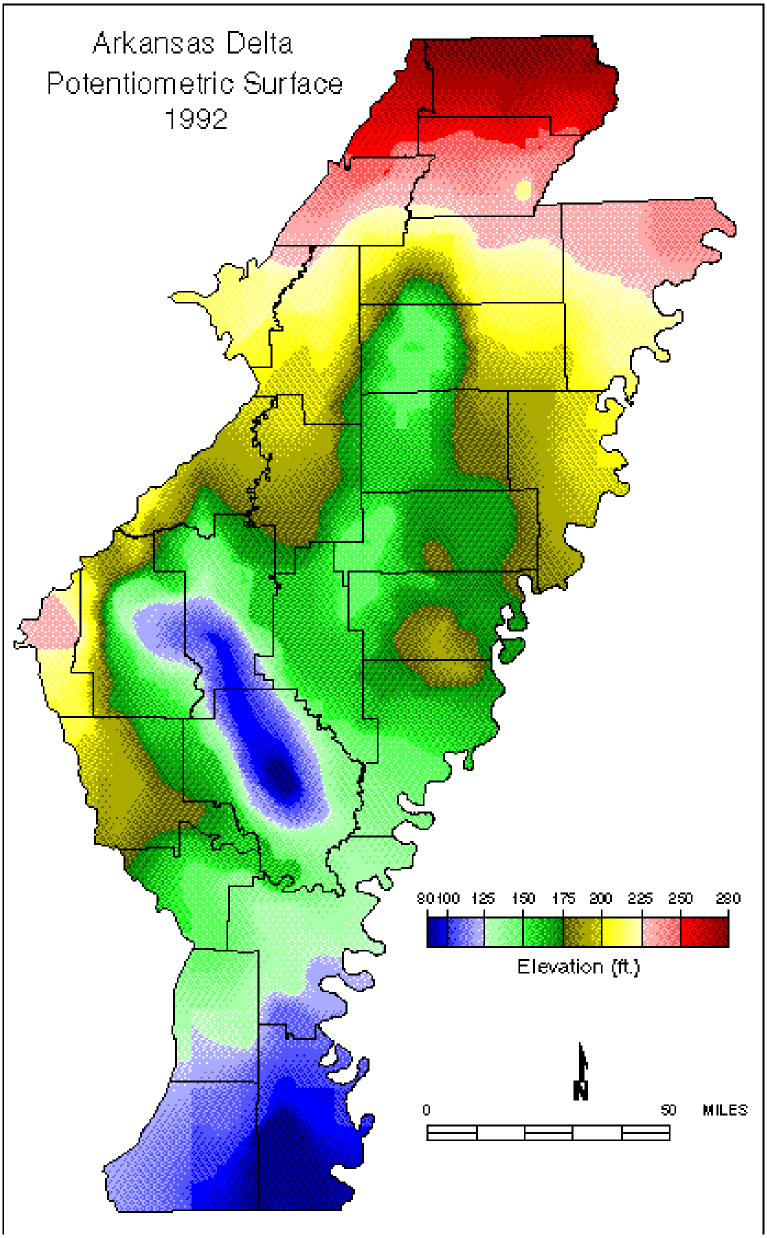


Fig. 7. Potentiometric surface of the Alluvial Aquifer in the spring of 1992.

There is between 6 and 10 m of head difference from one side of the ridge to the other, and the flow from the ridge to the aquifer is considered insignificant.

The upper unit, which consists of clay, silt and fine sand, confines the Alluvial Aquifer and is often referred to as the confining unit or clay cap. The confining unit consists of 6 to 18 m of silt, clay and fine sand. Because of the depositional conditions of the Alluvial Aquifer and confining unit, the top and bottom of the aquifer are not planar but are marked by numerous highs and lows. Deposition of the confining unit onto the coarser Alluvial Aquifer deposits has reduced the relief of the land surface. Confining unit thickness varies within the region and ranges from where the unit is absent to slightly more than 25 m in the Grand Prairie and to about 40 m at other locations. Thickness of the confining unit can vary substantially over short distances. The integrity of the confining unit partly governs recharge to the aquifer and is a function of the thickness of the sediments and the interconnection of transmissive sediments within the confining unit. As a result of the variability of confining unit thickness and the interconnection of the transmissive sediments, surficial recharge to the alluvial aquifer varies considerably within the alluvial plain.

Ackerman (1996) simulated the predevelopment status and the effects of continued use and development of the Alluvial Aquifer. Originally, flow in the aquifer consisted of inflow through the overlying confining unit, inflow from underlying aquifers and outflow to rivers. About 74% of the recharge was through the confining unit at an average rate of 2.0 cm/year, although there was considerable spatial variation. The simulated predevelopment potentiometric surface showed movement of water southward down the Mississippi River Valley and following the slope of the land surface toward the major rivers.

Significant extraction of water from the Alluvial Aquifer began in the early 1900s in the Grand Prairie (Griffis, 1972; Peralta et al., 1985). Primary water use was for agriculture, particularly the irrigation of rice. Over the years, pumpage from the Alluvial Aquifer has caused a decrease in outflow to rivers, an increase in recharge from rivers and an increase in recharge through the confining unit. In some areas, the decrease in outflow to rivers and increase in inflow have not been sufficient to meet the extraction demands. The long-term effect of this has been regional declines in water levels of the aquifer, reduction of water storage and decreases in well yields in the regions north of the Arkansas River, such as the Grand Prairie and west of Crowleys Ridge. In these areas large depressions in the potentiometric surface have resulted in increased hydraulic gradients and flow (Fig. 8). In the Grand Prairie, the saturated thickness has decreased to less than 15 m and is considered to be in danger of being depleted for irrigation. In areas near the Mississippi and Arkansas Rivers that are hydraulically connected, the level of the aquifer changes with water stage of the river. As the elevation of the rivers changes, water moves in and out of aquifer storage. In areas where the confining unit is thin, sandy or absent, recharge of the aquifer is significant. These areas generally correspond with the thickest parts of the aquifer.

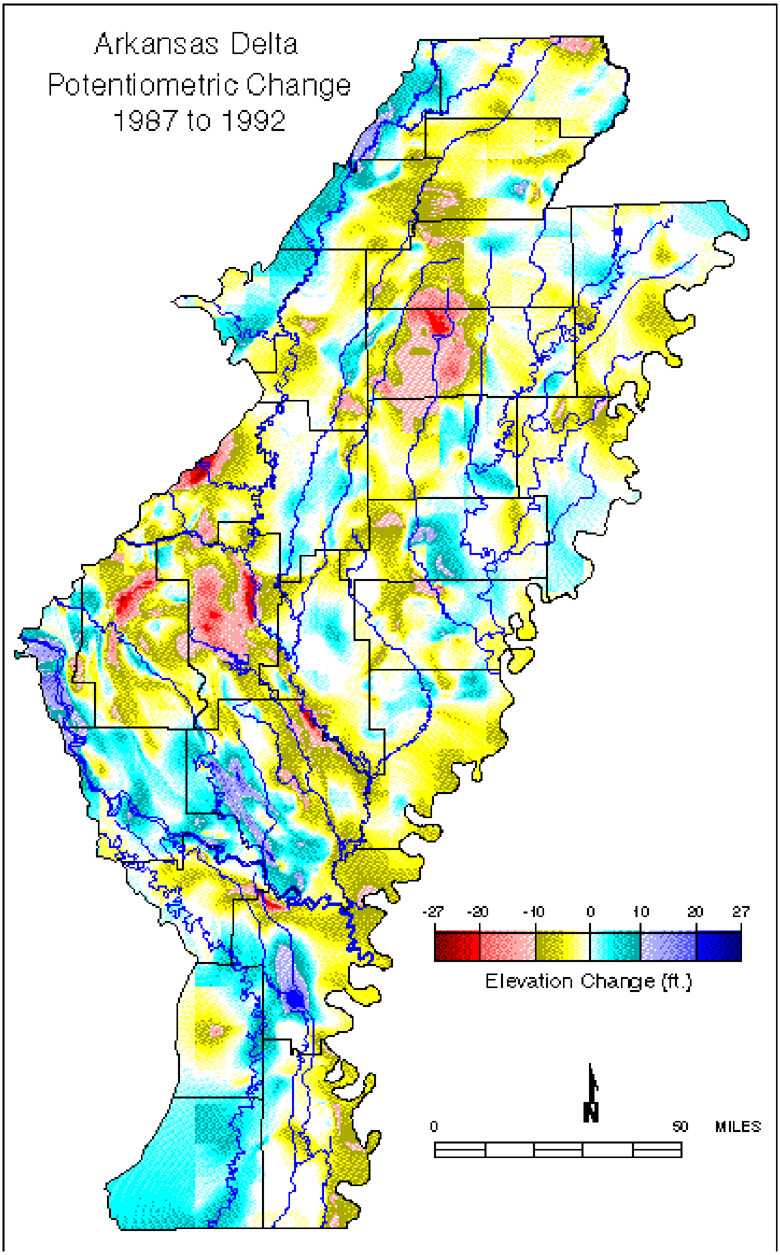


Fig. 8. Changes in potentiometric surface of the Alluvial Aquifer between 1987 and 1992.

Most irrigation wells in the Alluvial Aquifer are less than 50 m deep. Wells in the aquifer have relatively high yields, ranging from 1,000 to 2,000 gal/min but may yield as much as 5,000 gal/min.

Water in the Alluvial Aquifer generally is hard, averaging 240 mg/L of hardness as $CaCO_3$ and contains iron in excess of 1.0 mg/L. In parts of Chicot, Desha, Lincoln, Monroe and White Counties, the water contains as much as 3,750 mg/L of dissolved solids, which makes it unsuitable for long-term irrigation. The saline water is believed to have migrated upward from underlying, saline water-bearing beds through faults or abandoned oil test wells.

Cockfield Aquifer. This Eocene-age aquifer ranks fourth in total groundwater withdrawals in the eastern part of Arkansas (ASWCC, 1995). It is present in much of eastern Arkansas and is the sole source for ground water in some areas. Its principal use is for public-municipal and rural-domestic supply, and generally the water is of good quality for these purposes.

The Cockfield Aquifer generally consists of fine to medium sand in the basal part and silt, clay and lignite in the upper part. The beds are discontinuous and contain carbonaceous material throughout (Boswell et al., 1969). The yields of water are moderate to small; therefore, the aquifer is mostly used for domestic consumption.

The median concentrations of samples of water from the Cockfield aquifer are 220 mg/L dissolved solids, 16 mg/L hardness, 0.25 mg/L nitrate, 11 mg/L chloride and 140 ug/L iron. Based on these values, the water generally is soft and does not exceed the drinking water standards. Although most iron concentrations are considerably smaller than the 300 ug/L standard, more than 25% of the samples exceed the standard.

Sparta/Memphis Sand Aquifer. This Eocene aquifer ranks second in total ground water withdrawals in Arkansas (Table 6). Located in much of the eastern half of Arkansas, the Sparta Aquifer is used extensively for industry and public supply and increasingly for irrigation. Generally water in the Sparta Aquifer is of good quality for domestic drinking. Wells in the Sparta usually yield from 500 to 1500 gal/min with some wells having much higher yields.

Water in the Sparta/Memphis Sand Aquifer is generally soft and is a sodium bicarbonate type. The dissolved solids has a median of 218 ppm. Dissolved solid content increases downdip, due mostly to increases in sodium and bicarbonate.

Wilcox Aquifer. This Eocene-age aquifer occurs in most of the Gulf Coastal Plain of Arkansas but is a major source of water only in northeastern Arkansas, where it is known as the 1,400 foot sand. The aquifer is used primarily for public and industrial supplies and ranks third in total ground water withdrawals in eastern Arkansas. Wells yielding 500gal/min or more are possible in many locations. The Wilcox Aquifer has the best water quality of the principal aquifers in the state.

Nacatoch Aquifer. The Cretaceous-age Nacatoch Aquifer underlies the Gulf Coastal Plain of Arkansas but contains fresh water only in parts of northeastern and southwestern Arkansas. It is used primarily for public and industrial supplies and ranks fifth in total ground water withdrawals in eastern Arkansas. Most of the wells have low to medium yields with some wells yielding as much as 500 gal/min. The Nacatoch aquifer has water quality that is marginally acceptable for rural-domestic and public supply.

Potentiometric Surfaces of the Alluvial Aquifer

Several state and federal agencies monitor wells and springs throughout Arkansas in an effort to detect changes and/or trends in ground water levels and ground water quality. Measurements are made each spring in 666 wells in the Alluvial Aquifer and approximately 200 wells in the Sparta Aquifer to obtain static water levels that have not been affected by pumping during the growing season (ASWCC, 1995; Smith et al., 1997). During the fall season some measurements are made in the Alluvial Aquifer by the Natural Resources Conservation Service (NRCS) to observe the drawdowns that result from seasonal pumping for irrigation of crops.

The potentiometric water levels of the Alluvial Aquifer during the spring of 1992 and the changes in water level since 1987 are shown in Fig. 7 and 8. The general trend is that ground water levels are dropping slowly or remaining constant with only a few localized areas where water levels have increased. There are three areas in the Delta where ground water withdrawals significantly exceed natural recharge, resulting in consistently falling ground water levels (ASWCC, 1995). These problem areas are the Alluvial Aquifer in the Grand Prairie region, the Alluvial Aquifer in the Cache region (west of Crowleys Ridge) and the northern portion of the Boeuf-Tensas Basin in southeastern Arkansas. The aquifer had an average annual decline of 0.1 m in 255 wells sampled during the period of 1987-1992. The largest decline occurred in Prairie County, where 11 wells sampled had a 0.8-m decline per year (ASWCC, 1995).

The areas of greatest depletion of the Alluvial Aquifer are primarily due to irrigation, particularly of rice, soybeans and cotton. Over time, the increased pumping depths require more energy to bring the water to the surface and result in a lower yield. Also, the depletion has resulted in an intrusion of salt water in several locations in southeastern Arkansas (ASWCC, 1990). Since continued depletion of the aquifer is not sustainable, consideration should be given to the greater use of surface water supplies, such as surface reservoirs and river water diversions, in those areas where the ground water level is declining.

Critical Ground Water Areas

The Arkansas Ground Water Protection and Management Act, Act 154 of 1991 General Assembly, provides the ASWCC the authority to develop a comprehensive ground water protection program, designate critical ground water areas, cost-share on installation of water conservation practices, establish ground water rights with critical areas, establish fees for ground and surface water withdrawals, develop an educational/informational program and delegate management powers to regional water districts and conservation districts. The act also provides a regulatory program, given certain aquifer criteria exist. The requirement of a water right for the utilization of a well applies only to critical ground water areas in which the ASWCC has declared the regulatory program to be in effect. Critical ground water designation by the Commission will become effective after public hearings are held in every affected county describing the proposed action, the reasons therefore and the recommended boundaries. There will be no limitations on ground water pumpage unless an affordable alternative exists. Exemptions from the regulatory program may also be granted if an individual can demonstrate a 20% reduction in ground water use or an implemented conservation program. Water rights are transferable to replacement wells. Within one year of the establishment of the regulatory authority, newly constructed wells will be issued a water right for the amount requested.

In order to classify an unconfined aquifer as a critical ground water area, one or more of the following criteria must be met: 1) the saturated thickness of the formation is <50% of the total thickness of the formation; 2) the water level shows declines of >0.3 m/year within a five-year period; and 3) trends indicate degradation of water quality (ASWCC, 1996). Regulation will be considered only if the condition of the aquifer continues to degrade after implementation of incentive and voluntary programs. Critical ground water areas are delineated based upon hydraulic criteria and natural hydrogeologic boundaries.

The general trend in the Delta is that ground water levels are dropping slowly or are remaining constant with only a few localized areas where water levels have risen. In the spring of 1992, the potentiometric surface of the Alluvial Aquifer showed depressional areas in the Grand Prairie region (about 10,500 km^2) in and around Arkansas County, the Cache ground water area (about 18,925 km^2) west of Crowleys Ridge and in extreme southeastern Arkansas. These regions serve as candidates for designation as critical ground water extraction areas.

The water budget for the Grand Prairie region showed that the Alluvial Aquifer averages about 15 m of saturated thickness with a specific yield of 0.3 and a minimum protected static saturated thickness of 10 m, resulting in available water use of 6 m (ASWCC, 1997). This is equal to about 5 million gal or 15.56 million acre-ft of water. Currently, withdrawal from storage in the aquifer is about 268 Mgal/d (Ackerman, 1996). At this rate, the available volume of water stored in the aquifer will be depleted in about 50 years. Average recharge from the confining unit is estimated to be about 3.3 cm/year.

The water budget for the Cache ground water area indicates a saturated thickness of 33 m. Using a minimum saturated thickness of 10 m results in 33 m of available storage in the aquifer, which is equivalent to 32 million gal in available water for use before the minimum saturated thickness of 10 m would be encountered (ASWCC, 1997). Currently, recharge to the aquifer in this area is estimated at 1082 Mgal/d, mainly from the Cache, White and Black Rivers, which are hydraulically connected to the aquifer, from drainage moving through the confining unit and from the underlying water bearing formations. An estimated 1635 Mgal/d is withdrawn from the aquifer through wells. This water use rate is over 50% greater than the rate of recharge. Thus, the Cache ground water area is also being depleted, as is evident by declines in the potentiometric water levels in the area.

Soils

The soils of the Mississippi River Valley were formed from interactions of five factors: climate, parent material, topography, vegetation and time. The soil provides support and serves as the storage medium from which plants extract water, nutrients and oxygen. From a production view, variations in the quantity of water in the soil profile, and particularly in the rootzone, are the major causes of the year-to-year variations in seed yield. Therefore, soil characteristics have a major impact on water use and management in agriculture. Reviews of the soils and soil characteristics in eastern Arkansas can be found in Nelson et al. (1923), Brown et al. (1972) and McGrew (1973).

Soil Associations

Surveys of soil characteristics are developed by the NRCS in cooperation with the Arkansas Agricultural Experiment Station (AAES). Soil maps are made by field methods, using observations along soil delineation boundaries and traverses and determining map unit composition by field transects. The NRCS has established two geographic databases representing different intensities of mapping.

The State Soil Geographic database (STATSGO) map for Arkansas was developed at a scale of 1:250,000 and archived in 1- by 2-degree topographic quadrangle units. The STATSGO map for eastern Arkansas, with soil mapping units generalized from more detailed soil survey maps, is shown in Fig. 9. Map unit composition is determined by transecting or sampling areas on the more detailed maps and expanding the data statistically to characterize the whole map unit. In general, the map units are grouped as soil associations, which are representations of soil patterns in the landscape. Soil associations consist of two or more dissimilar components occurring in a regularly repeating pattern in the landscape (USDA-SCS, 1993). The major components of a soil association can be separated at a scale of 1:24,000 but are sufficiently different in morphology or behavior that the map unit cannot be called a consociation. The proportion of these two components may vary appreciably from one delineation to another, and the total percentage of inclusions in a map unit that are dissimilar to any of the major components does not exceed 15% if limiting and 25% if non-limiting. The STATSGO map for eastern Arkansas has 26 soil mapping units with three named components, indicating that multiple soil series are associated in the landscape.

Cooperative work is underway between NRCS and AAES to develop Soil Survey Geographic (SSURGO) databases for the counties in eastern Arkansas. SSURGO maps are made at scales ranging from 1:15,840 to 1:24,000 and digitized so that they duplicate the original county soil survey maps. These digital databases contain more detailed information than the STATSGO database on soils and soil attributes and can be used to make decisions on land use and land management by landowners, townships and counties. These data are archived in 7.5-minute USGS topographic quadrangle units and are patched to create county versions of SSURGO.

Major Land Resource Areas

Arkansas has been divided into eight Major Land Resource Areas (MLRA); two of these are found in the Mississippi Delta region of Arkansas (Fig. 10). An MLRA is an area of land with geographically associated land resource units, including soils, climate, water resources and landuses. MLRAs are useful as a basis for making decisions about national and regional agricultural concerns, identification of research needs and resource inventories and a broad base for extrapolating the results of research within national boundaries and serve as a framework for organizing and operating resource conservation programs (USDA-SCS, 1981). MLRAs usually cross state boundaries. The two MLRAs in the Mississippi Delta region of Arkansas will be used to show the major soil associations and soil series in the region. Selected characteristics of the MLRAs in eastern Arkansas are discussed below.

MLRA 131: Southern Mississippi Valley Alluvium. Regionally, this major land resource area occurs in eastern Arkansas, eastern Louisiana, western Mississippi, southeastern Missouri, western Tennessee and western Kentucky and covers approximately 97,913 km^2. It consists of gently sloping, broad flood plains and low terraces of the Mississippi River south of its confluence with the Ohio River. The Mississippi River crosses the area from north to south. Most of MLRA 131 is relatively flat with significant areas in swamps and wetlands. Oxbow lakes and bayous are extensive throughout the region.

In eastern Arkansas MLRA 131 consists of about 2.7 million ha and is located east of Crowleys Ridge, along the Mississippi River and in the White and Arkansas River basins. Controlling surface water by land shaping and artificially draining wet areas are major concerns in management of excessive water. Irrigation is also an important management component in crop production.

The soils in MLRA 131 are derived from parent materials deposited mainly during Holocene geological time (Fig. 11). The alluvium is a mixture of materials washed from many kinds of soils, rocks and unconsolidated sediments from 24 states ranging from Montana to Pennsylvania, deposited by the Mississippi

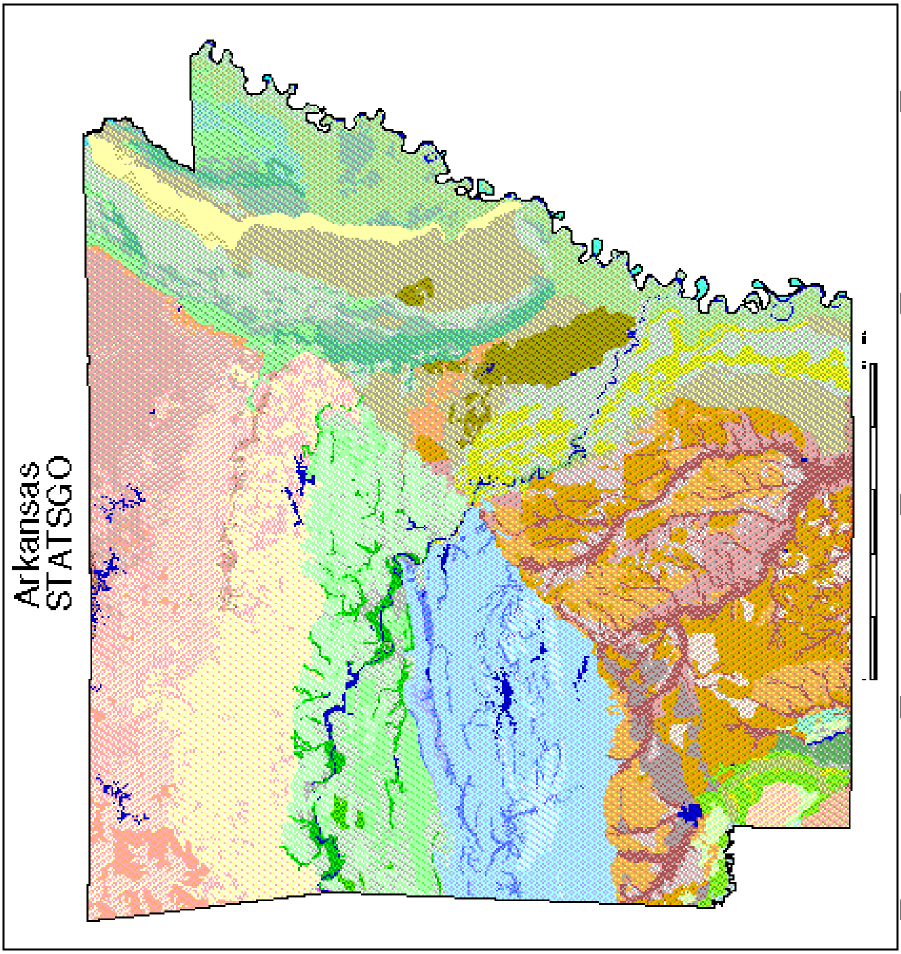

Arkansas
STATSGO

Fig. 9. STATSGO map for Arkansas. This map was developed from digitization of the soil association map of Arkansas.

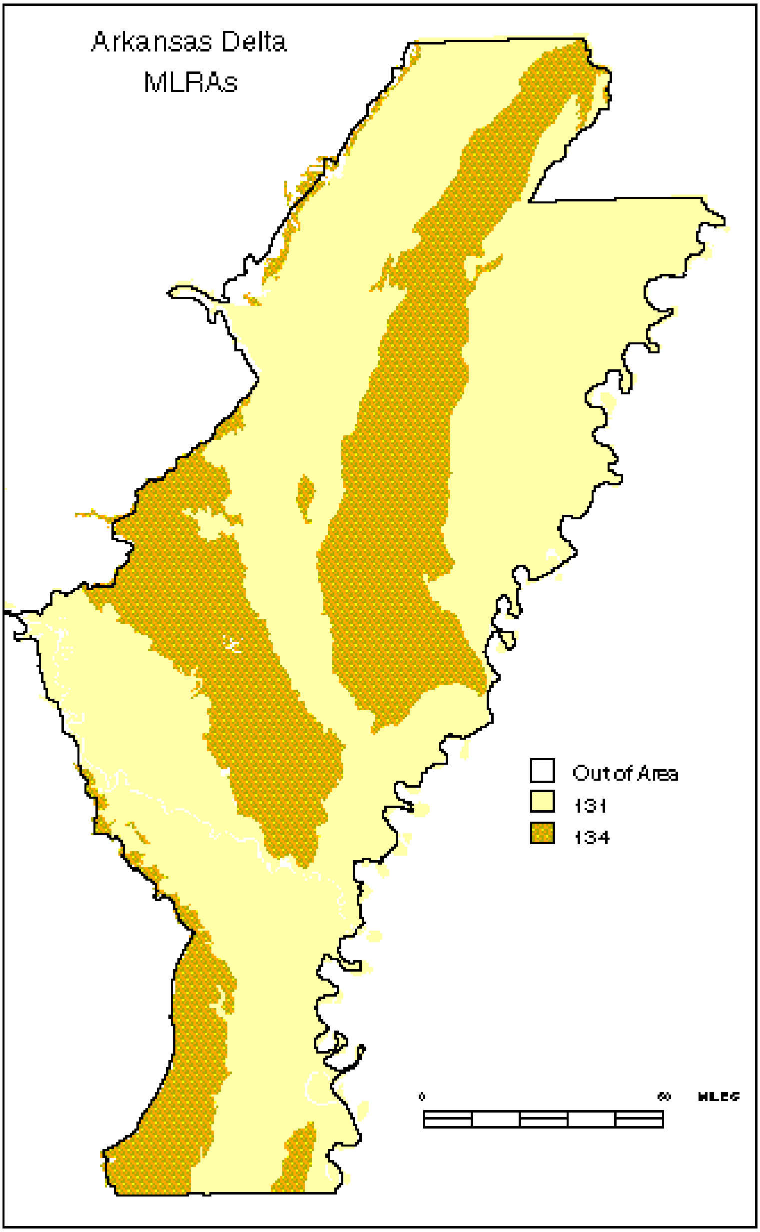


Fig. 10. Map showing the locations of the two major land resource areas (MLRAs) of eastern Arkansas.

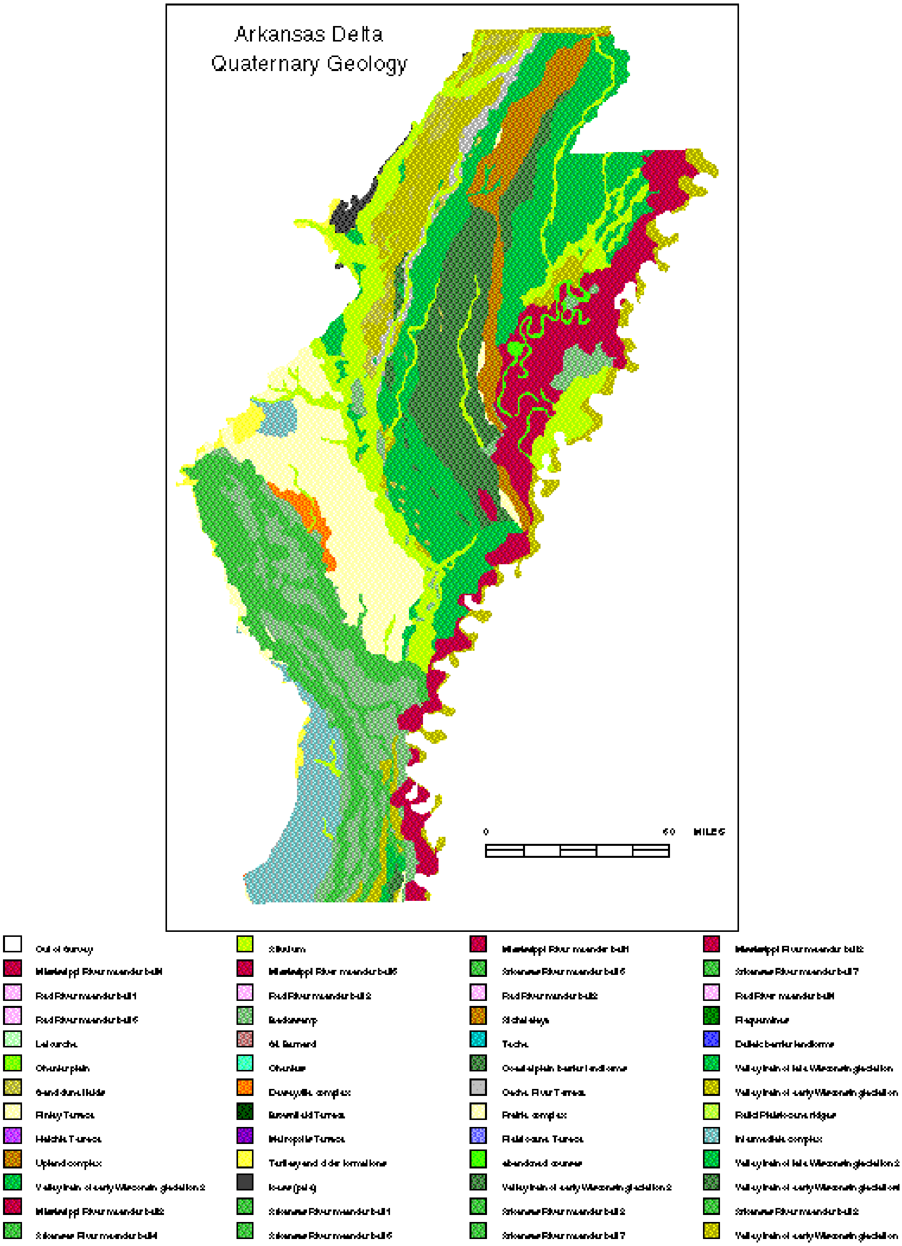


Fig. 11. Map of the quaternary geology of eastern Arkansas. This map was digitized from the data of Quaternary Geology of Lower Mississippi Valley, Louisiana Geological Survey, 1989

and Ohio Rivers and, in part, reworked by local tributaries of the Mississippi River. The wide ranges in texture of the alluvium result from differences in the site of deposition. When a river overflowed and spread over the flood plain, the coarse sediments were deposited first; therefore, sandy and loamy sediments were deposited in bands along the channel, resulting in low ridges known as natural levees. Soils such as Beulah, Crevasse, Dubbs and Robinsonville formed on the higher parts of these ridges. Finer sediments that have particle diameters greater than clay were deposited on the lower parts of natural levees as the flood waters spread and velocity decreased. Soils such as Yancopin, Dundee and Mhoon formed in these sediments. Where the water was left standing as shallow lakes or backswamps, the clays and finer silts settled. Soils such as Alligator, Bowdre, Earle, Forestdale, Sharkey and Tunica formed in these sediments of small particle diameters.

This simple pattern of sediment distribution is not always found along the Mississippi River, because through the centuries, the river channel has meandered back and forth across the flood plain. Sometimes the river channel cut out all or part of natural levees, and at other times sandy or loamy sediments were deposited on top of slack-water clay or slack-water clay on top of sandy or loamy sediments. The normal pattern of sediment distribution from a single channel has been severely truncated in many places, and more recent alluvium has been superimposed. Soils such as Bowdre, Earle and Tunica formed in these materials. Bowdre soils were formed in thin beds of clayey sediments over coarse sediments, and Tunica soils were formed in somewhat thicker beds of clayey sediments over coarser sediments.

The major soil associations in MLRA 131 and their approximate land areas are given in Table 7. These are relatively young soils and generally are classi-

Table 7. Major soil associations in the bottom lands and terraces of eastern Arkansas, Major Land Resource Area (MLRA) 131.

Soil Association	Approximate land area		Percentage of total
	acres	ha	
Foley-Jackport-Overcup	986,907	399,396	15.02
Kobel-Yancopin-Dubbs	533,671	215,974	8.12
Sharkey-Alligator-Tunica	1,321,094	534,639	20.10
Dundee-Sharkey-Fluvaquents	831,954	336,687	12.66
Amagon-Dundee-Sharkey	465,984	188,581	7.09
Sharkey-Steele-Tunica	204,198	82,638	3.11
Commerce-Sharkey-Fluvaquents	245,983	99,548	3.74
Perry-Portland-Rilla	958,148	387,757	14.58
Bruno-Crevasse-Coushatta	33,147	13,414	0.50
Rilla-Hebert-Perry	650,397	263,212	9.90
Others	282,934	14,503	4.3
Total area	6,514,417	2,636,349	99.99

fied taxonomically in the orders as Alfisols, Inceptisols, Vertisols and Entisols. These soils tend to have moist or wet moisture regimes, montmorillonitic and/or mixed mineralogy and thermic temperature class.

The Sharkey-Alligator-Tunica soils are the most extensive in MLRA 131. They are deep, poorly drained, very slowly permeable, level to nearly level, clayey soils on bottom lands. These soils are found on broad flats that were formerly back swamps and slack water areas of the Mississippi River and its tributaries. Sharkey and Alligator soils formed in clayey alluvium. Tunica soils formed in clayey alluvium 50 to 90 cm thick overlying loamy alluvium.

Soils in the Foley-Jackport-DeWitt association are deep, poorly drained to somewhat poorly drained, very slowly permeable, level to nearly level, loamy and clayey soils on broad flats of terraces. Foley soils formed in loamy sediments, Jackport soils formed in clayey sediments, and Overcup soils formed in loamy materials underlain by clayey sediments.

The Dundee-Bosket-Dubbs soils are deep, somewhat poorly drained and well drained, moderately slowly permeable and moderately permeable, on level to gently sloping loamy soils and bottom lands. These soils formed in loamy alluvium and are found on natural levees or low terraces bordering former channels of the Mississippi River and its tributaries. Dundee soils are slightly lower in elevation than the Bosket or Dubbs soils.

MLRA 134: Southern Mississippi Valley Silty Uplands. Regionally, this major land resource area occurs in eastern Arkansas, western Kentucky, western Tennessee, Louisiana and Mississippi. It covers about 51,410 km^2. The elevation ranges from 25 to 100 m above sea level. The sharply dissected plains have a thick loess and/or alluvial mantle that is underlain by unconsolidated sediments of sand, silt and clay, mainly of marine origin. Valley sides are hilly to steep, especially in the west. The intervening ridges are mostly narrow and rolling, but some of the interfluves between the upper reaches of the valleys are broad and flat. Stream valleys are narrow in the upper reaches but broaden rapidly downstream and have wide, flat, flood plains and meandering stream channels.

In Arkansas, MLRA 134 consists of about 1.4 million ha and is located mostly in the Grand Prairie region, Crowleys Ridge and the associated area immediately west and the area east of the Gulf Coastal Plain (Fig. 10). The loessial plains consist of broad, dominantly level to nearly level areas. Elevations range from 50 to 100 m above sea level. Slopes typically range from level to nearly level with a few areas with moderate slopes.

The soils in MLRA 134 developed in loess and/or alluvial deposits underlain by loamy and clayey sediments. The major soil associations are given in Table 8. These soils tend to be deep, medium textured and classified as Alfisols with mixed mineralogy and a wide range of internal drainage classifications. Also, these soils tend to be better drained and more permeable than those in MLRA 131.

Table 8. Areal extent of the major soil associations in the loessial plains and hills of eastern Arkansas, Major Land Resource Area (MLRA) 134.

Soil Association	Approximate land area		Percentage of total
	acres	ha	
Calloway-Henry-Grenada	2,172,892	879,357	61.66
DeWitt-Stuttgart-Hillemann	547,379	221,521	15.53
Loring-Oaklimeter-Tichnor	119,977	48,554	3.40
Loring-Memphis-Collins	389,807	157,753	11.06
Brandon-Collins-Saffell	83,589	33,828	2.37
Others	208,478	84,732	5.99
Total area	3,522,122	1,425,383	100

The soil association occupying the greatest land area in MLRA 134 is the Calloway-Henry-Grenada. These are deep, moderately well-drained to poorly drained, slowly permeable, level to moderately sloping, loamy soils on broad flats and side slopes of upland terraces of the Loessial Plains and were formed in deposits of loess. The level to nearly level soils in this association are used mainly for production of rice and soybeans.

The second most extensive soil association is the Crowley (DeWitt)-Stuttgart-Hillemann. These are deep, somewhat poorly drained and moderately well drained, very slowly permeable, level to gently sloping, loamy soils found on upland terraces. These soils are on broad flats and side slopes of terraces of the Loessial Plains and were formed in deposits of loess over clayey alluvium.

The soil associations dominated by Loring soils occur mainly on Crowley's Ridge and on hilltops and hillsides of the Loessial Hills. Elevations range from 60 to 150 m above sea level. These soils developed in loess deposits underlain by gravelly, sandy, loamy or clayey marine sediments. Slopes range from nearly level to steep. These areas are used mainly for pasture and timber production.

Dominant Soil Taxonomic Units

Selected characteristics of the dominant soil series that relate to the transport of water in MLRA 131 and 134 are presented in Tables 9 and 10, respectively.

The soils in MLRA 131 tend to be classified as Inceptisols, Entisols, Vertisols or Alfisols. Inceptisols are mineral soils that generally occur on young, but not recent, land surfaces. Entisols are young mineral soils that do not have genetic horizons or have only the beginning of such horizons. Vertisols have extensive shrink and swelling capacities. Alfisols are soils that have a B horizon with accumulated iron and aluminum and a base saturation of more than 35%. The mineralogy of the clays tends to be either mixed or montmorillonitic. Collectively, the soils in MLRA 131 have low slopes, poor internal drainage and very

Table 9. Selected characteristics of the dominant soils in Major Land Resource Area (MLRA) 131 that relate to water transport.

Great group /Series	Family	Approx. area	Drainage class	Permeability	Slope range	Hydrologic group
		acres				
Haplaquepts						
Perry	Very-fine, montmorillonite, nonacid, thermic Vertic	646,476	poorly	very slowly	0 - 3	D
Portland	Very-fine, mixed, nonacid, thermic Vertic	215,958	somewhat poorly	very slowly	0 - 3	D
Tunica	Clayey over loamy, montmorillonitic, nonacid, thermic Vertic	167,189	poorly	very slowly	0 - 5	D
Epiaquerts						
Sharkey	Very-fine, smectitic, thermic Typic	1,043,632	poorly	very slowly	0 - 5	D
Dystraquerts						
Alligator	Very-fine, montmorillonitic, thermic Alic	246,165	poorly	very slowly	0 - 5	D
Hapludolls						
Desha	Very-fine, montmorillonitic, thermic Vertic	121,295	somewhat poorly	very slowly	0 - 3	D
Bowdre	Clayey over loamy, montmorillonitic, thermic Fluvaquentic	52,114	somewhat poorly	slowly	0 - 8	C
Moreland	Fine, mixed, thermic Vertic	44,711	somewhat poorly	very slowly	0 - 3	D
Hapludalfs						
Dubbs	Fine-silty, mixed, thermic Typic	136,822	well	moderately	0 - 8	B
Bosket	Fine-loamy, mixed, thermic Typic	89,685	well	moderately	0 - 14	B
Rilla	Fine-silty, mixed, thermic Typic	293,891	well	moderately	0 - 5	B
Fluvaquents						
Commerce	Fine-silty, mixed, nonacid, thermic Aeric	176,889	somewhat poorly	moderately slowly	0 - 5	C
Mhoon	Fine-silty, mixed, nonacid, thermic Typic	91,652	poorly	slowly	0 - 5	D
Convent	Coarse-silty, mixed, nonacid, thermic Aeric	30,273	somewhat poorly	moderately	0 - 3	C
Natraqualfs						
Foley	Fine-silty, mixed, thermic Albic Glossic	249,223	poorly	very slowly	0 - 3	D
Endoaqualfs						
Amagon	Fine-silty, mixed, thermic Typic	204,973	poorly	slowly	0 - 3	D
Dundee	Fine-silty, mixed, thermic Typic	310,927	somewhat poorly	moderately slowly	0 - 8	C
Forestdale	Fine, montmorillonitic, thermic Typic	57,580	poorly	very slowly	0 - 8	D
Ochraqualfs						
Hebert	Fine-silty, mixed, thermic Aeric	202,692	somewhat poorly	moderately slowly	0 - 5	C
Epiaqualfs						
Jackport	Very-fine, montmorillonitic, thermic Chromic Vertic	217,959	poorly	very slowly	0 - 3	D
Glossaqualfs						
Calhoun	Fine-silty, mixed, thermic Typic	297,483	poorly	slowly	0 - 1	D
Udifluvents						
Robinsonville	Coarse-loamy, mixed, nonacid, thermic Typic	30,669	well	moderate-moderately rapid	0 - 5	B

Table 10. Selected characteristics of the dominant soils in Major Land Resource Area (MLRA) 134 that relate to water transport.

Great group /Series	Family	Approx. area	Drainage class	Permeability	Slope range	Hydrologic group
		acres				
Hapludults						
Brandon	Fine-silty, mixed, thermic Typic	27,519	well	moderate/rapid	2 - 50	B
Hapludalfs						
Memphis	Fine-silty, mixed, thermic Typic	79,685	well	moderate	0 - 45	B
Fluvaquents						
Arkabutla	Fine-silty, mixed, acid, thermic Aeric	104,043	somewhat poorly	moderate	0 - 2	C
Falaya	Coarse-silty, mixed, acid, thermic Aeric	71,604	somewhat poorly	moderate	0 - 2	D
Fragiudalfs						
Calloway	Fine-silty, mixed, thermic Glossaquic	505,742	somewhat poorly	slow	0 - 5	C
Grenada	Fine-silty, mixed, thermic Glossic	322,999	moderately well	moderate/slow	0 - 12	C
Loring	Fine-silty, mixed, thermic Oxyaquic	466,024	moderately well	moderate	0 - 20	C
Fragiaqualfs						
Henry	Coarse-silty, mixed, thermic Typic	403,812	poorly	slow	0 - 2	D
Glossaqualfs						
Calhoun	Fine-silty, mixed, thermic Typic	297,483	poorly	slow	0 - 1	D
Paleudalfs						
Tippah	Fine-silty, mixed, thermic Aquic	88,434	moderately well	moderate/slow	0 - 12	C
Dystrochrepts						
Oaklimeter	Coarse-silty, mixed, thermic Fluvaquentic	26,877	moderately well	moderate	0 - 2	C
Albaqualfs						
Crowley(Dewitt)	Fine, montmorillonitic, thermic Typic	382,219	somewhat poorly	very slow	0 - 3	D
Natrudalfs						
Stuttgart	Fine, montmorillonitic, thermic Typic	186,268	mod. well to somewhat poorly	very slow	0 - 3	D
Argiaquolls						
Jeanerette	Fine-silty, mixed, thermic Typic	20,957	poor	slow	0 - 1	D
Epiaqualfs						
Routon	Fine-silty, mixed, thermic Typic	20,239	poorly	slow	0 - 3	D
Endoaqualfs						
Tichnor	Fine-silty, mixed, thermic Typic	180,354	poorly	moderately slow	0 - 3	D

slow permeability and belong to hydrologic groups C and D; these soils tend to have lower infiltration of water and higher runoff potentials. In particular, soils in hydrologic group D have high runoff potential and low infiltration rates when thoroughly wetted and tend to have high contents of swelling clays, or a claypan or clay layer at or near the surface. Also, a permanent or perched water table or shallow soils over nearly impervious material are frequently found in soils in this MLRA. The relatively flat topography, relatively low infiltration rates, high shrink-swell potential and poor internal drainage with the profile give rise to significant problems in soil water management. Practices such as land leveling have been developed to aid removal of excess surface water.

The soils in MLRA 134 tend to be Alfisols, which were formed either in a loess mantle that has varying thickness or alluvial sediments that range from clay to gravelly sandy loam or from sedimentation. Crowleys Ridge marks the eastern boundary between the silty uplands and the alluvium. The soils in MLRA 134 tend to have a much wider range of these drainage and runoff characteristics and, therefore, not as many problems in poor physical conditions as compared with those soils in MLRA 131. However, if farmed for a significant time duration, many of these soils tend to crust at the soil surface and have tillage pans that severely restrict the infiltration and redistribution of water and root distribution within the profile.

LANDUSE

Vegetation of the Delta of Eastern Arkansas

The vegetation map of the Delta is shown in Fig. 12. Seven vegetation categories were developed, and their areal extent in the Delta is presented in Table 11. Agriculture is by far the largest landuse category in the region and in 1992 occupied about 2.8 million ha or about two-thirds of the land area in the region. Compared to other humid areas in the U.S., this is a higher-than-usual percentage of the land area in cropland agriculture. The next largest landuse category is woodlands, which collectively occupy about 26.8% of the land area in the Delta. The percentage of landuse occupied by urban areas is only about 0.4%. The region is an important cropland area with rice, soybean, cotton, grain sorghum and wheat grown by highly mechanized methods. Irrigation is an important water management component in crop production in the region.

There are slight differences in landuse when considered by MLRA. In MLRA 131 cropland agriculture represents about 70% of the area, woodland 23.5% and pasture 2.2%. The remaining small percentage is used for urban, water and miscellaneous purposes. The wettest areas that are not artificially drained remain in woodlands, which are important for hardwood timber production, wildlife habitat and as surface water retention areas.

Most of MLRA 134 is farmland with about 56.2% in cropland consisting of mostly cotton, rice, soybeans, grain sorghum, corn and wheat. About 4.8% of

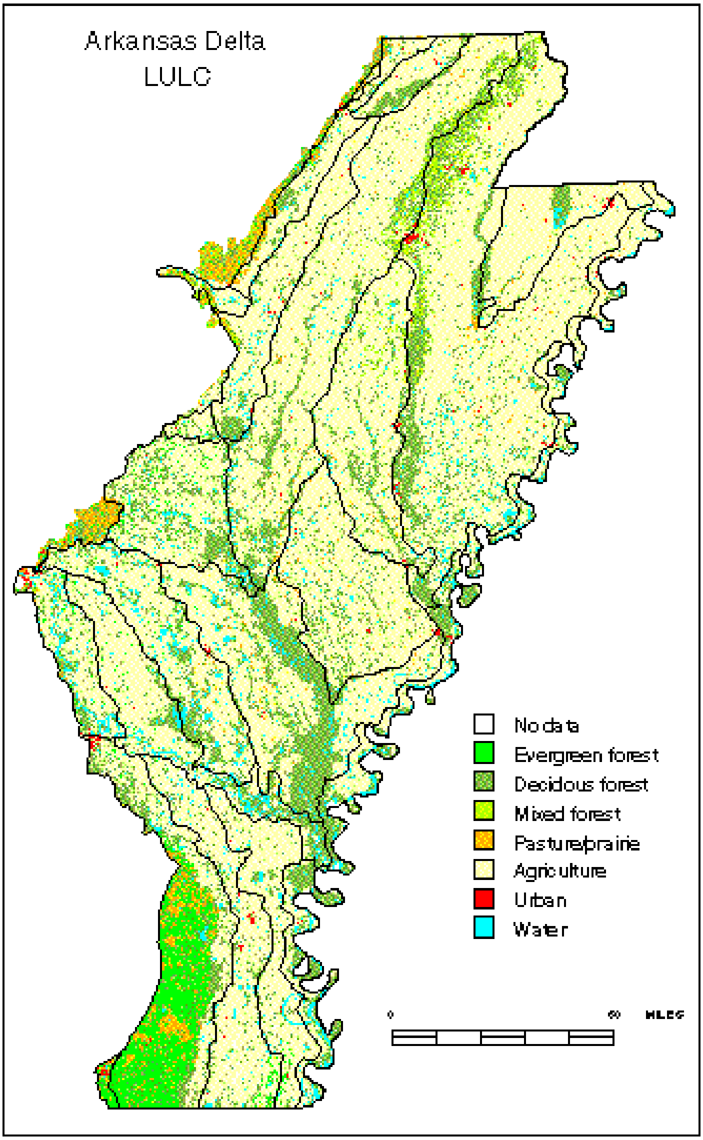


Fig. 12. Vegetation map of the Arkansas Delta taken from Thematic Mapper 1992.

Table 11. Areal extent of the seven vegetation categories of the Mississippi Delta region in eastern Arkansas.

Vegetation category	---------Areal extent---------		Percentage of total
	acres	ha	
Evergreen forest	362,294	146,618	3.47
Deciduous forest	2,281,228	923,200	21.82
Mixed forest	154,310	62,448	1.48
Pasture/prairie	285,257	115,442	2.73
Agriculture	6,913,969	2,798,045	66.14
Urban	42,704	17,282	0.41
Water	414,435	167,720	3.96
Total	10,454,196	4,230,755	100.00

Source: the Advanced Very High Resolution digital map of the U.S. in 1990.

the area is in pasture or prairie, and about 36.3% is in woodlands of mixed pine and hardwoods. About 2.6% of MLRA 134 is used for urban development, water or other purposes.

Cropping Patterns

Historically, significant changes have occurred in the area of cropland harvested. The total area and the area harvested for selected crops grown in Arkansas since 1965 is shown in Fig. 13. These data show that the area of these crops harvested has been dynamic and depends on numerous factors such as weather, price, soil characteristics, pest management and government programs.

Soybeans have the largest area harvested, which ranged from 2.08 million ha in 1979 to 1.26 million ha in 1992. During this time significant marginal lands such as pastures were plowed, and the acreage of cotton declined due to drought, insects and price. Production of soybeans requires much lower inputs than production of cotton. The subsequent decline in harvested acreage after 1979 can be attributed to lower prices, increases in cotton acreage and removal of much of the marginal lands from production. The annual harvested acreage of soybean has fluctuated between 1.2 to 1.4 million ha since the mid 80s.

The historical summary of the area harvested in Arkansas is shown in Fig. 13. Here, we present data for the area of production and the average state yields since 1970 as well as the state average yields of the irrigated (I) soybeans since 1985. Note that the highest area in production also occurred in 1979 (2.05 Mha) and the highest yields (2300 kg/ha) in 1994. In general, state-average soybean yields have increased at a rate of 68 kg/ha/year over the past decade while the area in soybean production has stabilized around 1.4 million ha. The irrigated yields have increased at 46 kg/ha/year over the past decade.

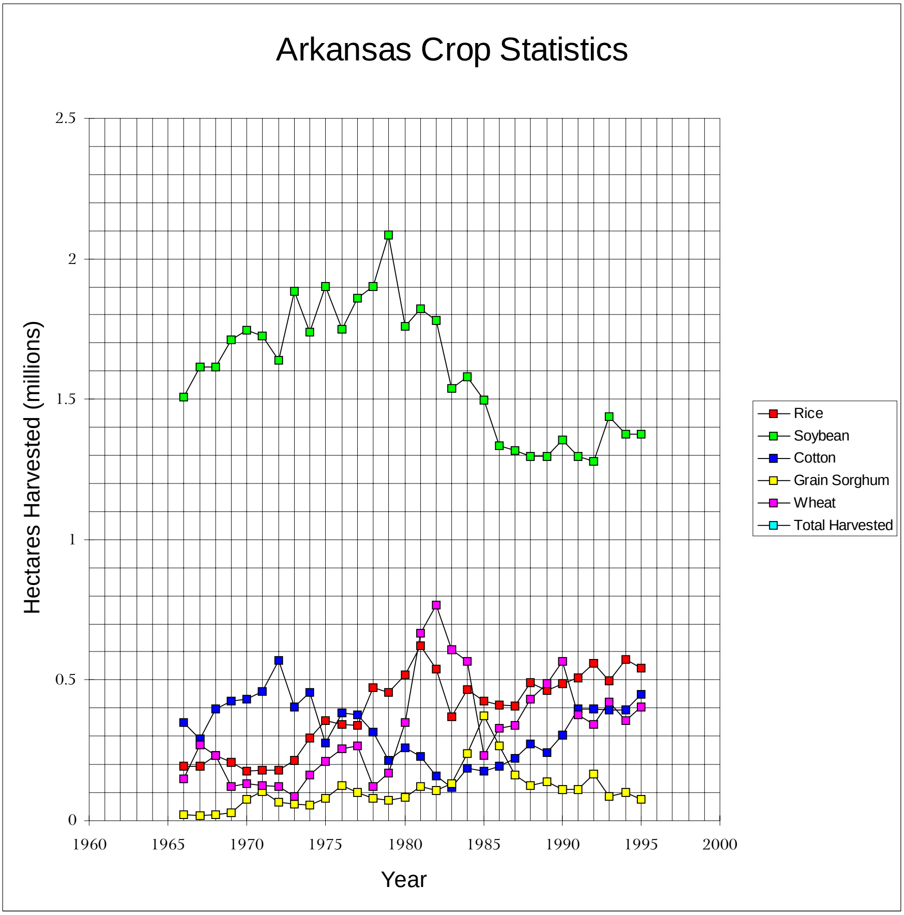


Fig. 13. Areal extent of the major agronomic crops grown in Arkansas between 1966 and 1995.

For rice, restricted acreage controls or marketing quotas were removed in 1974, and harvested acreage peaked in 1981. The effects of low price, government farm programs and costs associated with pumping considerable amounts of water on marginal lands led to the small decline in rice acreage. Harvested acreage gradually increased after 1983. The increase in state-average yield of rice was related to the introduction of the higher yielding variety 'Starbonnet' in 1968 with almost 70% of the planted acreage in the early 1970s. The subsequent decrease in yields was primarily due to the production of rice on marginal lands. The annual harvested acreage has fluctuated between 0.4 and 0.6 million ha since the mid 1980s.

Harvested acreage of cotton peaked in 1972 at 0.58 million ha. The subsequent reduction in harvest acreage was due to lower prices, poor weather during the growing season, insects and late-maturing varieties. The introduction of short-season cultivars and pyrethorid insecticides along with greater prices, irrigation, exports and domestic usage led to increases in harvested acreage and yields after 1983.

USE OF IRRIGATION IN ARKANSAS AGRICULTURE

Irrigation of Crops

The use of irrigation as a management tool in crop production in Arkansas has increased almost three-fold over the past 20 years (Table 12). According to the agricultural census, the irrigated area increased by 301,700 ha between 1974 and 1978. The marked increase of irrigated area can mostly be attributed to the expansion of rice production during this period. Between 1978 and 1992, however, 411,475 ha was added to the area of cropland irrigated. This additional irrigated acreage can be attributed mostly to the increased irrigation of soybeans and cotton. Over this 18-year period, the average annual increase in irrigation area was 39,621 ha. However, over the past 10 years, the average annual increase in irrigation declined to 27,488 ha, representing about a 30% change. During the same 18-year time interval, the annual percentage of the total cropland irrigated in the Delta increased from 14 to 37%.

In 1994 Arkansas ranked sixth in the U.S. in total cropland area irrigated (USDA-ERS, 1996). An estimated 3.196 million acre-ft of water was applied with 90.47% of the area irrigated from on-farm wells (i.e., groundwater), 9.53% from on-farm surface sources and only 0.46% from off-farm sources. This relatively high percentage use of ground water in Arkansas can be contrasted with the national average of about 50% (USDA-ERS, 1996) and shows that Arkansas has a considerably greater dependence upon ground water supplies as compared with the nation. The state-average depth of irrigation applied was 1.1 acre-ft/acre. Of the total irrigated area, the primary crops irrigated were cotton (15.07%), rice (100%) and soybeans (36.86%). Irrigation was reported in all 75 counties in 1994.

Soybeans and rice were the two most extensively irrigated crops in 1995 (Table 13); cotton ranked third in acreage irrigated. The sum of the irrigated area for these three crops is given in Table 13 and indicates a greater acreage irrigated in 1995 than in 1992 (Table 12). About 57% of the harvested area of these three crops was irrigated in 1995.

In eastern Arkansas, production of irrigated rice and soybeans complement each other in many respects. These crops usually are planted on a 1:1 or 1:2 year rice:soybean rotation, which allows the growers to use the same well and, to some extent, similar irrigation equipment in the same field over years. Also, the soils where both crops are grown tend to have poor internal drainage,

Table 12. Historical summary of the areal extent and percent of the total cropland irrigated in Arkansas.

Year	Acreage		Percentage cropland
	cropland	irrigated	irrigated
	------------------acres------------------		
1974	6,593,703	940,107	14.3
1978	7,580,307	1,685,307	22.2
1982	7,484,316	2,022,695	27.0
1987	6,477,365	2,406,338	37.2
1992	7,295,095	2,701,651	37.0

Source: the Agricultural Census.

Table 13. Harvested and irrigated area and percentage irrigated of the three major crops in Arkansas during 1995.

Crop	Acres harvested	Acres irrigated	Percentage irrigated
	--------------million---------------		
Soybeans	3.40	1.42	41.8
Rice	1.34	1.34	100.0
Cotton	1.11	0.57	51.4
Total	5.85	3.33	56.9

Source: the 1995 Agricultural Census of Arkansas.

which allows only small losses of irrigated water due to drainage below the root zone. For the most part, little rotation of cotton with soybeans and rice is practiced. Cotton tends to be grown on the coarser-textured soils with the greater internal drainage and plant-available water in the profile.

These agricultural census data indicate that changes have occurred in the area of these crops harvested and that the proportion of the cropland irrigated has also increased in the past 20 years. This also indicates that more growers have adopted water management as an important component in their crop production practices.

Irrigation Water Use from the Alluvial Aquifer

The relationships among cropland irrigated, water used and irrigation applied within each county in 1994 are presented in Table 14. The percentage of the harvested cropland that was irrigated varied by county from a low of about 9% in Independence County to a high of about 81% in Arkansas County with a county average of 42.6%. The average daily water used per acre varied from 419 gal/d/acre in Clay County to 3515 gal/d/acre in Lawrence County with a county average of 1614 gal/d/acre. The area irrigated per well varied from 12.5 ha in White County to 132 ha in Clay County with a county average of 30.6 ha per well. The depth of irrigation water applied per year varied from 2.2 cm in Clay County to 18.6 cm in Lawrence County with a county average of 8.5 cm/

Table 14. Relationships between irrigated cropland and water use by county. The base irrigated data were taken from the 1994 ASWCC (see Table 5) and Agricultural Census reports.

County	Irrigated cropland	Harvested land	Percent irr.	Water use Irr. area per acre	Volume per well	Applied per acre	Depth
	acres	acres	%	gal/d/acre	acres/well	gal/acre/year	in./year
Arkansas	272,596	335,860	81.16	1169.5	132.6	426,866	15.72
Ashley	61,608	111,363	55.32	1295.3	69.3	472,780	17.41
Chicot	85,226	210,584	40.47	1580.5	74.8	576,884	21.25
Clay	126,600	257,422	49.18	418.6	324.6	152,804	5.63
Craighead	155,793	296,331	52.57	2027.7	59.2	740,107	27.26
Crittenden	54,697	281,814	19.41	1764.3	66.0	643,957	23.72
Cross	148,993	219,666	67.83	1714.8	68.0	625,919	23.05
Desha	120,256	219,666	54.74	1661.5	77.5	606,431	22.34
Drew	33,329	60,476	55.11	1290.2	80.3	470,911	17.34
Greene	86,621	193,579	44.75	1962.6	52.0	716,339	26.38
Independence	7,629	85,492	8.92	1638.5	40.6	598,047	22.03
Jackson	120,613	298,424	40.42	2236.9	47.6	816,471	30.07
Jefferson	79,624	228,802	34.80	1868.8	48.6	682,106	25.12
Lawrence	72,100	189,822	37.98	3514.6	44.5	1,282,816	47.25
Lee	64,525	265,422	24.31	2117.0	39.5	772,708	28.46
Lincoln	57,791	131,128	44.07	1694.0	61.2	618,323	22.77
Lonoke	169,789	271,511	62.53	1541.9	66.2	562,799	20.73
Mississippi	94,490	457,375	20.66	1268.9	75.9	463,155	17.06
Monroe	70,607	183,810	38.41	2462.9	40.1	898,969	33.11
Phillips	102,536	319,850	32.06	1008.4	82.9	368,076	13.56
Poinsett	207,075	361,552	57.27	1789.7	95.6	653,237	24.06
Prairie	157,005	242,007	64.88	1058.6	86.6	386,376	14.23
Pulaski	14,034	59,787	23.47	470.3	77.1	171,655	6.32
St. Francis	81,993	241,708	33.92	2064.8	57.0	753,656	27.76
White	36,826	143,258	25.71	1219.2	30.9	445,025	16.39
Woodruff	124,563	228,068	54.62	1130.4	67.1	412,578	15.20
Mean	100,266	229,761	42.6	1614	75.6	589,192	21.7
s	60,257	94,722	16.7	631	55.1	230,140	8.5
%CV	60.1	41.2	39.1	39.1	72.9	39.1	39.1

year. These data indicate that there is a wide variation in irrigation water applied in eastern Arkansas.

Estimates were made of the irrigation water applied to the five major agronomic crops grown in eastern Arkansas in 1994. The estimated average depth of irrigation for each crop was determined by averaging the estimates of the two senior authors along with those of P. Tacker (Extension Engineer, personal communication, January 1998). The three-member panel were in close agreement on the estimates of depth applied. These estimates, which are presented in Table 15 for each crop, show that the greatest volume of irrigation water was applied to rice. Almost 70% of the total irrigation water was applied to rice with almost 22% to soybeans and almost 7% to cotton. The estimated total annual volume of irrigation water was in 1994 1.663 trillion gallons (T gal).

Estimates were also made of the water extracted from the Alluvial Aquifer using the 1994 ASWCC and Agricultural Census data. The volume of water extracted per year was estimated to be

$$4375.8 \text{ Mgal/day} * 365 \text{ days/year} = 1{,}597{,}167 \text{ Mgal/year} = 1.597 \text{ Tgal}$$

Comparison of this annual extraction from the Alluvial Aquifer with the estimated volume of irrigation showed close agreement. Thus, knowledge of the depth of water applied and the total irrigated acreage of each crop was within 4% of the annual estimated volume of water extracted from the Alluvial Aquifer by the ASWCC. This close approximation supports the conclusion that irrigation is the overwhelming user of water from the Alluvial Aquifer.

Estimations were also made of the time that the Alluvial Aquifer would remain viable for irrigation. The assumptions made in these calculations include the following.

1. Recharge into and outflow from the aquifer is insignificant as compared with extraction.

Table 15. Relationship among agronomic crop, estimated depth of irrigation applied, volume of water applied and percentage of the total water applied.

Crop	Area irrigated	Estimated depth	Volume applied	% of total
	M acres	in.	Mgal/y	
Soybeans	1.493	9	364,810	21.9
Rice	1.420	30	1,156,600	69.5
Cotton	0.470	9	114,845	6.9
Corn	0.090	10	24,435	1.5
G. Sorghum	0.025	4	2,715	0.2
Total	3.498		1,663,405	100.0

Source: these irrigated data were obtained using the 1994 agricultural census, and the estimated depth was obtained from the panel of knowledgeable scientists.

2. There was a 200-Tgal storage capacity in the aquifer before significant irrigation began in the early 1900s.
3. There was a 20% reduction in storage due to irrigation prior to 1964. This resulted in a remaining storage capacity of 160 Tgal in 1964.
4. The annual water use rate between 1965 and 1994 was equal to the slope of the linear regression line between the extraction from the Alluvial Aquifer (ASWCC) against the annual irrigated acreage between 1975 and 1994 (Ag Census). The regression equation was

$$Y = 993 + 0.0012X \quad [1]$$

where Y is the water use (Mgal/d) from the Alluvial Aquifer and X is the irrigated cropland (acres). The coefficient of determination was 0.86. The annual extraction between 1965 and 1994 was estimated from this equation based on the annual irrigated acreage and resulted in 32 Tgal extracted from the aquifer over this 30-year period. Therefore, by 1994 an estimated (160 - 32 Tgal) or 128 Tgal remained in the aquifer.

For the scenario of 50% of initial storage capacity, i.e., 100 Tgal, it would take only 16.8 years to reach this capacity; i.e., by 2011 one-half of the aquifer would be depleted. For the scenario of 25% of initial storage capacity remaining, 46.9 years is required to reach this storage capacity; i.e., by 2041 three-fourths of the aquifer would be depleted. These calculations show that the Alluvial Aquifer has a finite life. On the average by 2011, 50% of the aquifer will have been depleted; by 2041, 75% of the aquifer will have been depleted.

The slope of the regression line of 0.0012 Mgal/d/million acre is equivalent to 0.438 Mgal/year per irrigated acre. This volume of water represents a depth of 41 cm of water applied annually to all irrigated cropland. This is in close agreement with the 1994 average county water use of 159.35 Mgal/day and 1.42 million ha of irrigated cropland, which results in an average depth of 40.4 cm of irrigation water.

Aquaculture

Aquaculture is the dominant water use for nonirrigated agriculture. Aquaculture in Arkansas consists primarily of catfish and minnow farms and, to a lesser extent, trout farms and fish hatcheries. The largest withdrawals for aquaculture are in Lonoke County and are from ground water.

FUNDAMENTAL SOIL-PLANT-WATER RELATIONSHIPS

Yield of a field planted to an agronomic crop such as soybean, rice or cotton is a function of the interactions between the genetic potential of the cultivar and the environment, specifically the weather, soil and pests. Once the seed are selected and planted, the environment constrains the growth, development and yield. For the most part, these environmental constraints are governed by the flows of mass and energy during the growing season. We begin with a description of the fundamental equations expressing the conservation of mass and energy.

The Law of Conservation of Mass and Energy is used to account for the movements of mass and energy in a field over time and space. The generalized form of the balance equation can be expressed as

$$\text{Accumulation} = \text{Inflow} - \text{Outflow} + \text{Generation} - \text{Consumption}. \qquad [2]$$

The units can be differential units such as length per unit time, e.g., cm/day, mm/day, in./day, or integral units such as cm, mm or in. The inflow term refers to all flows of mass and energy into a field; outflow refers to all flows from a field. The difference between the inflow and outflow is the net accumulation. The generation term includes all production processes within the field, and the consumption term includes all extraction processes within the field. There are three conservation equations that are especially important in soil-crop-water management.

Soil Water Balance Equation

The basic principle governing the cumulation and changes in soil water in a cropped field is the water balance equation. This equation accounts for all of the inputs and outputs of water in the field and can be expressed mathematically as

$$P + I - ET \pm D \pm R = \Delta W \qquad [3]$$

where P is the precipitation, I is the irrigation, ET is the evapotranspiration, D is the net drainage, R is the net runoff, and ΔW is the change in soil water status. Each of the terms in equation [3] can be expressed in differential units such as cm/day, mm/day, cm/year or in integral units as cm, mm, etc. For most practical purposes, the time scales on a field basis are days, months, seasons or years. It is important to maintain consistency in the units of the terms in equation [3]. Since evaporation (E) from the soil and transpiration (T) from the crop are similar physical processes and are difficult to separate experimentally, they often are combined to form the term evapotranspiration (ET).

Measurements of the soil water balance usually involve quantifying all of the variables except one. Since the storage capacity of the soil profile is limited and rainfall in Arkansas is cyclic, over a long period of time the outputs must equal the inputs. Over a short time period, however, changes in storage of soil water will be significant. Thus, values of ΔW, P, I, D and ET are dynamic.

In many soil water management studies in the field, values of D and R have been assumed to be negligible within certain time intervals. This results in the working equation

$$P + I - ET = \Delta W \qquad [4]$$

which is known as the soil-water depletion equation. The units of equation [4] can be either differential or integral units. We have found that equation [4] can be used in Arkansas to give reasonable values of ET when rainfall is negligible or occurs in small increments and intensities with no runoff. Oftentimes, values of P, I and ΔW are known and equation [4] is solved for ET; in other situations, if values for P, I and ET are known, equation [4] can be solved for ΔW.

The soil water balance method measures the average value over areas of a field or plot. Other methods effectively measure point values and can be used to estimate the spatial and temporal distributions of the various soil water parameters at selected locations within a field.

Crop Water Balance Equation

A quantitative model for the plant water status may also be expressed as a simple mass balance equation. The plant water balance equation is

$$W \cong (A - E) + S \qquad [5]$$

where W is the water status of the plant, A is the water absorbed principally through the roots, E is the water lost primarily by transpiration through the leaves, and S is the water stored in the plant. Since the amount of water stored by most crops is small ($S < 0.15$ kg/kg), the crop water status is generally proportional to the difference between the water gained and water lost. The net effect is that during daylight, E normally exceeds A, resulting in a progressive decrease in W, which leads to internal water deficits in the crop. At night, stomatal closure and reduced atmospheric demand for water retard E, which allows the water to equilibrate, and the deficits are reduced or eliminated. If water is not limiting, A is approximately the same as E on a daily basis.

The amount of water stored in the crop is small compared with the amount of water that passes through the crop in transpiration (Turner and Burch, 1983). Water loss by transpiration provides cooling to the plant but is essentially an inevitable consequence of the uptake from a relatively dry atmosphere of CO_2 for photosynthesis. Six molecules of CO_2 and six molecules of water are required to provide one sugar molecule. Numerous studies have been conducted that quantify the amount of water used (i.e., ET) in the production of 1 kg of soybean. Values of water use efficiency for soybeans grown in eastern Arkansas will be given later.

Energy Balance Equation

Solar radiation provides almost all the energy received at the surface of the earth. Therefore, the energy balance equation describes how this energy is partitioned at the surface of a field. Mathematically, the energy balance equation can be expressed as

$$Rn = H + LE + M - G \qquad [6]$$

where Rn is the net radiation, H is the energy used in heating the air (sometimes known as the sensible heat), LE is the latent heat of evaporation, M is the sum of the miscellaneous energy terms such as photosynthesis and respiration, and G is the soil heat. Usually, the terms in equation [6] are expressed in differential units such as $MJ/m^2/day$ because of the dynamic changes that these terms undergo during a day, month and season.

Values of Rn, which quantify the net radiation absorbed by a surface, are the total radiation arriving minus the reflected shortwave and the emitted longwave radiation. Therefore, Rn is the difference between total upward and total downward radiation fluxes and is a measure of the energy available at the surface. During daylight hours, the dominant radiation flux is the incoming shortwave (solar) radiation. The amount of shortwave radiation incident upon the surface is controlled by the solar angle, the amount and density of cloud cover and the transmissivity of the atmosphere; in general, assuming that cloud cover is relatively constant, the incident solar radiation will start from zero at sunrise, reaching a maximum at solar noon, then declining to zero at sunset, generally following a half of a sine wave. Typical daily integrated amounts of incoming solar radiation in the summer months would range from 836 to 2720 $J/cm^2/day$ (200 to 650 $cal/cm^2/day$). For most agricultural surfaces such as crops and soils, about 20 to 25% of the incident solar radiation is reflected back to space. Note that the reflectivity of water is considerably less than that of most other surfaces, typically being in the range of 7 to 9%.

The long wave (thermal or far-infrared) radiation is relatively constant with a net outward flux of energy. Thus, the net radiation tends to be negative (energy leaving the surface) at night and positive (energy into the surface) during the daylight hours. Typical integrated values for daily net radiation in the summer months in the Delta will range from 630 to 2090 $J/cm^2/day$ (150 to 500 $cal/cm^2/day$). At most environmental temperatures, the latent heat of vaporization is about 2,424 J/cm^3 (580 cal/cm^3).

When water does not limit evaporation and transpiration, most of the net radiation is utilized in the vaporization of water in evapotranspiration. Under well-watered conditions in the Delta region, the ratio of LE/Rn is typically around 0.8. Thus, on a day when the net radiation is 1670 J/cm^2 (500 cal/cm^2, LE would be about 2090 J/cm^2 (400 cal/cm^2), and the amount of ET would be (400 cal/cm^2)/(580 cal/cm^3) or about 7 mm. As the soil dries and soil water becomes less available to the roots, water for ET becomes less available, and a larger proportion of the net radiation goes into heating the soil and the atmosphere.

Numerous experiments have been conducted in which the parameters in the water and energy balance equations have been quantified. In this document, we emphasize those studies that were conducted in the field in Arkansas rather than those that were conducted in the more controlled environments of the laboratory and greenhouse.

Crop Drought Indicators

Several plant parameters have been used to determine the status of drought in the field. These studies have generally shown that stress of crops from drought does not develop suddenly but increases gradually and at different rates, depending on the supply of water available to the crop in the soil profile and to the atmospheric demand.

Physiological Processes

The basic processes in the plant that are most sensitive to drought stress are altered first, and such alterations, in turn, may lead to many secondary and tertiary changes. The order of decreasing sensitivity to drought stress seems to be

1. cell growth,
2. cell wall synthesis and protein synthesis,
3. stomatal opening and CO_2 assimilation,
4. respiration and
5. sugar accumulation.

The effects of plant water status on physiological processes have been widely studied (Kozlowski, 1968). Initially, the index of water status most often used, because of its convenience and reliability, was the ratio of plant water content to dry weight or to the corresponding water content in fully turgid tissue. Methods to measure other physiological indices, particularly osmotic potential, leaf water potential and leaf water vapor diffusion resistance, have been used frequently.

Gardner (1968) stated that "much of the time the atmospheric conditions may have a much greater influence than soil factors over the transpiration rate." Water movement in the liquid phase of the soil-crop system occurs in response to differences in the potential energy of water in different parts of the soil-crop system. The water potential of the crop must be lower than that in the soil if water is to move from the soil into the plant. Thus, the energy status of water in soil sets an upper limit to the energy of water in the crop. It seems that whatever the influence of soil water upon crop response, it must be exercised through the effect upon the components of the potential energy of water in the plant.

The main problem associated with attempts to relate crop response directly to soil-water potential is that the soil-plant-atmosphere system is dynamic and is never in equilibrium so long as the crop is transpiring. There are resistances to movement of water through the soil and the crop so that, although the soil water potential may set an upper limit to the crop-water potential, the crop normally is at a considerably lower water potential than the soil.

Jung and Scott (1980) reported on the diurnal and seasonal variations in leaf water potential (Ψ), stomatal diffusion resistance (R) and leaf temperature (T) of irrigated (I) and non-irrigated (NI) 'Forest' soybeans at RREC near Stuttgart.

The soil is a Crowley silt loam, which has been reclassified recently as a DeWitt silt loam. In the NI soybeans, values of Ψ decreased earlier in the day and increased later in the afternoon than Ψ values of I soybeans. The stomates of NI soybeans were partially closed during the daylight hours and closed earlier in the afternoon than stomates of I plants. Leaf temperatures of the NI soybeans increased earlier in the morning and remained higher later in the afternoon than leaf temperatures of I soybeans. As the drought intensified, differences in Ψ, R and T between the NI and I soybeans increased. Maximum differences during the day were approximately $\Delta\Psi$ = -4 bars, ΔR = 6 sec/cm, and ΔT = 5.5 C and were usually found at midday and mid afternoon late in the growing season. Generally, the differences in these parameters between soil water regimes were lower at midmorning. The cumulative effects of these differences in the plant water and temperature parameters were reflected in lower dry matter and seed production of the NI soybeans by 5500 and 2550 kg/ha, respectively.

Work reported by Turner and Burch (1983) suggested that soybean leaf expansion under field conditions is less sensitive to water deficits than earlier studies had indicated. They found that soybean leaf expansion rates were maximal in the afternoon when leaf water deficits reached a maximum. The strong correlation between extension growth and ambient temperature suggested that the rate of leaf expansion may have been determined largely by temperature and was unaffected by leaf water deficits as low as -12 and -14 bars.

The initial decrease in the rate of photosynthesis per unit leaf area is a result of water deficits and is generally thought to arise from stomatal closure. There is little change in stomatal resistance as leaf water potential decreases until a critical or threshold potential is reached below which the stomatal resistance increases markedly. This critical potential at which stomates close varies with species and leaf age, and small differences between cultivars have been reported. There is no unique critical value for stomatal closure for a particular species or cultivar; stomatal closure varies with the leaf in the canopy, leaf age, growth conditions and rate of drought stress.

Whole Plant

In production of crops such as soybeans, the seasonal dry matter production of the whole or component parts of the plant, i.e., the net accumulation of CO_2, is indicative of how the plant partitions its resources. Mathematically, this can be represented as

$$DW = f_s Dw_s + f_l Dw_l + f_p Dw_p \qquad [7]$$

where DW is the dry weight of the whole plant, Dw_s, Dw_l and Dw_p are the dry weights of the stem, leaves and pods, respectively, and f_s, f_l and f_p are the partitioning coefficients of the stems, leaves and pods, respectively. Both dry weights of the plant components and the partitioning factors vary with plant age and water management. The partitioning coefficients are fractions, which must sum to 1.0.

The effects of drought on the distribution of assimilates to the various plant component parts depend on the stage of development of the crop, the intensity of drought stress, the prehistory of stress and the degree of sensitivity to stress of the various plant organs. Usually during reproductive growth, photosynthesis by the leaves is more sensitive to water deficits than seed growth, and assimilates move preferentially from the lower leaves, stems and roots and to the pod and seed. Although the degree of stress may be sufficient to reduce the rate of net photosynthesis, it may not affect the pattern of distribution of assimilates.

Scott and Batchelor (1979a) calculated the leaf weight ratio (LWR), specific leaf area (SLA) and leaf area ratio (LAR) for I and NI field-grown 'Lee 74' soybeans grown on a Crowley (DeWitt) silt loam in dry and wet seasons. LWR represents the average fraction of the whole plant dry weight in the form of leaves. SLA is the leaf area per unit leaf weight and represents the mean of the leaf area expansion over the whole plant per unit leaf weight. LAR is a morphological index of plant form and at any time represents an integration of the effects of assimilate translocation to the leaves and partitioning of the assimilates between leaf area and plant weight. In the dry year, significant differences due to water management were found after mid-reproductive growth. The I soybeans had lower LWR and higher SLA and LAR than the NI soybean. During the wet year, no differences were found in these plant characteristics due to water management.

Nutrient Uptake

Water management has been shown to affect nutrient uptake by soybeans. Nutrient uptake of the crop is related to dry weight of the component parts of the crop as follows

$$NU = Dw_s C_s + Dw_l C_l + Dw_p C_p \qquad [8]$$

where NU is the accumulation of a nutrient element, and C_s, C_l and C_p are the concentrations of the element in the stems, leaves and pods, respectively. Each term in equation [8] varies temporally during the growing season. The effects of water management on nutrient uptake can be expressed on both dry matter accumulation and elemental concentration of the component parts of the crop.

In a three-year field study, Batchelor and Scott (1979) found that accumulation of the nutrient elements N and K by Lee 74 soybeans was significantly enhanced by irrigation in the two relatively dry years but was not affected in the relatively wet year (Table 16). There was a tendency for the Lee 74 soybeans grown on the Sharkey clay to have higher nutrient accumulations than those grown on the Crowley silt loam. Approximately 75 and 65% of the final N and K contents were accumulated after the beginning of reproductive growth.

Table 16. Uptake of nitrogen and potassium by irrigated (I) and nonirrigated (NI) 'Lee 74' soybeans grown for three years on two soils in eastern Arkansas.

		Plant accumulation				Dry matter	
		Nitrogen		Potassium			
Soil	Year	I	N	I	N	I	N
		kg/ha					
Sharkey clay	1	269.1	269.1	186.9	186.9	9,488	9,103
	2	348.7	188.4	256.8	132.9	15,527	9,707
	3	186.2	112.3	217.2	130.4	8,274	5,309
Crowley silt loam	1	231.0	212.8	168.8	154.3	8,399	8,612
	2	197.2	127.4	160.8	128.0	11,235	8,820
	3	181.9	114.0	145.0	125.0	7,082	4,682

Scott and Brewer (1982) developed a mathematical model to describe the translocation of nutrient elements in soybeans. They used the results from the same field study as Batchelor and Scott (1979) to quantify the transport of N, K, Ca and Mg in I and NI Lee 74 soybeans grown on two soils. Mass balance equations were used to describe the instantaneous rates of change in the amounts of a given element in the compartments, assuming that the elements move at a rate that is proportional to the concentration in the compartment from which it flows. The four compartments were soil, stems, leaves and pods. Uptake rates of N, K, Ca and Mg, crop growth rates and nutrient transport coefficients varied considerably during the growing season and between plant component part and were higher in the I soybeans grown on the clayey soil. Uptake and translocation rate coefficients of N by the soybeans were greater than those of K, Ca and Mg. During late pod-fill, translocation of N and K out of the leaf compartment and into the pod compartment was quantified, with the highest translocation rates in the direction toward the pods.

Seed Yield

For soybeans, the economic yield is expressed by the quantity of seed per unit area. However, the seed are only a proportion of the total dry matter. Therefore, the effects of drought on the distribution of assimilates, i.e., the products of photosynthesis, to the seed are important. Translocation of assimilates is affected by drought because of the influence of drought on the rate of photosynthesis, the rate of utilization of the products of photosynthesis or the loading and unloading of the phloem.

In humid regions such as eastern Arkansas, maximization of seed yield is the most frequently used indicator of plant response to drought. From a soybean grower's standpoint, one of the most successful programs is the "extension verification" demonstration. With the financial support of the Arkansas Soybean Promotion Board, personnel in the Cooperative Extension Service annually conduct on-farm, relatively large-field demonstrations, which incorporate water management technology into their recommendations (Ashlock et al., 1995). The historical summary for the full-season soybeans is presented in Table 17.

Over the past decade with all of the differences in weather during the growing seasons, and over a rather large diversity of soil characteristics, the I soybeans had the highest yield; the highest annual yield, obtained under irrigation, was 4469 kg/ha. These results indicate that over the numerous environments and cultivars, seed yields of well-managed fields of I soybeans averaged 954 kg/ha more than the NI yields.

For Arkansas, the state-average soybean yields in 1994 are presented in Table 18. Comparing the irrigated state yields with the yields shown in the previous table indicates that the yields in the irrigated extension demonstration fields are about 21% higher than the state average yields, and the yields of the NI soybeans were about the same (i.e., approximately 2100 kg/ha). The difference in yield (I - NI) during 1994 using the water management technology on the farm was only 471 kg/ha, a 50% lower yield in the use of irrigation technology. The differences in yields between those obtained in extension verification demonstrations and the application on the farm have been fairly consistent over the past 20 years. Economically, the break-even price ($/acre) is about the same for both I and NI treatments. However, even though the operating costs are higher with the I soybeans, the yields are higher also. The result is that there is lower risk associated with irrigation of soybeans. The average cost of irriga-

Table 17. A summary of the yields from the extension verification demonstration fields in Arkansas.

Category	I[1]	NI
Seasons (years)	12	8
Number of fields	101	24
Average field area (ha)	19.8	14.9
Average yield (kg/ha)	3091	2137
Average yield (bu/acre)	46.0	31.8

Source: Ashlock et al., 1995.
[1]I = irrigated; NI = nonirrigated.

Table 18. Arkansas state-averaged soybean seed yields in 1994.

	Yields	
Management Category	kg/ha	bu/acre
Overall	2285	34.0
Irrigated only	2554	38.0
Nonirrigated only	2083	31.0
Double cropped	1949	29.0

Source: the Arkansas Agricultural Census, 1994.

tion water in Arkansas is about $0.70/cm ($1.75/acre-in.) of water (Dillon et al., 1997).

From a management standpoint, many Arkansas growers rotate soybeans with other agronomic crops, such as rice and wheat. Three management schemes have been developed in Arkansas: full season, double cropped with wheat and early planted-full season. Therefore, the yields of soybean must be considered in context with the entire farm management, of which water management is an important component. These issues are discussed in greater detail later.

Water Use Efficiency

In the more arid regions, the macroscopic effects of drought on crops grown in the field are quantified by relating plant growth to the water used. One of the most frequently used quantitative expressions of plant productivity during drought is water use efficiency (WUE). Water use efficiency is defined as the ratio of plant productivity to the total water lost. Mathematically, this equation is expressed in a couple of forms:

$$\text{Water Use Efficiency} = \text{dry matter/ET} \quad [9]$$

or

$$\text{Water Use Efficiency} = \text{seed yield/ET.} \quad [10]$$

The typical units of WUE are kg/ha/cm. The numerator of equations [9] and [10] expresses the net utilization of solar radiation by the crop minus the effects of losses to drought and pests in a given area; the denominator depends on the energy available, vapor pressure deficit, soil physical properties and plant rooting characteristics. Usually, cultural practices that increase storage of water in the soil lead to increased crop productivity more than a reduction in ET. Therefore, higher values of WUE result in greater plant productivity per unit of water used, i.e., a more-efficient plant from a water use perspective.

Since the Mississippi Delta region in eastern Arkansas is humid, the frequency and amounts of rainfall during the growing season are quite variable (Bruce et al., 1985). Under NI conditions in this region, the seasonal rainfall variability leads to considerable variability in the uptake of water and nutrient elements as well in the growth, development and yield of crops (Scott et al., 1986b).

Scott et al. (1987) summarized the results of a five-year study on water management of Lee 74 soybeans (Maturity Group VI) grown on a Crowley (DeWitt) silt loam at RREC near Stuttgart, Arkansas. Crop water use was simulated using the water balance equations in the crop model SOYGRO (Ritchie, 1972). Results of annual water use during vegetative growth are presented in Table 19. These results showed that over the five years, water used during vegetative growth in both I and NI soybeans was similar, about 22 cm, but differed among years. The water lost from soil evaporation was only 1 to 2 cm

Table 19. Water use by 'Lee 74' soybeans grown on a Crowley (DeWitt) silt loam during vegetative growth at RREC[1] near Stuttgart, Arkansas. The parameters T, E and ET represent transpiration, evaporation from the soil and evapotranspiration, respectively.

	Irrigated			Nonirrigated		
Year	T	E	ET	T	E	ET
	---cm---					
Vegetative growth						
1974	3.8	10.9	14.7	3.8	10.9	14.7
1975	12.9	13.0	25.9	13.9	11.6	25.5
1976	12.9	14.1	27.1	10.6	12.9	23.5
1977	11.8	12.3	24.2	10.5	11.1	21.6
1978	12.7	14.0	26.7	12.0	10.0	22.0
Mean	10.8	12.9	23.7	10.2	11.3	21.5
SD	4.0	1.3	5.2	3.8	1.1	4.1
%CV	37	10	22	37	10	19
Reproductive growth						
1974	20.9	16.1	37.0	21.2	15.8	37.0
1975	34.0	17.2	51.2	27.7	15.8	43.5
1976	37.4	16.5	53.9	19.2	14.8	34.0
1977	36.6	16.2	52.8	25.0	14.9	39.9
1978	34.8	18.6	53.4	22.4	14.3	36.7
Mean	32.7	17.0	49.7	23.1	15.1	38.2
SD	6.7	1.0	7.1	3.3	0.7	3.6
%CV	21	6	14	14	5	10

[1]RREC = Rice Research and Extension Center, Stuttgart, Arkansas.

lower than that lost from transpiration during vegetative growth. During reproductive growth, however, the water used by the soybeans was much higher and was considerably higher in the I soybeans than in the NI soybeans (Table 18). There were large differences in ET due to water management during reproductive growth. The I soybeans used about 30% more water than the N soybeans during this period of growth with about 60% of the total water used lost by transpiration from the crop.

Values of E and T during vegetative and reproductive growth were summed to obtain seasonal estimates (Table 20). The ratio of T to ET was also calculated for each growing season. These results indicate that ET of the I soybeans was greater than that of the NI soybeans and that the ratio of T to ET was about the same for both water management treatments. Thus, in comparison to the NI soybeans, the I soybeans lost more water but accumulated more dry matter. The lowest ET occurred during the growing season with above-normal rainfall, 1974.

Seasonal water use efficiencies were also calculated using dry matter production (DM) and seed yield (SY), and the results are presented in Table 21.

Table 20. Sum of water used by 'Lee 74' soybeans grown on a Crowley (DeWitt) silt loam at RREC[1] near Stuttgart, Arkansas. The parameters T and ET represent transpiration and evapotranspiration, respectively.

	Irrigated		Nonirrigated	
Year	ET	T/ET	ET	T/ET
	cm	cm/cm	cm	cm/cm
1974	51.2	0.482	51.7	0.484
1975	77.1	0.608	69.0	0.603
1976	81.0	0.621	57.5	0.518
1977	77.0	0.629	61.5	0.577
1978	80.1	0.593	58.7	0.586
Mean	73.3	0.587	59.7	0.554
SD	12.5	0.060	6.3	0.050
%CV	17	10	11	9

[1]RREC = Rice Research and Extension Center, Stuttgart, Arkansas.

Table 21. Seasonal water use efficiencies of the 'Lee 74' soybeans grown on a Crowley (DeWitt) silt loam at RREC[1] near Stuttgart, Arkansas. The parameters DM, ET and SY represent plant dry matter, evapotranspiration and seed yield, respectively.

	Irrigated		Nonirrigated	
Year	DM/ET	SY/ET	DM/ET	SY/ET
	---------------kg/ha/cm---------------			
1974	169.2	53.4	148.7	52.9
1975	194.9	37.5	175.5	27.2
1976	152.7	37.6	153.1	28.1
1977	169.3	32.5	212.0	34.6
1978	161.5	29.5	220.4	32.1
Mean	169.5	38.1	181.9	35.0
SD	15.7	9.2	33.0	10.5
%CV	9	24	18	30

[1]RREC = Rice Research and Extension Center, Stuttgart, Arkansas.

These results indicate that in terms of dry matter accumulated by the end of the growing season, WUE was greater in the NI soybeans. When WUE was calculated on a seed yield basis, however, the I soybeans had slightly higher values of WUE than the NI soybeans. This suggested that perhaps the I soybeans produced more dry matter than was needed for the amount of seed produced. In terms of economic yield, however, the I soybeans were slightly more efficient users of the available water. Considering the declining ground water supplies in the critical ground water areas in the Delta, considerations of the water use efficiency of crops may become more important in eastern Arkansas in the future.

WATER MANAGEMENT OF RICE

Rice is unique among grain crops grown in Arkansas because of its need for and ability to tolerate ponding of water on the soil surface. The rice production systems in current use in Arkansas make rice the crop with the highest water requirements.

The quantity of water needed for rice production depends on the weather during the growing season, the soil, the textural and mineralogical composition of the subsoil, the maturity group of the rice and water management practices such as delayed flooding, mid-season drain, etc. The depth of water used during the growing season in the Delta ranges from 46 cm to more than 91 cm and averages about 76 cm/year. This wide difference in water use is related to the maturity group of the rice, the amount of water available, which is largely determined by the ability of the soil to retain a flood, and the water management philosophy of the individual producer. Soils with high contents of smectitic clays in the B horizon tend to swell upon wetting, thereby restricting internal drainage losses.

The seasonal water balance of a rice field can be developed from equation [3]. The inputs of water consist of the rainfall (PPT) during the season and the irrigation water (IRR) applied. Outflows consist of evapotranspiration (ET), deep seepage (DSEEP), lateral seepage (LSEEP) and surface drainage (SDRAIN). Thus, equation [3] for a rice field becomes

$$IRR + PPT = ET + DSEEP + LSEEP + SDRAIN \qquad [11]$$

Evapotranspiration from a field of seeded rice is closely related to potential evapotranspiration during the non-flooded time and to pan evaporation during the flooded time. In a field-verified model, Ferguson and Gilmour (1981) used pan evaporation to predict ET where ET was calculated as a pan coefficient times pan evaporation. Values of the pan coefficient are given in Table 22.

Over the rice growing season, for Arkansas Delta climatic conditions, these calculations give a typical seasonal ET of 55.0 to 61.0 cm. This ET will vary depending upon the length of the crop-growing season as well as with the weather during the season.

Deep seepage is defined as water moving vertically downward below the root zone of the rice and can vary dramatically with soil texture and profile characteristics. Ferguson (1979) used seepage rates during the flooded season as presented in Table 23. The variable seepage rate on clay soils was 6.4 mm/day at the start of the flood, reduced linearly to 1.5 mm/d by 15 July and then reduced linearly to 1 mm/d at the end of the season. For a typical 90-day growing season, deep seepage losses were 135, 270, 460 and 250 mm for the low, medium, high and variable seepage groups, respectively.

Lateral seepage is a field loss only on the periphery of the field. Ferguson et al. (1986) showed that on clayey soils with normal-sized fields, the lateral

Table 22. Ratio of rice evapotranspiration to pan evaporation (pan coefficient) as a function of crop age.

Crop age	Description of general conditions	Pan coefficient
days		
-10 - 15	Land preparation, seeding and germination	0.60
16 - 35	Seedling growth up to flood establishment	0.84
36 - 55	Vegetative growth but visible water	0.99
56 - 85	Canopy closure and shading of water	0.95
86 - 116	Heading and senescence	0.68

Table 23. Deep seepage rates for selected Arkansas Delta soils under flooded conditions.

Seepage group	Seepage rate	Typical soils
	mm/day	
Low	1.5	Crowley, Stuttgart silt loam
Medium	3.0	Henry, Calloway silt loam
High	5.1	Boskett, Dubbs, Rilla silt loams
Variable	6.4 to 10	Sharkey, Perry clay

seepage losses, while perhaps a nuisance, were not a significant portion of the water budget for the field.

Surface drainage amounts will vary with the number of times the field is drained, the water status of the field when drainage occurs and pump operation when the field is pumped up through the season. Normal season drainage may be as low as 5.0 cm but can be as high as 15.0 cm or more.

Average precipitation during the rice growing season is about 25.0 cm but can be considerably less or more. Excessively large rains can increase surface drainage amounts by causing the farmer to drain the field in order to prevent levees from washing out.

Using the preceding data, the typical rice water budget for the various soil seepage groups would be as given in Table 24. Thus, the normal irrigation requirements would vary from 56.5 to 89.0 cm. Those soils with higher deep seepage losses have higher irrigation requirements. These data are based on a 90-day irrigation season; consequently, varieties of rice with a different irrigation season will have different irrigation requirements.

Huey (1977) listed 10 measures that minimize water used by rice production: 1) select soils and fields that hold a flood, 2) improve topography, 3) survey and construct levees accurately, 4) use underground pipe systems instead of canals for delivery, 5) drain when necessary, 6) flood only 5 to 10 cm rather than 15 to 20 cm, 7) use short-season cultivars, 8) reuse waste water, 9) minimize pumping at peak power periods and 10) shut off the pump before the water reaches the last levee.

Table 24. Typical annual water balance of rice for various soil groups.

Seepage group	ET[1]	DSEEP	DRAIN	PPT	IRR
	--------------	--------------	cm	--------------	--------------
Low	58.0	13.5	10.0	25.0	56.5
Medium	58.0	27.0	10.0	25.0	70.0
High	58.0	46.0	10.0	25.0	89.0
Variable	58.0	25.0	10.0	25.0	68.0

[1]ET = Evapotranspiration; DSEEP = deep seepage (internal drainage); DRAIN = surface drainage; PPT = precipitation; IRR = irrigation.

Sometimes after planting of the rice and before the permanent flood is applied, the fields may require a flushing of water to encourage greater germination and seedling growth, salinity control near the soil surface, activation of a herbicide for weed control and the incorporation of early N fertilizations. During the flushing of the field, irrigation water is applied, and the water that does not infiltrate the soil profile is drained.

Usually, the irrigation water is initially applied after the seedlings reach the four- to five-leaf stage and a minimum height of 15 cm. This usually occurs three to four weeks after emergence. Water flows from the top bay by gravity through levee gates to other bays of the field. At least 50% of the fertilizer N required by a given cultivar should be applied to the dry soil surface and the permanent flood applied and maintained until physiological maturity.

A continuous shallow flood ranging between 5 and 10 cm for the season is desired to minimize N losses, weed infestations, energy costs and water use. Once the permanent flood is established, drainage of the field may be needed due to a plant nutrient deficiency such as P and Zn and for straighthead control.

Between two and three weeks after heading, it is recommended that the pump be turned off. Under the weather conditions of the Delta, it normally takes an additional two to three weeks for the field to dry so that harvest combines can be used in the field.

WATER MANAGEMENT OF SOYBEANS

Overall Water Management Strategy in Arkansas

Two of the more important aspects of soybean production are the spatial and temporal distributions in production and seed yield. Soybean production is influenced by several factors, including management, weather and soils, and all of these factors are also spatially and temporally distributed (Scott, 1985).

The reasons for the extensive irrigation in Arkansas are 1) the abundance of relatively cheap ground water, 2) humid climate, 3) reasonably level topography, 4) chemically fertile soils and 5) research studies that show that significantly higher seed yields result from proper irrigation scheduling.

Another important aspect of water management is strategies that should be implemented when excessive water has occurred, i.e., flooding. These conditions occur when an intense rainfall or a series of rainfall events occur within a short period of time or when excessive irrigation has been applied, or a combination of the above events. Prolonged flooding has serious implications to crop growth and development. It is not uncommon in the Delta to have both drought and prolonged flooding conditions during the same growing season, even in the same field.

Irrigation Methods

The preponderance of irrigation in Arkansas is gravity or surface irrigation. The rice crop is essentially 100% irrigated using flood irrigation with contour levees. Since soybeans are generally grown in conjunction with rice, much of the soybean acreage is irrigated using contour levee flood irrigation. The use of furrow irrigation on soybeans has increased to a significant portion of the area due in part to the availability of large diameter 'lay-flat' irrigation pipe that does not have to be moved during the irrigation season. Much of the cotton acreage is furrow irrigated.

Overhead irrigation has generally increased in the past two decades due primarily to the labor reductions achieved with center pivot systems. Estimated acreage under center pivot irrigation in 1996 was 100,000 ha. The center pivot systems are generally used on soybeans, cotton and corn in eastern Arkansas.

Irrigation application efficiency is defined as the percentage of water applied that infiltrates into the root zone for use by the crop. Losses include deep seepage below the root zone, tailwater runoff and evaporation of water in transit. Generally, the conditions in irrigated areas of Arkansas are such that deep seepage is not a major loss. Evaporation of water in transit, including the spray from overhead irrigation, is not generally of major significance in eastern Arkansas (Pitts et al., 1987).

Application efficiency of flood irrigation on rice is generally from 80% to 90%, depending upon the amount of deep seepage and the number and amount of surface drainage. Flood irrigation on soybeans is less efficient since some runoff is necessary every irrigation, usually ranging from 70% to 80%. The crop loss due to levee construction normally is in the range of 7% to 15%.

Furrow irrigation is generally less efficient due to the amount of surface runoff necessary each time if the lower end of the row is to be adequately irrigated. Typical application efficiencies for furrow irrigation range from 50% to 70%. Studies on surge irrigation on clayey soils in eastern Arkansas indicated no application efficiency or uniformity improvement with surge irrigation when compared with conventional furrow irrigation.

Center pivot systems generally are relatively more efficient than the surface irrigation systems since surface runoff for a well-designed system is minimized. Efficiencies typically range from 85% to 95%.

Irrigation Scheduling Strategies

At the beginning most of our studies were conducted in the field. Prior to this time, the recommendations were to irrigate whenever the soybeans needed water (Thompson and Caviness, 1969). Decisions to irrigate were made mostly by position characteristics of the leaves at the top of the canopy, which is considered to be a qualitative strategy. If the leaves were drooped, then irrigation was recommended.

Our approach to irrigation-soil water management of soybeans has been "that prescribed amounts of water are applied to a specified soil depth to which soil-water levels are to be maintained." The thickness of the control depth depends on the crop rooting characteristics and on the soil water transport characteristics. The control level is the soil water pressure at which irrigation is to be initiated. Its magnitude depends on the water and aeration transport characteristics of the soil and on the tolerance of the crop to drought and poor aeration. The frequency of irrigation depends on 1) the depth of the control zone, 2) the specified soil-water pressure and 3) the current water demands of the soil and crop, i.e., the ET and the amount of irrigation previously infiltrated and retained in the soil profile.

Two quantitative approaches were developed using these concepts over the years. Both irrigation scheduling approaches are compatible and have been well received by those soybean growers who use quantitative irrigation scheduling techniques. A brief summary of these two approaches is given below.

Measurement of Soil Water Pressure

First, the effects of proper soil water management on crop yield were distinguished. Field research plots were established on two soils having differing surface textures, a silt loam and a clay.

The first irrigation scheduling strategies were developed as follows:

Control depth in the profile: 30 cm;

Control soil water pressure to initiate irrigation: 550 cm of water, or -55 kPa, or 55 cbar of soil water tension;

Irrigation scheduling criteria: Apply 5 cm of irrigation water whenever the soil water matric pressure is the control pressure.

Tensiometers were installed throughout the field at a depth of 30 cm and read three times each week beginning at mid-vegetative growth. Our approach was to have all of the instruments in the field and working by 4 July when the full-season soybeans (MG V and VI) are in mid-vegetative growth. Irrigation is applied when the average soil water pressure at the 30-cm depth was -0.55 bar (-55 kPa or 55 cbar). This control depth of 30 cm was established because about 75% of the soybean roots were found in this depth interval at the beginning of reproductive growth (Scott et al., 1986b). Therefore, our control zone for management is the top 30 cm, and we monitored the soil water pressure at the base of the control zone with tensiometers. In essence, we use the deeper depths of the soil profile as a reservoir of water to be used whenever water management mistakes were made.

Irrigations scheduled at lower soil water pressure (or higher matric potentials) result in more irrigations, lower amounts of water per application, possibly greater lodging and no practically significant increases in seed yield. Irrigations scheduled at higher soil water pressures (or lower matric potentials) result in fewer irrigations, greater amounts of water applied per application, greater plant drought stress and lower yield.

Use of tensiometers required the growers to go into the field to read the Bourdon gauge of the tensiometer two to three times each week. The advantages of this method include the knowledge gained about 1) the water retention characteristics of the soil and water extraction by the plants, 2) the spatial variability of soil physical parameters such as textural class and water retention of the soil, and 3) the opportunity to observe the location and intensity of pests such as insects, diseases and weeds. The disadvantages of the tensiometer method include 1) the need to replenish the water in the tensiometer, 2) the installation of tensionmeters at 30 cm is often below the plow pan, a layer which severely restricts the redistribution of water and roots within the profile, 3) at least two measurements are required each week in order better to understand the soil water extraction patterns, and 4) the soil water pressures represent point measurements, which with several tensionmeters reflect the spatial variability in the field.

De Angulo (1988) examined the spatial and temporal variability of soil water pressure and other soil properties in soybeans grown on a Sharkey clay at Keiser. He found that the coefficient of variation (CV) of the soil water pressures at 30 cm declined exponentially with time after an irrigation. The %CV 14 days after an irrigation was about 25%. This %CV was used to determine the number of tensiometers required to be within difference of 5, 10 and 15 kPa from the field mean soil water pressure. His calculations showed that fewer tensiometers were needed as the difference from the mean increased. For example, at a CV of 25%, a total of 53, 13 and 6 tensiometers are required at 5, 10 and 15 kPa from the field mean soil water pressure.

Computer Simulation

Our second irrigation scheduling strategy was developed to ease the work involved in determining when to schedule soybean irrigations and to facilitate planning of irrigation applications. This strategy, developed over a number of years by Ferguson et al. (see Cahoon et al., 1990) uses a microcomputer-based program to assist in scheduling irrigations in the humid Mid-South. In the development of the computer program, three criteria were considered: 1) the program must be user friendly and require a minimum of day-to-day meteorological data; 2) the program is to be system based as opposed to field based;

and 3) the program should be useful as a prediction tool as opposed to a monitoring tool.

The Arkansas Irrigation Scheduler is available for stationary and towable center pivot, for furrow and for flood irrigation systems and currently has the capability for scheduling irrigation on soybeans, cotton, corn and grain sorghum. Once initialized, the system requires daily inputs of maximum air temperature, rainfall and irrigation amounts (for sprinkler systems only).

The program uses a soil water accounting method that determines the soil water deficit, which is defined as the soil water at the well-drained upper limit (field capacity) less the actual soil water content, integrated over the rooting depth. The water deficit for any day, then, is the soil water deficit from the previous day plus ET minus effective precipitation minus effective irrigation. Working from the perspective of soil water deficit as opposed to the absolute amount of available soil water makes the system much less complex and more useable from a grower standpoint.

The daily pan evaporation is calculated using an empirical relationship between pan evaporation (Etp) and daily maximum air temperature and day length. That relationship takes the form:

$$Etp = a + b*Tm^2 + c*Tm + d*DYL \qquad [12]$$

where Tm is the maximum daily air temperature, DYL is the day length, and a, b, c and d are regression coefficients that are specific for the location. Regression coefficients were determined for several locations in the Mid-South region. The term DYL is calculated internally in the program based upon day of the year and latitude and consequently is transparent to the program user. This equation predicts pan evaporation with accuracy similar to other minimum input equations and is sufficient for irrigation scheduling in humid regions where day-to-day variations in pan evaporation are relatively large (Cahoon et al., 1990).

Actual daily crop ET is calculated in the computer program as

$$ET = Etp*Cc*Cp \qquad [13]$$

where Cc is the crop coefficient, and Cp is the pan coefficient (0.86). The crop coefficient is dependent upon the crop and the growth stage and is modified if the soil surface is wet, such as following rainfall or irrigation. The crop coefficient for bare, dry soil starts at about 0.2 and parallels the development of crop leaf area index (LAI) up to an LAI of about 3.0 where the crop coefficient of most crops is taken as 1.0. Senescence and a consequent reduction of the crop coefficient is based upon age of the crop and day of the year.

The allowable soil water deficit is set by the user within guidelines recommended in the program. A soil water deficit of 50 mm is recommended and frequently used. The Scheduler program uses daily air temperatures and no rainfall to make a projection suggesting when the next irrigation should begin. It also takes into consideration other fields that need irrigating with the same irrigation system. The Arkansas Irrigation Scheduler has been used by extension agents, individual growers, consultants and others. Over 200 copies of the computer program were distributed throughout the Mid-South region in 1995.

Response of Cultivars

Annually, Dombek et al. (1995) conduct the soybean cultivar testing program in Arkansas. In 1994, the results indicated that cultivar, soil (location) and irrigation were important criteria in determining seed yield. The results are summarized by maturity group for two locations at which I and NI soybeans were grown and are presented in Table 25.

Seed yields of soybean were higher when grown under I than when grown under NI and on the clayey soil than on the silt loam soil. These yields are also considerably higher than those obtained in the extension verification demonstrations and on growers' fields. The yield differences were 1992 kg/ha and 714 kg/ha greater than the state average I yields and 793 kg/ha and 743 kg/ha on the NI state average yields, respectively.

Similar differences in yield due to maturity group were found when grown under I, but under NI conditions there were significant differences. The average NI seed yields were similar on the two soils. One particularly interesting observation is that within a maturity group, the %CV was higher with the NI soybeans than with the I soybeans. Bowman et al. (1993) concluded that irrigation for the purpose of improving statistical aspects of soybean performance trials may be productive sometimes but not always. The interactions between cultivar and water management created with irrigated trials require that I and NI yields be reported separately.

Long-term Economic Evaluation

Dillon et al. (1997) conducted an economic evaluation of the influence of I and NI on soybean production. Simulations were made for a 130-ha field of soybeans grown on a Crowley (DeWitt) silt loam at Stuttgart for 40 years. They found that the optimal unrestricted scenario for profit maximization was for I

Table 25. Summary of the yield data (kg/ha) by Dombek et al. (1995). RM, I and NI represent maturity group, irrigated and non-irrigated conditions, respectively.

Maturity	Soil textural class			
	Clay		Silt loam	
group	I	NI	I	NI
IV (<RM 4.7)	4502	2191	3562	3219
IV (RM 4.8 or 4.9)	4334	2399	2950	2903
V	4738	3313	3501	2675
VI	4610	3602	3058	2506
Mean	4546	2876	3268	2826

soybeans when double cropped with winter wheat. An average annual irrigation depth of 26 cm of water achieved a mean soybean yield of 2806 kg/ha and wheat yield of 3837 kg/ha. Full-season I soybean production was the next-most-profitable enterprise with a soybean yield of 3347 kg/ha from 28.3 cm of irrigation water. Dryland full-season soybeans had both the lowest returns and the greatest production risks.

Flooding Strategies

Flooding is a common occurrence in the humid regions of the world. Temporary flooding may result either from poor soil drainage following irrigation or heavy rain or from a rising water table because of net water movement into the root zone from adjacent areas. In addition, prolonged flooding can result from localized depressions at the land surface caused by tillage and harvesting operations and/or natural phenomenon and from application of excessive irrigation.

In Arkansas, a significant portion of the harvested soybeans is grown in rotation with rice, a crop that requires extensive amounts of water during the growing season. For the most part, these crops are grown on poorly drained, slowly permeable soils and irrigated by the flood method. Many growers have the facilities to flood irrigate both crops. The flood method is considered by some to be one of the most inefficient methods of irrigation; however, use of best irrigation practices results in little water lost from the field. The flood method of irrigation requires uniformly sloping fields so that the water can be readily removed from the surface. However, if the fields are large (> 20 ha) or have a low slope or numerous depressional areas, there may be difficulty in the timely removal of irrigation water from the field, particularly around the inlet. Similar problems associated with prolonged flooding occur during the growing season whenever an extensive rainfall event occurs. The result is water ponded on the soil surface, which restricts the exchange of gases between the soil and the atmosphere. Observations of soil and plant properties have indicated that the effects are spatially and temporally dependent (Scott and Oosterhuis, 1989).

The exchange of soil gases such as O_2 and CO_2 between the soil and the atmosphere is known as soil aeration. Flooding restricts the exchange of gases between the soil and the air, resulting in depressed O_2 availability to crop roots, microorganisms and nodules (Glinski and Stepniewski, 1985; Stolzy and Sojka, 1984). Restricted soil aeration limits the development of an efficient root system, impairs respiration of an established root system and prevents the orderly functioning of essential biological processes associated with optimum plant growth. Plant roots and nodules must be supplied with oxygen at a rate supporting maximum respiration or the plant will suffer. The response of soybeans to flooding depends on the cultivar, growth stage at flooding, duration of the flood and depth of the flood.

Soil Indicators

The effects resulting from the flooding of soil are relatively rapid compared with the effects from drought. Flooded (or waterlogged) soils have high water contents. Since the amount of O_2 in a given soil is roughly inversely proportional to the water content, waterlogged soils are characterized by the absence of O_2. If the soil contains sufficient organic matter and is biologically active, waterlogging will be followed by the rapid disappearance of O_2 and the reduction of the soil. The rate of reduction is directly related to the amount of fresh organic matter present, soil temperature, microorganism and root activity, soil chemical status and the duration of the flood. The soil aeration status is characterized by spatial and temporal measurements of oxygen concentration, oxygen diffusion rate (ODR) and redox potential (Eh).

Oxygen, which is primarily transported into a soil profile by diffusion, may be consumed as a result of 1) microbial respiration where it is used as an electron acceptor, 2) chemical oxidation of reduced ions such as Fe and Mn and 3) biological oxidation of NH_4^+ and C and perhaps sulfides. Over time with prolonged flooding, these processes result in the development of an oxidized (aerobic) layer at the soil surface.

Upon depletion of O_2 in the soil by microorganisms and plant roots, many soil microorganisms use alternate compounds as electron acceptors. If an energy source is available to the organisms and sufficient time is allowed and an appropriate soil temperature exists, a sequence of reduction of oxidized compounds occurs in the soil. Nitrate, nitrite, the higher oxides of Mn, hydrated ferric oxide and sulfate may be reduced sequentially. Therefore, flooded soils are characterized by increased concentrations in the soil solution of reduced ions such as Fe^{2+}, Mn^{2+}, NH_4^+ and S^{2-}. These ions subsequently become readily available for plant uptake. In addition, under anaerobic conditions organic substrates may not be decomposed completely to CO_2. Intermediate compounds, including lactic acid, ethylene, ethanol, acetaldehyde and aliphatic acids, may be present in abnormally high concentrations in anaerobic soils and may affect plant growth.

Flooding also affects surface strength and the rate of movement of water in the profile. Puddled soils have low strength and restricted soil water movement. Soft, low-strength soil reduces trafficability, making it difficult to use large combines for harvest and other field work, which may cause ruts and depressional areas in the field. Therefore, the fields should be drained long before harvest. Saturation during prolonged flooding also increases water lost by internal drainage and surface runoff. Flooded upland fields with smectitic clays tend to have saturated surface horizons and unsaturated subsoils. Lowland areas with high ground water levels tend to have saturated subsoils. Water lost by internal drainage is water not available to the plant roots.

Plant Indicators

Upon flooding, the depletion of the remaining soil O_2 by microorganisms and roots leads to changes in several physiological processes within the plant, changes that, in turn, influence crop growth and survival. Since soybean roots are exposed to the adverse soil aeration conditions, it is expected that changes occur in the uptake of water, gases and nutrient elements. Restricted soil aeration limits the development of an efficient root system, impairs respiration of an established root system and prevents the orderly functioning of essential physiological processes associated with optimum plant growth.

The detrimental effects of waterlogging on soybean growth are usually attributed to inadequate O_2 supply to sustain root respiration and nodule functions. In the absence of O_2, root respiration may proceed along a fermentative pathway, rapidly consuming the available pool of stored carbohydrates. Instead of CO_2, alcohol is the predominant byproduct released. Active uptake of nutrients is greatly decreased due to the slowing of energy conversion. Until O_2 is depleted from the flooded soil profile, shoots continue to respond as though irrigated. However, when soil O_2 is depleted, eventually plant growth processes such as dry matter accumulation, height, leaf area and elemental contents are affected. These changes are in part responsible for the variable susceptibility or resistance to flood injury and related disease.

Examples of Soil and Crop Response to Prolonged Flooding

The results of several field studies have been published on prolonged flooding of soybeans grown in eastern Arkansas (Spooner, 1961; Scott et al., 1989; Scott et al., 1990; Oosterhuis et al., 1990; Sallam and Scott, 1987). Soil and crop characteristics have been monitored over time in order to evaluate the changes that occur upon flooding.

First, prolonged flooding studies of soybeans were conducted in 1982 at RREC on a Crowley (DeWitt) silt loam. Forest soybeans were flooded for seven days at a constant flood height of 3 cm at two growth stages, V4 and R2. Variations in selected soil characteristics as a function of time after flooding are shown in Figs. 14 and 15. Immediately after flooding, values of Eh and ODR at the 1-cm soil depth declined until two days after the flood was removed (Fig. 14). This indicated that oxygen was removed from the soil, resulting in depressed soil aeration. The Eh values indicate that the reduced forms of Mn and Fe should become more available for plant uptake. After the flood was removed and the soil began to dry, values of Eh and ODR increased, indicating that soil aeration improved as oxygen diffused into the profile. Temperatures at two soil depths near the surface after flooding are shown in Fig. 15. During the flood, soil temperatures in the flooded plots were 4-5 C lower at the 1-cm depth and 2-4 C lower at the 10-cm depth than in the control plots at 1300 hours. After the flood was removed, the differences in soil temperature between the two treatments at a given depth decreased.

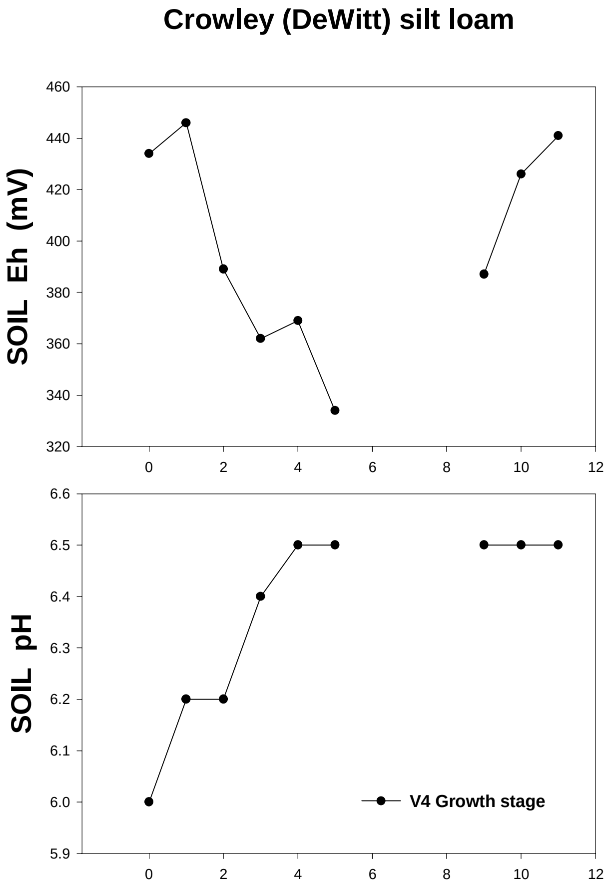


Fig. 14. Temporal distributions of redox potential (Eh) and oxygen diffusion rate (ODR) during and after flooding of soybeans grown on a Crowley (DeWitt) silt loam.

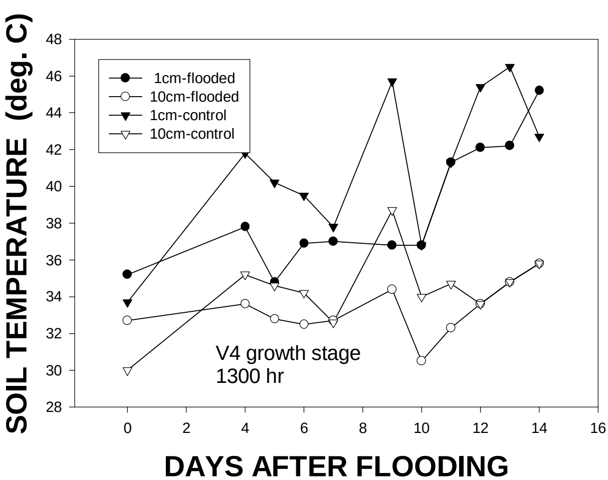


Fig. 15. Temporal distributions of soil temperature at two depths during and after flooding of soybeans grown on a Crowley (DeWitt) silt loam.

The effects of prolonged flooding also were found on soybean growth and development. At maturity, plant heights, dry weight and elemental accumulation of nutrients were depressed as compared to the controls. By late September, the soybeans flooded for seven days at V4 had higher average concentrations of N, P and K and lower average dry weights than the well-irrigated controls (Fig. 16). The soybeans flooded at R2 had lower average concentrations of N, P and K and higher concentrations of Na, Mn and Fe than the controls. Dry weights and accumulations of the elements were also affected by growth stage at flooding. The soybeans flooded at R2 had lower dry weights and accumulations of N, P, K, Ca and Mg and higher accumulations of Na, Fe and Mn than the controls.

Scott et al. (1989) determined the influence of prolonged flooding on soybeans grown on two poorly drained, slowly permeable soils, a Sharkey clay and a Crowley (DeWitt) silt loam (Table 26). Evaluations were made of the growth, development and seed yield of eight determinate soybean cultivars belonging to MG V and MG VI. The flood was continuously ponded 3 cm above the soil surface at either the V4 or R2 growth stages for 2, 4, 7 or 14 days. Soil water pressures were monitored at four depths in the profile. Flood duration effects on the above-ground soybean plant were manifested in yellowing and abscission of leaves at the lower nodes, stunting and reduced dry weight and seed yield. Canopy height and dry weight decreased linearly with duration of the flood at both growth stages. The growth rates were 25 to 35% less when the soybeans were flooded at the R2 growth stage than when they were flooded at V4. A linear relationship was found between seed yield and monthly average crop growth rates for the four weeks following flooding. A linear decrease in seed yield with flood duration was also found. On the Sharkey clay, rates of seed yield reduction were 157 and 124 kg/ha/day of the flood for the soybean flooded at R2 and V4, respectively. On the Crowley (DeWitt) silt loam, seed yield reduction rates were 101 and 53 kg/ha/day of the flood duration for the soybean flooded at R2 and V4, respectively. Crop susceptibility factors (CS) were determined by dividing the decline in yield by the unstressed control, when the two-day flooded soybean cultivars were considered as the controls. Values of CS ranged from 0 to 0.6 and were linearly related to flood duration after two days. The slopes of the lines were 1.5 times greater for the flood applied at R2 than for the flood applied at V4, and 2.4 times greater with the soybeans grown on the Sharkey clay than with those grown on the Crowley (DeWitt) silt loam. This showed that the determinate soybean cultivars were more susceptible to prolonged flooding during early reproductive growth than during early vegetative growth and when grown on the clayey soil than when grown on the silt loam.

Seed yields of the soybean cultivars ‘DPL 105’ and ‘Ring Around 604’ tended to be the highest, whereas yields of ‘Essex’ tended to the lowest. For a given cultivar, seed yields were lower on the Sharkey clay than on the Crowley

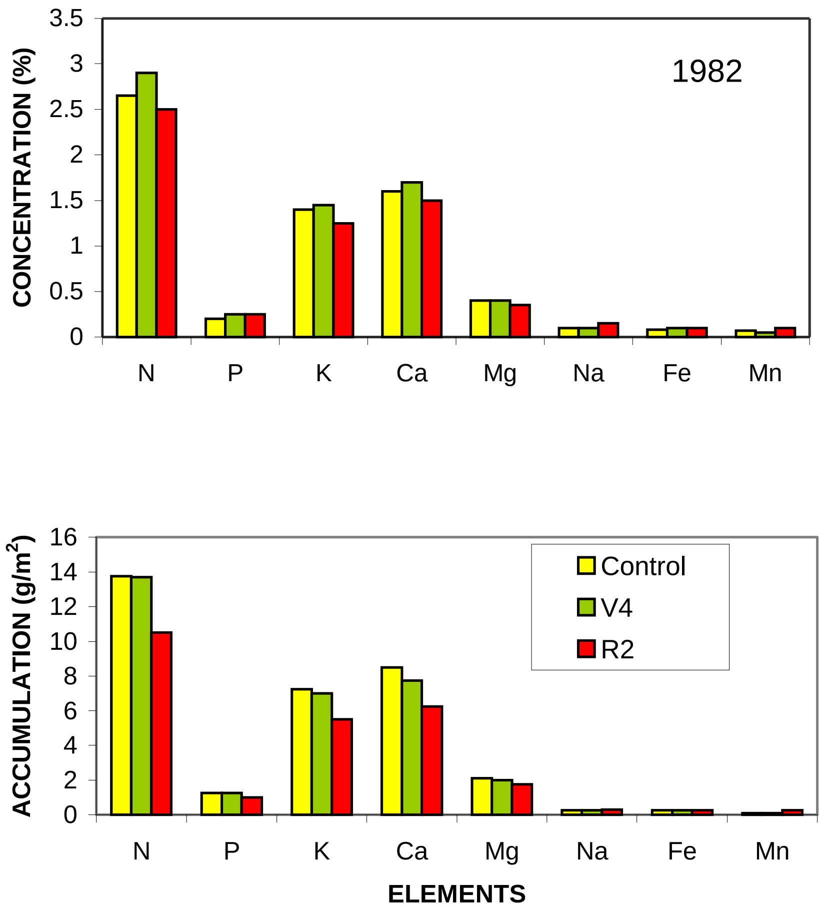


Fig. 16. Influence of flooding on the concentration and accumulation of nutrient elements by soybeans grown on a Crowley (DeWitt) silt loam. The analyses were made 23 September 1992.

Table 26. Relationship between the soybean growth stage and seed yield when flooded at two growth stages on two soils.

Soil	Growth stage	Mean	Yield Range	SD[1]	%CV
		----------------	----------kg/ha----------	----------------	
Crowley	V4	3027	521	182	6.0
(DeWitt)	R2	2539	509	167	6.6
Sharkey	V4	1814	999	312	17.2
	R2	1305	878	297	22.7

[1]SD = significant difference.

(DeWitt) silt loam and when flooded at R2 than at V4. The variability in yield within the same group of cultivars was higher on the clayey soil and at the R2 growth stage.

The influence of temporary flooding on selected soil properties and soybean response at three growth stages on a Sharkey clay was reported by Scott et al. (1990). Eight determinate soybean cultivars were flooded for seven days at a constant flood height of 3 cm. The control soybeans were flood irrigated for 6 hours four times during the growing season as scheduled by the tensiometer method. Soil indicators measured included soil water pressure, Eh, ODR and pH. Plant response was determined from canopy height, above-ground dry weights and elemental concentrations.

Values of soil Eh at 1 cm corrected to pH 7 tended to decline after the flood from a high of 443 millivolts (mV) before flooding to a low of 292 mV, which was found on day 9, i.e., two days after the flood was removed. These Eh values indicated the disappearance of oxygen and nitrate and the appearance of reduced forms of Mn and Fe in the soil solution (Turner and Patrick, 1968). After the flood was removed, values of Eh gradually increased in response to drying of the soil. Little change was found in soil pH during and for one week after the flood with an average pH of 6.4. Temporal relationships of ODR were correlated with those of Eh. A gradual decrease in ODR occurred during and for two days after the flood was removed. This was followed by a gradual increase in ODR after the flood was removed. The decrease in ODR while the soil was flooded was attributed to the swelling of the clayey soil and to the extraction of oxygen by microorganisms and plant roots. After the flood was removed, ODR increased as soil water pressure decreased.

Canopy heights of the determinate soybeans increased during the growing season to a maximum during late August. On a given date, canopy heights were dependent on the growth stage at the initiation of the flood. In comparison with the control treatment, prolonged flooding tended to inhibit the increase in plant height for a short time period. The soybeans flooded during vegetative growth tended to recover to some extent as evidenced by increasing height. However, they remained stunted in comparison to the control soybeans. Canopy heights of the soybeans at flooded R2 decreased during the remainder of the growing season, due to lodging. As a result, canopy heights of the flooded soybeans were always lower than those of the control soybeans.

Dry weights increased during the growing season for all treatments, but the magnitude was influenced by the growth stage at the time of flooding. Usually for one to two weeks after prolonged flooding, dry weight remained constant then recovered. Flooding at R2 significantly reduced dry matter accumulation at maturity.

Plant concentrations of the various nutrient elements varied during the growing season and with flood treatment. Concentrations of N in the flooded soybeans soon after the flood was removed were lower than those of the control soybeans. This was attributed to a reduction in the fixation and uptake of N, which was caused by the lack of oxygen and perhaps by denitrification. During vegetative growth, N concentrations in the soybeans increased to values higher than the control within three weeks after the flood was removed. Apparently, drying of the wet soil contributed to the increased activity of the nodules, resulting in higher fixation rates and concentrations of N in the above-ground portion of the plant. Flooding at R2 significantly reduced the plant N concentration during much of the reproductive portion of the season. However, at physiological maturity N concentrations were similar to those for the control soybeans, indicating a recovery of these soybeans. Concentrations of Mn, Fe and Al were much higher in the soybeans flooded at R2 than in the other treatments. This indicated that the soybeans flooded at R2 accumulated these elements to a greater extent than those grown in the other treatments. Concentrations of Ca, Mg and Na were similar in the flooded and non-flooded soybeans, indicating that flooding had little or no effect on the availability of these nutrient elements in the soil.

Seed yields were influenced by growth stage at flooding, cultivar and growth stage-cultivar interaction. The highest seed yields were obtained with the controls, followed by the yields of the seven-day flood at V1 and V4 growth stages. Both yields were lower but not significantly different from the yields of the controls. The lowest seed yields were obtained from those soybeans flooded for seven days at the R2 growth stage.

Oosterhuis et al. (1990) examined the short-term effects of flooding on several soybean physiological parameters at V4 and R2 growth stages. The cultivars were grown on a Crowley (DeWitt) silt loam. Diurnal measurements of net photosynthesis, stomatal conductance (g) and components of leaf water potential were recorded on two cultivars, Essex and Forest, on four consecutive days following flood application and again at 14 days after the flood was removed. Photosynthesis of Essex was reduced significantly within 48 hours of flooding by 33 and 32% for the V4 and R2 growth stages, respectively, while reductions of 16 and 22% in photosynthesis of Forest were evident. Reductions in stomatal conductance of 46 and 24% occurred within 48 h for Essex and Forest in the V4 stage, although in the R2 growth stage both cultivars experienced an approximate 48% reduction in stomatal conductance. However, the decline in photosynthesis with flooding was only partially explained by changes in g. Photosynthesis was correlated with stomatal closure at low g, but at higher values of g, an approximate 20% reduction in photosynthesis was observed, presumably due to non-stomatal limitations. Flooding did not affect components of leaf water potential, indicating that the decreases in photosynthesis and g were not associated with plant water-deficit stress. Flooding of Essex and Forest at either the V4 or R2 growth stage significantly reduced the dry matter accumulation during the flooding treatment and the subsequent growth. Final seed yields were reduced significantly by 52 and 40% for Essex and Forest, respectively. Overall, the Forest cultivar appeared more tolerant to excess water than did Essex.

Sallam and Scott (1987) examined the effects of prolonged flooding at V1 and V4 growth stages of soybeans grown on Crowley (DeWitt) silt loam, emphasizing root parameters. Maturity Group V Forest soybeans were subjected to a seven-day flood with a constant flood height of 2.5 cm. Prolonged flooding significantly reduced all soybean root and shoot growth parameters. Linear relationships with positive slopes were found among root extension, root area and root weight. Flooding at the V1 growth stage completely inhibited root nodulation during the time of measurement. The shoot:root ratio, which was greater at V4 than at V1 for the flooded and the controls, increased with time after flooding for both growth stages. Seven days after the flood was removed, the shoot:root ratio was significantly lower in the flooded soybeans than in the controls.

APPLICATION OF WATER MANAGEMENT STRATEGIES

Irrigation

Extractable Soil Water

The influence of extractable water in the soil profile, W, on the water absorbed by soybean roots during wet and dry seasons was illustrated by Scott (1980). Data were presented for the relationships between the percent extractable (or available) water in the soil profile and time during the growing season for soils having either 10 and 20 cm of extractable water in the root zone. For purposes of the study, the soybeans were considered to be drought stressed when the soil water content in the profile decreased below the critical threshold of 0.30*W. The number of days the water content remained below this value was designated as the number of drought days. The data showed that soybeans grown on soils with greater amounts of extractable water experienced a lower number of drought days, regardless of the rainfall distribution during the growing season. Therefore, the greater the value of W, the less droughty the soil. Soybeans grown on soils with lower W required irrigating sooner in the season and required a greater number of irrigations during the season. From a water-management perspective, soils with greater values of W usually are best suited for soybean production.

Row Spacing and Plant Population

Water availability and water use rates as affected by row spacing have become major considerations in soybean production, particularly in the drier regions of the U.S. Results of numerous studies have shown that soybean yields are frequently increased by planting in narrow rows up to some threshold density. Increased yields from narrow rows can vary with seeding rate and cultivar.

Double Cropping

Double cropping (DC) of soybeans and wheat has proved successful under the longer growing seasons in the southeastern U.S. Between 25 and 40% of the soybean cropping area is doublecropped with soybeans, usually following a small grain such as wheat. Double cropping has been successful in the southern U.S. with soybeans as the second crop. Since weather plays a major role each year in determining the yield and the quality of grain and soybean produced, variable results from one year to the next were directly related to the amount of rainfall between planting and emergence, suggesting the increased importance of water management in DC systems.

In Georgia, Boerma and Ashley (1982) evaluated the effects of late and ultra-late planting dates in two row widths (51 and 91 cm) for I and N soybeans over three years. The late and ultra-late planting dates ranged from 5 to 10 weeks later than the full-season crop. They found that delays of planting from early July to late July resulted in an average yield reduction on the I plots of 53 kg/ha/day and 19 kg/ha/day for the NI treatments. In a dry season, I increased yield 355% in the late planting and 115% in the ultra-late planting. In an intermediate rainfall season, I increased yield 38% for the late and 15% in the ultra-late planting. The 51-cm row averaged 17% higher yield than the 91-cm rows when averaged over all years. Both I and NI treatments received an initial irrigation to obtain a stand, which points out the importance of timely water status at planting.

The magnitude of the yield reduction from delays in planting can sometimes be offset by irrigation in order to obtain maximum yields from late-planted soybean. Without irrigation, the yield decrease from the delay until adequate rainfall was received would be even larger. Under present management schemes, the late-planted soybean usually has a lower-yield potential.

Water use was quantified in a three-year field study of DC wheat and soybean at Fayetteville by Daniels and Scott (1991). They found that sprinkler irrigation significantly increased soybean yield in two of three years (Table 27). The three-year mean was 2406 kg/ha and 1704 kg/ha for I and NI soybean, respectively. When irrigation significantly increased yield, the I soybean had a higher WUE than NI soybean (Table 28). Planting date had a significant effect on soybean yield and WUE in only one of three years and only when planting date was confounded with row spacing. Burning of wheat stubble produced significantly higher soybean yields only when herbicide interference by standing wheat stubble was observed. Stubble management had no effects on soybean ET or WUE. When averaged over the three years, the combined yield of DC wheat and soybean was 5576 and 4874 kg/ha for the I and NI soybeans, respectively. For the DC system, the combined ET was 70.3 and 58.3 cm for the I and NI soybeans, respectively. The three-year mean WUE for the cropping system was 79.3 and 83.6 kg/ha cm of water for the I and NI systems, respectively.

Table 27. Grain yields of wheat and soybean during a three-year study.

	Seed yield (kg/ha)		
Year	Wheat	Irrigated soybean	Nonirrigated soybean
1986	2090	2174	1730
1987	3360	2249	2040
1988	4060	2794	1343
Mean	3170	2406	1704

Table 28. Water used and water use efficiency by the wheat and soybeans during a three-year study.

	Cropping system		
Year	Wheat	Irrigated soybean	Nonirrigated soybean
		Evapotranspiration(cm)	
1986	38.7	43.6	-
1987	33.1	38.0	28.6
1988	26.7	31.0	22.4
Mean	32.8	37.5	25.5
		Water use efficiency (kg/ha cm)	
1986	54.0	47.0	-
1987	102.0	59.2	70.6
1988	152.0	90.1	60.0
Mean	96.6	64.1	66.8

Drought Avoidance

In recent years, there has been a trend in the Mid-South region to include use of early soybean production systems (ESPS) to lower production inputs and improve yields. Early-maturing soybean cultivars such as those in maturity groups III and IV have been used more frequently over the past several years in the southern region of the U.S. The advantages of ESPS primarily include

1. some drought avoidance,
2. good yield potential on marginal and nonirrigated land,
3. better pricing options due to harvest occurring as much as six weeks earlier than for conventional cultivars (MGs V and VI),
4. shorter management system,
5. risk reduction and
6. effect on weed spectrum.

In contrast to traditional cultivars, early-maturing soybean cultivars offer drought avoidance. Compared with the regularly planted soybeans, early-season soybeans are exposed to the lower ET, higher rainfall and lower air temperatures during the early portion of the growing season.

In southeastern Arkansas, studies conducted by Vories (1997) have shown that MG III and IV cultivar yields equaled those of MG V and VI when irrigated, with all yields averaging 3610 kg/ha. MG III and IV cultivars yielded as well as or better than conventional cultivars with an average of two to three fewer irrigations. Also, harvest of the early-maturing cultivars occurred as much as six weeks earlier than that of the later-maturing MG V and VI cultivars in the same trial. The highest reported yield has been 5046 kg/ha with flood irrigation on MG III and IV cultivars.

The disadvantages of ESPS include the following.

1. March and April are typically cool and wet, conditions favoring disease pathogens such as phytophthora root rot, stem canker and sudden death syndrome. Cool weather may also cause soybeans to emerge slowly and be competitive to those weed species better adapted to these weather conditions.
2. Since the seed of MG III and IV cultivars were developed and produced in the more northern areas of the U.S., these cultivars may not be as resistant to cyst nematodes as those cultivars produced in the South.
3. The seed produced in the southern region of the U.S. may have a lower germination percentage and seed quality.

Nutrient Placement and Addition

Little information is available on irrigation effects and the placement of nutrients on soybean yield. Lutz and Jones (1975) evaluated the effects of irrigation and the placement of lime, P, K and micronutrients on the yield and composition of soybean on a Davidson clay loam in Virginia. They found that soybean yields were increased each year with irrigation with an average annual increase for three years of 0.51 Mg/ha or 22%. Yields were unaffected by P and K treatments during the first two years, but in the third year, yields were lower where the P and K had not been applied. Fertility treatments did not affect the oil or protein concentration in the seed, nor did they affect the yield. Irrigation appeared to have little influence on the oil and the protein concentration of the soybean seed. No interactions of irrigation and nutrient placement were reported for seed yields or oil and protein concentrations.

In Arkansas, Sabbe and DeLong (1997) found no significant effects of P and K additions on yields of selected soybean cultivars in maturity groups IV, V and VI grown on two soils: Desha and Calloway silt loams under I and NI conditions. Two fertilizer rates were broadcast incorporated prior to planting of eight cultivars. The main effects of irrigation were significant, resulting in an average increase of about 1485 and 974 kg/ha on the Calloway soil in 1995 and 1996, respectively and 1942 and 927 kg/ha on the Desha soil in 1995 and 1996, respectively. They concluded that on these soils the selection of the cultivar had a greater effect on yield than fertilizer application.

Tillage

Tillage has long been considered an essential crop production practice, with one benefit being increased water conservation through runoff control and improved infiltration. Although tillage has been extensively criticized in recent years, it improves infiltration of water and controls or prevents runoff on some soils. This is accomplished by changing parameters such as surface roughness, creation of micro-depressions, loosened compacted layers, creation of furrows, land forming, etc. (van Doren and Reicosky, 1997).

Infiltration of water is influenced by conditions at the soil surface, in the tillage layer and within the profile. Surface and tillage layer factors affecting infiltration include soil aggregation, surface roughness and porosity, surfactants and water repellents and crop residues. Profile factors include depth to slowly permeable or impervious layers, soil texture and type of clay and previous crop, especially with regard to rooting types and depths and residual soil water content (Unger and Stewart, 1983).

Conservation tillage rates among the top advances in crop production practices in recent agricultural history. Among the many benefits ascribed to conservation tillage is decreased runoff, which decreases soil erosion and increases water conservation. The large decreases in runoff result from surface residues, which are an integral part of the systems. Surface residues dissipate the energy of falling raindrops, thus protecting surface soil from dispersion, decreasing surface sealing and increasing infiltration. Surface mulches decrease runoff and evaporation.

Keisling et al. (1995) conducted a three-year tillage study on NI soybeans grown on Sharkey silty clay and Calloway-Loring-Henry silt loam. Pre-plant tillage consisted of disking once or twice with a finishing disk harrow and following this operation with a Do-All. Post-plant tillage, which consisted of plowing with a cultivator as necessary to control weeds or to break up soil crusting. No interaction was found between pre-plant and post-plant tillage (Table 29). Neither type of tillage affected the yield of soybean on Sharkey clay. Both types of tillage affected the yields on the Calloway-Loring-Henry silt loam during a dry growing season (1993), pre-plant tillage having four times the effect of post-plant tillage. During the wet growing seasons (1992, 1994), neither pre- nor post-plant tillage affected soybean yields on the silt loam soil.

Flooding

Several management practices have been developed to overcome the detrimental effects of waterlogging.

Surface Drainage

Surface drainage with precision land leveling assures timely field operations and optimum crop growth on slowly permeable, alluvial soils. The elimination of water ponding in surface depressions allows the surface layers of soil to dry

Table 29. Soybean yields as affected by tillage.

Soil texture	Year	Tillage: Pre-plant Yes	Pre-plant No	Post-plant Yes	Post-plant No
		kg/ha			
Clay	1992-1994	3232	3286	3252	3273
Silt loam	1992	2016	1888	2029	1882
	1993	1801	1068	1519	1344
	1994	2500	2460	2466	2486
	1992-1994	2090	1814	2009	1888

Source: Keisling et al. (1995).

faster and reduces the amount of water infiltrating and redistributing through the soil profile.

Time and Length of Flood

Scott et al. (1989) conducted a prolonged flooding study with eight soybean cultivars grown on two soils and at two growth stages. The results are presented in Table 30.

The percent daily yield reduction was calculated by dividing the slopes of the regression lines by the yields of the two-day flooded soybean. For the soybeans grown on the Sharkey clay, the percentage daily reductions in yield were 5.0% and 7.7% for the V4- and R2-flooded soybeans, respectively. For the soybeans grown on the Crowley (DeWitt) silt loam, the daily reductions were 1.6% and 3.6% for the same growth stages, respectively. When expressed as daily yield loss, these reductions translated to 53.4 and 100.8 kg/ha/day on the Crowley (DeWitt) silt loam and 124.4 and 153.2 kg/ha/day on the Sharkey clay. These differences indicate that the daily rate of yield losses due to prolonged flooding was greater on the clay soil than on the silt loam and at the R2 growth stage than at V4.

Table 30. Effects of flood duration on the average seed yields of soybeans grown on two soils in eastern Arkansas.

Days of flood	Crowley (DeWitt) V4	Crowley (DeWitt) R2	Sharkey V4	Sharkey R2
	kg/ha			
2	3231	2796	2491	2281
4	3130	3188	2054	1688
7	3160	2366	1778	896
14	2586	1809	930	355

Nitrogen Fertilizer Application

Scott and Wells (unpublished data) broadcast two types of N fertilizers to flooded Forest soybeans grown on a Crowley (DeWitt) silt loam. Several broadcast rates of N fertilizer ranging to 100 kg/ha of NH_4NO_3 and urea were applied within two days after the flood had been removed from the soybeans that had been flooded for seven days at the V4 growth stage. The results indicated that the broadcast applications of N did not increase the ability of the soybeans to recover from prolonged flooding.

EFFECTS OF WATER MANAGEMENT ON SOIL WATER STATUS

A field experiment was conducted in 1976 to determine the effects of water management of soybeans on seed yield and on the spatial and temporal distributions of the soil physical properties water content, water pressure and plant extractable water. The study was conducted on two soils: a Kobel silty clay, which has been reclassified as a Sharkey silty clay at the Delta Branch Experiment Station (DBES) at Clarkedale, Arkansas, and a Crowley (DeWitt) silt loam at RREC near Stuttgart. General characteristics of the soil and yield response of the Lee 74 soybeans to the water management treatments are found in Scott et al. (1986b). In this document, we explore the same dataset to a greater extent.

Kobel (Sharkey) Clay

At DBES, only 12.2 cm and 0 cm of rain were recorded during July and August, respectively, i.e., the two middle months of the growing season. Water was applied to the I soybeans by the furrow method four times during this period: 21 July, 28 July, 11 August and 20 August using tensiometer irrigation scheduling. Irrigations were scheduled whenever the soil water pressure at the 30-cm depth was approximately -500 cm. This soil water pressure was chosen in order to control the development of cracks in the shrinking-swelling clayey Sharkey soil, which aided the management of water during irrigation and prevented significant drought stress of the crop. The NI soybeans received only rainfall. Seed yields reflected the amount of water received and were 2789 and 1633 kg/ha for the I and NI soybeans, respectively.

Water content in the soil profile was measured gravimetrically six times during the growing season in the row to a depth of 100 cm (Fig. 17) and converted to volumetric water contents. On 8 June, which was approximately two weeks after planting of the soybeans, the water contents approximated the amount of water retained in the soil profile before significant drought stress occurred. With the exception of that near the soil surface, the highest soil water contents in the Sharkey profile were measured 8 June. Over time, water was removed from the soil profile due to extraction by soybean roots, drainage beyond the root zone and evaporation at or near the soil surface. As the growing season progressed, more soil water tended to be removed from deeper depths of the profile in both soil water management treatments.

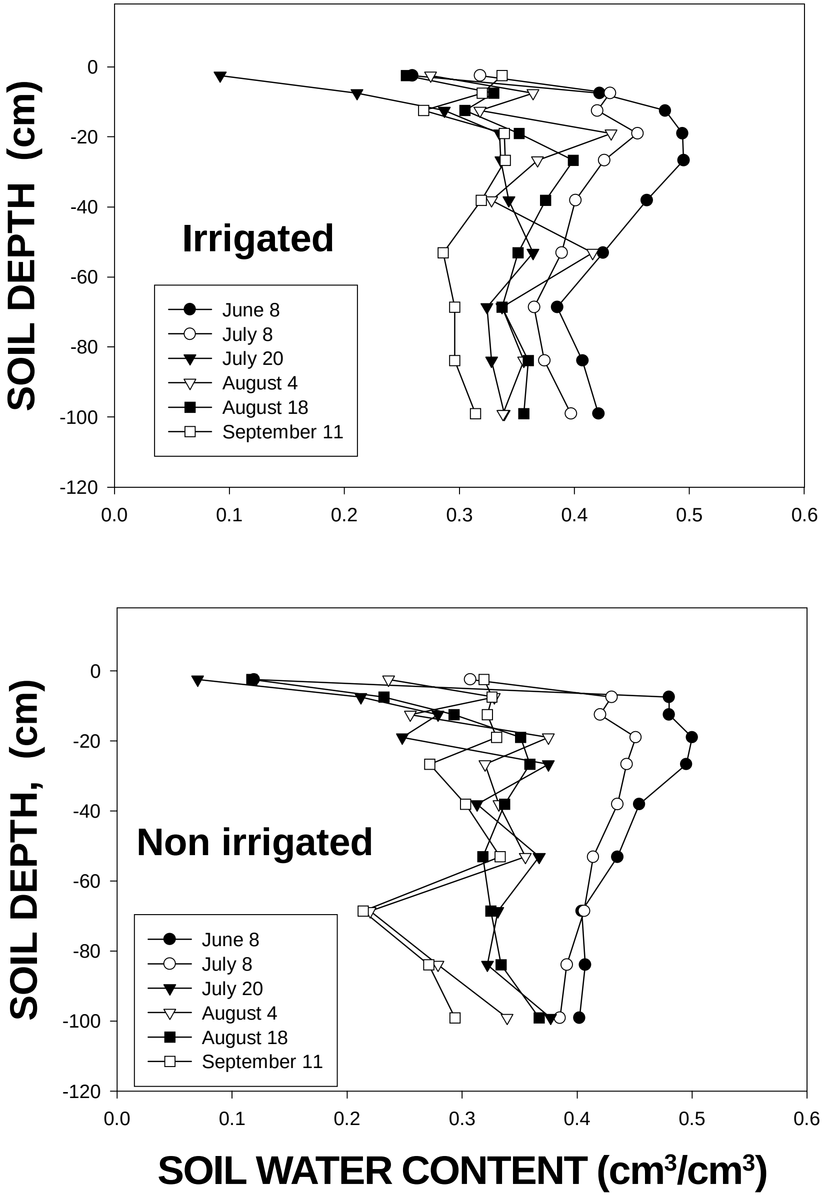


Fig. 17. Soil water content distributions of irrigated and nonirrigated soybeans grown on Sharkey silty clay at Clarkedale.

The range of water contents in the Kobel (Sharkey) profile during the growing season was determined at a given depth by subtracting the lowest recorded volumetric soil water content (i.e., the lower limit) from the highest recorded volumetric soil water content (i.e., the upper limit) regardless of the water management treatment (Fig. 18). These differences in water content between the upper and lower limits in the profile indicate that considerable amounts of water were removed from the deeper depths of the Sharkey soil in both water management treatments. Also, the fact that the upper and lower limit water content curves did not come together at 100 cm indicates that some extraction of soil water occurred at depths below 100 cm.

The differences in soil water content in the profile were highest at or near the surface and decreased exponentially with depth (Figure 18). Using regression techniques, the exponential decay models for the differences in water content were

Irrigated soybeans

$$\Delta\Theta(z) = 0.224*\exp(-0.0094)z \quad R^2 = 0.999 \qquad [13]$$

Nonirrigated soybeans

$$\Delta\Theta(z) = 0.257*\exp(-0.0084)z \quad R^2 = 0.999 \qquad [14]$$

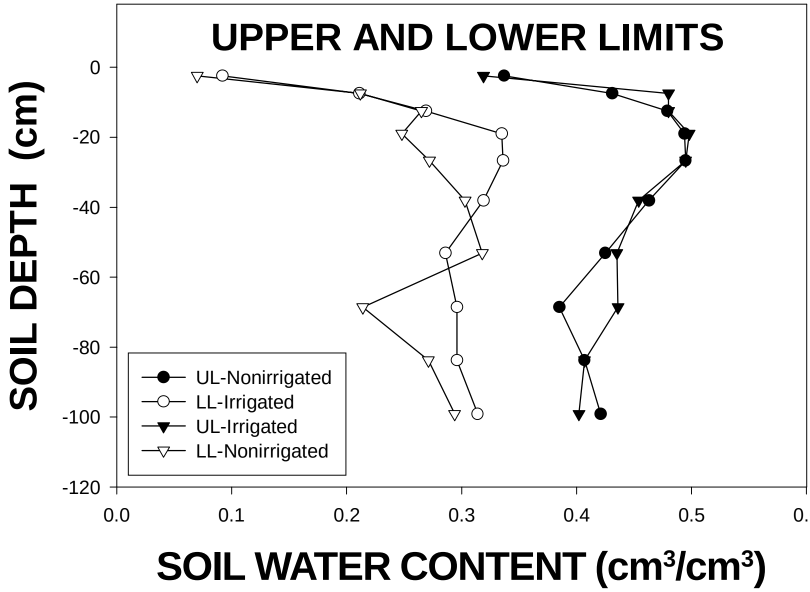
where $\Delta\Theta$ is the difference in volumetric soil water content (cm^3/cm^3) between the upper and lower limits and z is the soil depth (cm), positive downward. Since the internal unsaturated movement of water in the Kobel (Sharkey) soil is slow and evaporation occurs primarily at the surface and through secondary cracks, the removal of water from the Sharkey profile was primarily due to root extraction. According to the regression models, the NI soybeans had a slightly greater $\Delta\Theta$ at the surface and lower curvature than the I soybeans. This indicates that a greater range in water content was found.

The distribution of soybean root length density in the row measured in the same plots at the R2 growth stage in the previous year (Scott et al., 1986b) is shown in Fig. 19. At this physiological growth stage, soybeans have developed their root system almost fully and explored the soil profile. Interestingly, the root length distribution in the Kobel (Sharkey) profile also could be modeled with an exponential decay with depth. The regression model was

$$RD(z) = 2.49*\exp(-0.03615)z \quad R^2 = 0.999 \qquad [15]$$

where RD is the root length density (cm/cm^3), which is a function of soil depth z. The fact that both root length density and seasonal soil water extractions were exponentially related to depth serves to verify the impact of the soybean roots on extraction of water from the Kobel (Sharkey) profile.

Combining equations [13] or [14] and [15] gives values of $\Delta\Theta(z)$, which were related to RD by the regression equation



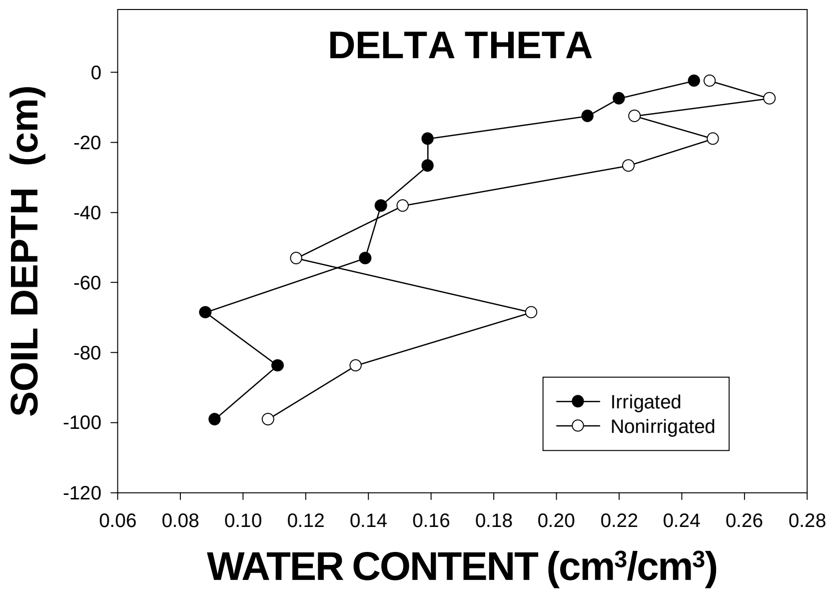


Fig. 18. Relationships between the upper and lower limits and volumetric soil water content and between ΔΘ and volumetric water content of the Sharkey silty clay loam.

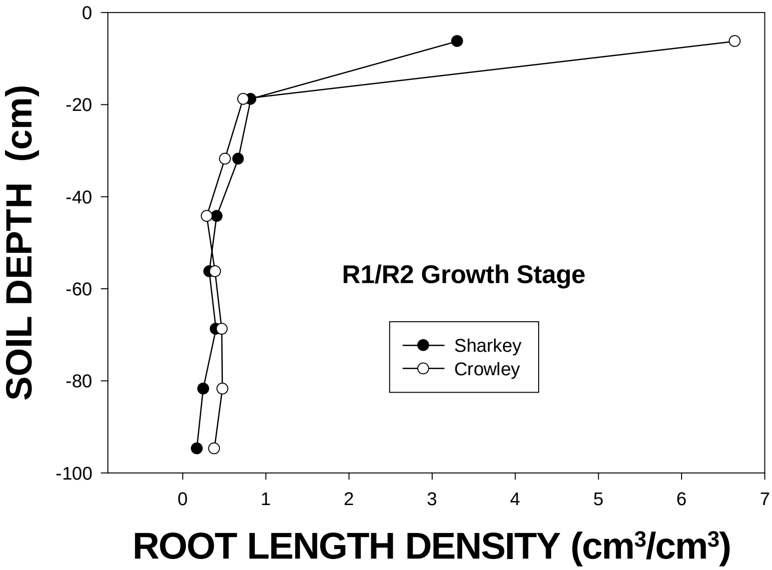


Fig. 19. Root length density distributions in the Sharkey and Crowley (DeWitt) soils during 1975 at the R1/R2 growth stages.

Irrigated soybeans

$$\Delta\Theta(z) = 0.177 + 0.0355*\text{LnRD} \quad R^2 = 0.987 \qquad [16]$$

Nonirrigated soybeans

$$\Delta\Theta(z) = 0.208 + 0.0382*\text{LnRD} \quad R^2 = 0.990 \qquad [17]$$

This shows that the seasonal extractions of soil water in the Sharkey soil were highly correlated with the natural logarithm of root length density of soybeans at the beginning of reproductive growth. The NI soybeans had a slightly greater intercept and slope than the I soybeans.

The ratio $\Delta\Theta$/RD was computed to estimate the efficiency of the roots for extraction of soil water. The efficiency term has units of cm^3 of water/cm of root length. Values of the ratio were regressed against depth in the profile, and the resulting equation was

Irrigated soybeans

$$\Delta\Theta/\text{RD} = 0.090*\exp(0.0268z) \quad R^2 = 0.999 \qquad [18]$$

Nonirrigated soybeans

$$\Delta\Theta/\text{RD} = 0.103*\exp(0.0278z) \quad R^2 = 0.994. \qquad [19]$$

These regression equations indicate that the efficiency of extraction of soil water by the roots increased exponentially with depth and that the NI soybeans were slightly more efficient than the I soybeans.

The plant-extractable water for soybeans grown on the Sharkey soil was estimated by integrating the area between the distributions of upper and lower limit volumetric water contents to a depth of 100 cm. For soybeans grown on the Sharkey silty clay, the depth of plant-extractable water was 17.9 cm. This is considered to be a relatively high amount of extractable water; however, not all of this water is available to the plant during the early growth stages due to the limited exploration of the root zone.

Soil water pressures were measured with tensiometers placed in the soybean row beginning in early July. Differences were found in the spatial and temporal distributions of soil water pressures due to water management (Fig. 20). The soil water pressures at 30 cm were the most dynamic, reflecting the greater activity in extraction of water by the soybean roots near the soil surface and the additions of water. At the 30-cm depth, values of water pressure decreased rapidly beginning in early July, due primarily to the extraction of water by the roots at this depth. In the NI plots, soil water pressures were beyond the operational range of the tensiometers between 20 July until the 4.6-cm rain 29 July. After 9 August, the water pressures at this depth were beyond the operational range of the tensiometers. In contrast, the tensiometers in the I plots continued to operate properly and showed the seasonal fluctuations in soil water pressure due to the gains of water from rainfall and irrigation and the losses of water by extraction by roots, drainage and evaporation.

The effects of irrigation on soil water pressures of the Sharkey soil can be determined by observing the changes in pressure in the I plots after irrigation. A couple of days after a furrow irrigation event, the soil water pressure at the 30-cm depth had increased to values ranging between -100 and -200 cm of water (Fig. 20). This shows that the soil profile was not saturated at this depth even from application of irrigation and that redistribution of water within this smectitic, clayey soil is slow. Apparently, swelling of the soil upon wetting the soil surface reduced the downward movement of water to lower portions in the profile.

In early July, the soil water pressures deeper in the profile were higher than those at 30 cm (Fig. 21). In general, day-to-day fluctuations of soil water pressures decreased with depth in the profile. In the NI plots, soil water pressures decreased at progressively deeper depths as a result of the lack of rainfall during August and continued extraction of water by the roots. As a result, the soil water pressures were beyond the operating range of the tensiometers in the upper portion of the soybean root zone by the middle of August. The decrease in soil water pressure with time at the 120-cm depth verified that extraction of water by the soybeans occurred beyond the 100-cm depth in the Sharkey soil in both water management treatments.

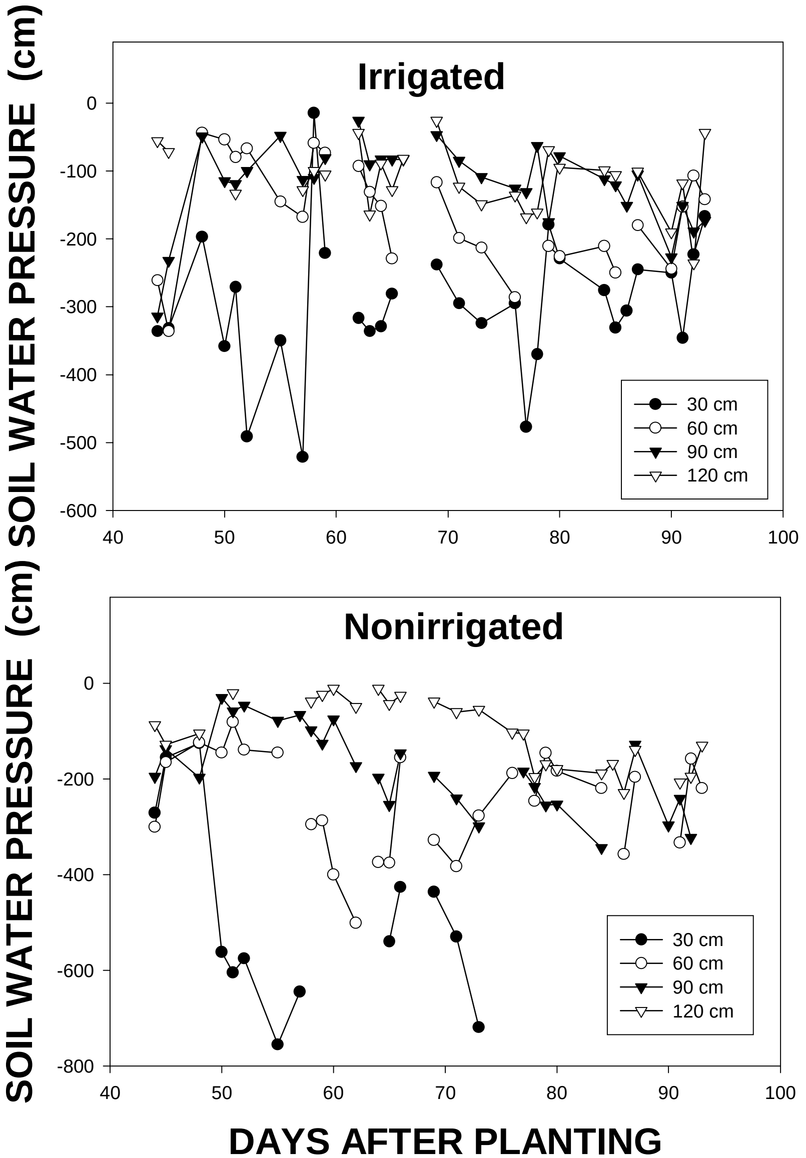
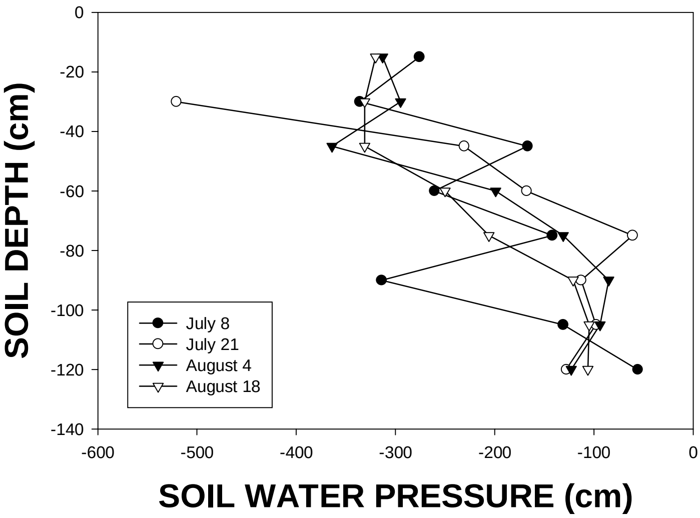


Fig. 20. Soil water pressure at four depths as a function of days after planting on the Sharkey silty clay loam.

IRRIGATED



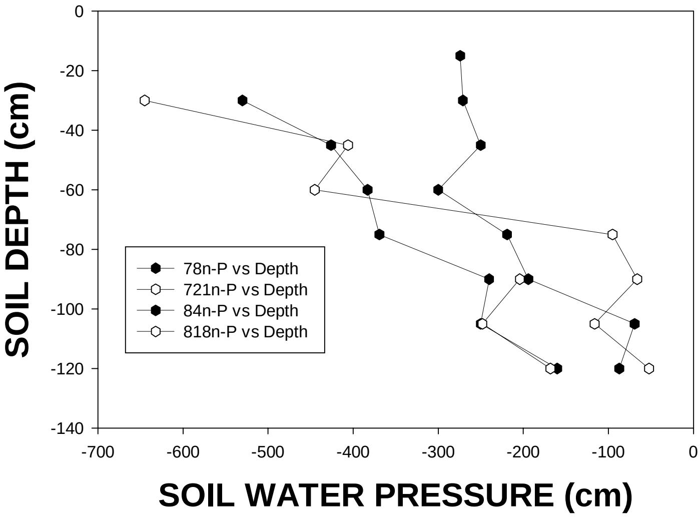


Fig. 21. Soil water pressure in the Sharkey profile at four dates during the growing season.

Crowley (DeWitt) silt loam

At RREC near Stuttgart, a total of only 4.2 cm and 3.0 cm of rain were recorded at the study site during July and August, respectively. Both rainfall totals were lower than the long-term monthly means for this location (Fig. 2). Water was applied by the furrow method to the I soybeans five times during the 1976 growing season: 19 July, 26 July, 5 August, 10 August and 20 August using the tensiometer irrigation scheduling method. Seed yields were 2890 kg/ha and 2068 kg/ha for the I and NI soybeans, respectively.

The soil water content distribution in the profile was measured six times during the 1976 growing season in the row to a depth of 100 cm (Fig. 22). On 11 June, which was approximately three weeks after planting of the soybeans, water contents in the soil profile indicated that the soil was wet but not saturated. After 15.2 cm of rainfall in June, the profile wetted, and the highest soil water content in the Crowley profile was measured 8 July. Over time, water was removed from the profile due to extraction by soybean roots, drainage beyond the root zone and evaporation at or near the soil surface. As the growing season progressed, more soil water tended to be removed from deeper depths of the profile in both soil water management treatments. The lowest soil water contents were measured during either of the August sampling dates.

The range of water contents in the Crowley (DeWitt) profile during the 1976 growing season was determined by subtracting the lower limit from the upper limit, regardless of the water management treatment (Fig. 23). The differences in water content between the upper and lower limits in the profile indicate that considerable amounts of water were removed from the deeper depths of the profile. Also, the fact that the upper and lower limit water content curves did not come together at 100 cm indicates that some extraction of soil water occurred at depths beyond 100 cm. However, the shapes of these curves do not particularly resemble those found with the Sharkey clay. In general, the largest values of $\Delta\Theta$ in the Crowley (DeWitt) soil were in the Btg horizons, not near the surface as found with the Sharkey soil. The pinching of the $\Delta\Theta$ curves at the 15-cm depth can be attributed to the presence of a tillage pan.

The influence of the tillage pan was also observed on the root length density (RD) where there was a sharp decline in root density at the 15-cm depth (Fig. 19). Obviously, linear, polynomial and exponential models do not adequately describe the $\Delta\Theta(z)$ and RD(z) relationships in the Crowley (DeWitt) soil. Similarly, the relationship between $\Delta\Theta$ and RD was non linear. This indicates that the soybean roots that penetrate the pan and explore the soil below are particularly efficient extractors of soil water. Since the internal movement of water in the Crowley soil is slow and evaporation occurs primarily at the surface, the removal of water from the profile is primarily due to root extraction.

The ratio $\Delta\Theta(z)/RD(z)$ was best fit with a third order polynomial. The regression equation was

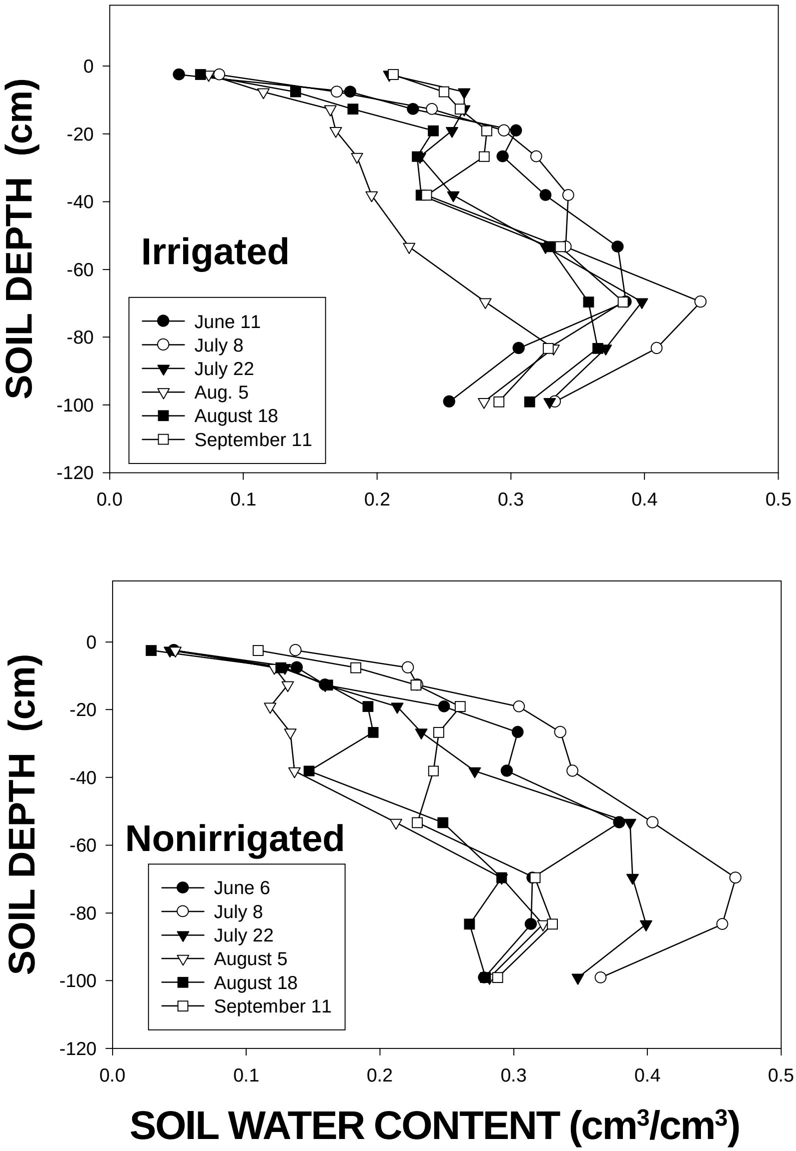


Fig. 22. Soil water content distributions of irrigated and nonirrigated soybeans grown on Crowley (DeWitt) silt loam at the Rice Research and Extension Center near Stuttgart, Arkansas.

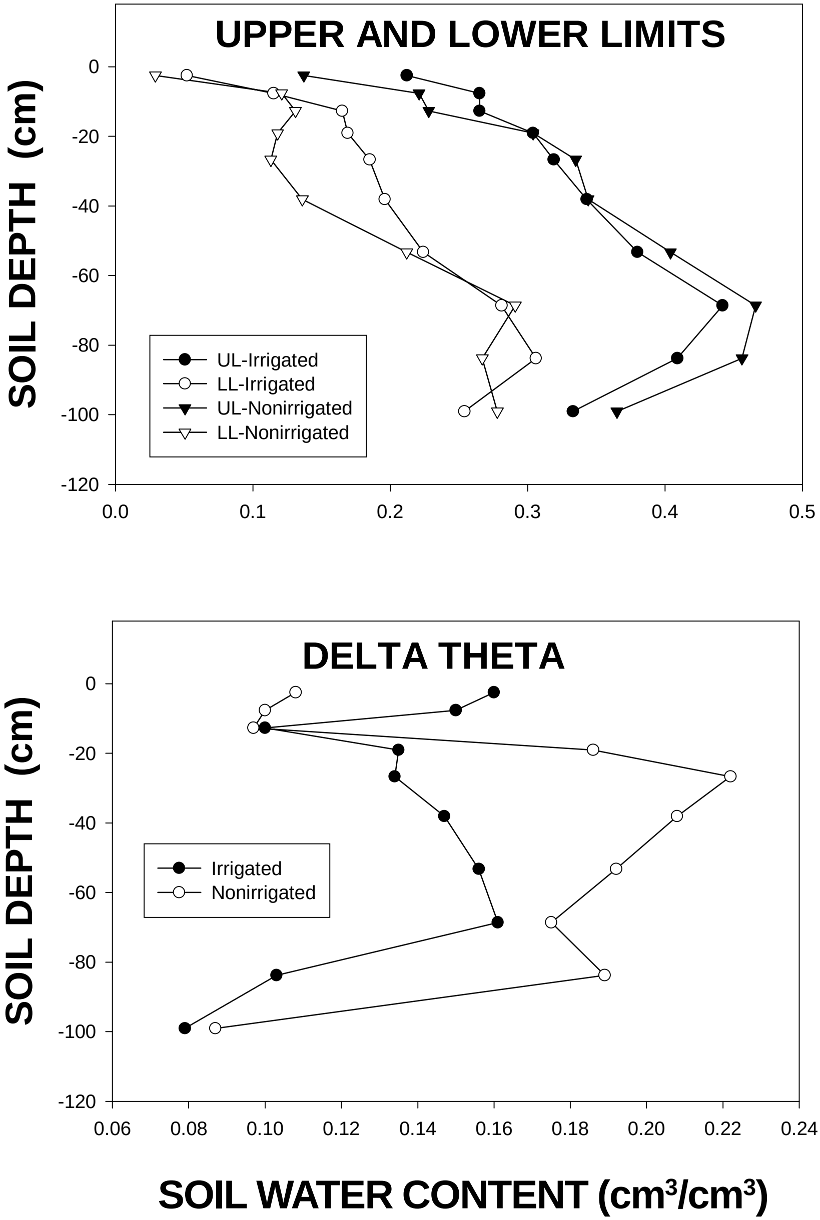


Fig. 23. Relationships between the upper and lower limits and volumetric soil water content and between ΔΘ and volumetric water content of the Crowley (DeWitt) silt loam.

$$\Delta\Theta(z)/RD(z) = -0.307+0.0374z-0.00055z^2 + 2.26E\text{-}06z^3 \qquad [20]$$

with an R^2 of 0.962. This equation shows that the highest efficiency of water extraction was in the middle of the root zone, i.e., near the 50-cm depth.

The plant-extractable water for soybeans grown on the Crowley soil was estimated by integrating the area between the upper and lower limit volumetric water contents to a depth of 100 cm. For soybeans grown on the Crowley (DeWitt) silt loam, the depth of plant-extractable water was 18.5 cm of water, which is slightly higher than with the Sharkey clay.

Soil water pressures were measured with tensiometers placed in the soybean row beginning in early July. Differences were found in the spatial and temporal distributions of soil water pressures due to water management (Fig. 24). The soil water pressures at 30 cm were the most dynamic, reflecting the greater activity in extraction of water by the soybean roots near the soil surface. At the 30-cm depth, values of soil water pressure decreased rapidly beginning in early July, due primarily to the extraction of water by the roots at this depth. In the NI plots the soil water pressures were beyond the operational range of the tensiometers between 14 July and 4 August. After 9 August the water pressures at this depth were beyond the operational range of the tensiometers. In contrast, the tensiometers in the I plots continued to operate properly and showed the seasonal fluctuations in soil water pressure due to the gains of water from rainfall and irrigation and the losses of water by extraction by roots, drainage and evaporation.

In early July, the soil water pressures deeper in the profile were higher than those near the surface (Fig. 25). In general, the soil water pressures decreased with depth in the profile over time due primarily to the deficit of rainfall and high evaporative demand. This was particularly evident in the NI plots, where the soil water pressures were beyond the operating range of the tensiometers in the upper portion of the soybean root zone by late July. The decrease in soil water pressure with time at the 120-cm depth verified that both I and NI soybeans extracted soil water beyond the 100-cm depth in the Crowley (DeWitt) soil.

SUMMARY

Crops such as soybeans, rice and cotton grow and develop with their roots in the soil and shoots in the air. Most often, they are grown in climatic and soil environments that are unfavorable for growth. Rates of crop growth reflect the integration of the spatial and temporal variations in each environment and the genetic potential of the crop. Of primary importance to crop growth is the water status of the soil and atmosphere. The water status of both soil and atmospheric environments is dynamic and varies during each day of the growing season and spatially over the field.

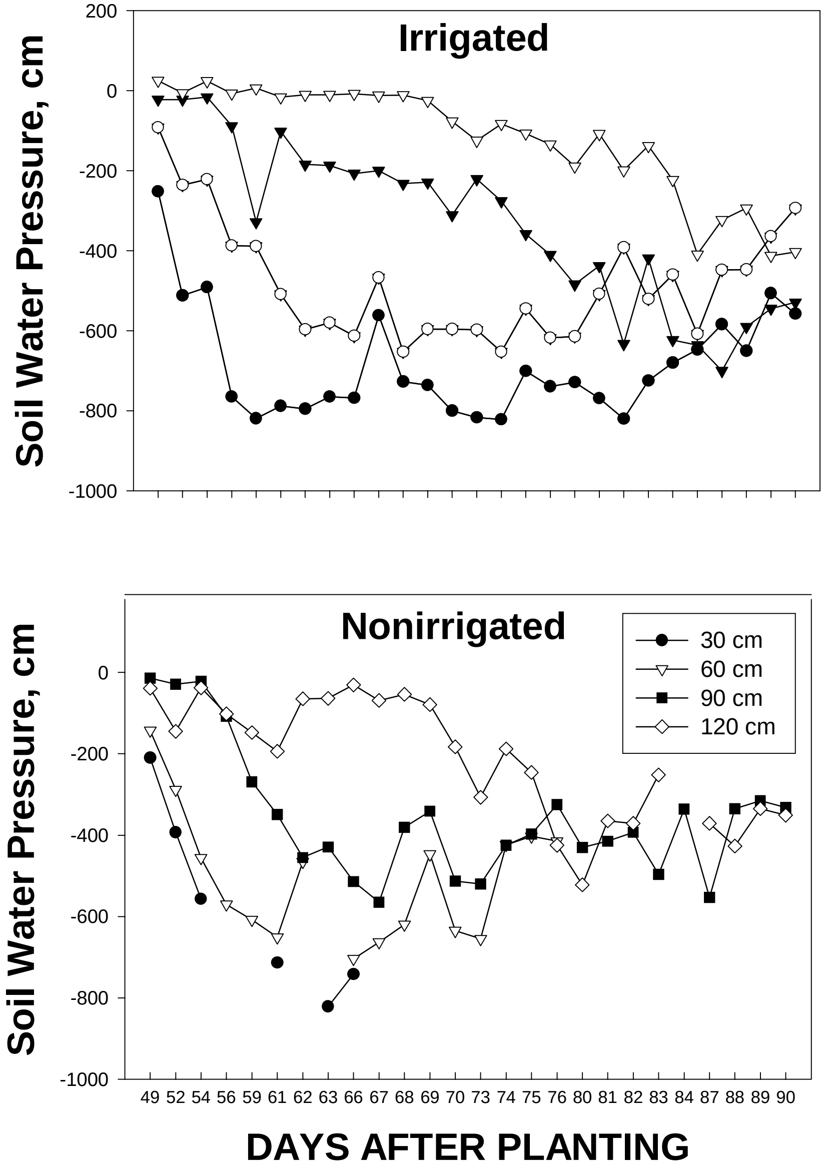


Fig. 24. Soil water pressure at four depths as a function of days after planting on the Crowley (DeWitt) silt loam.

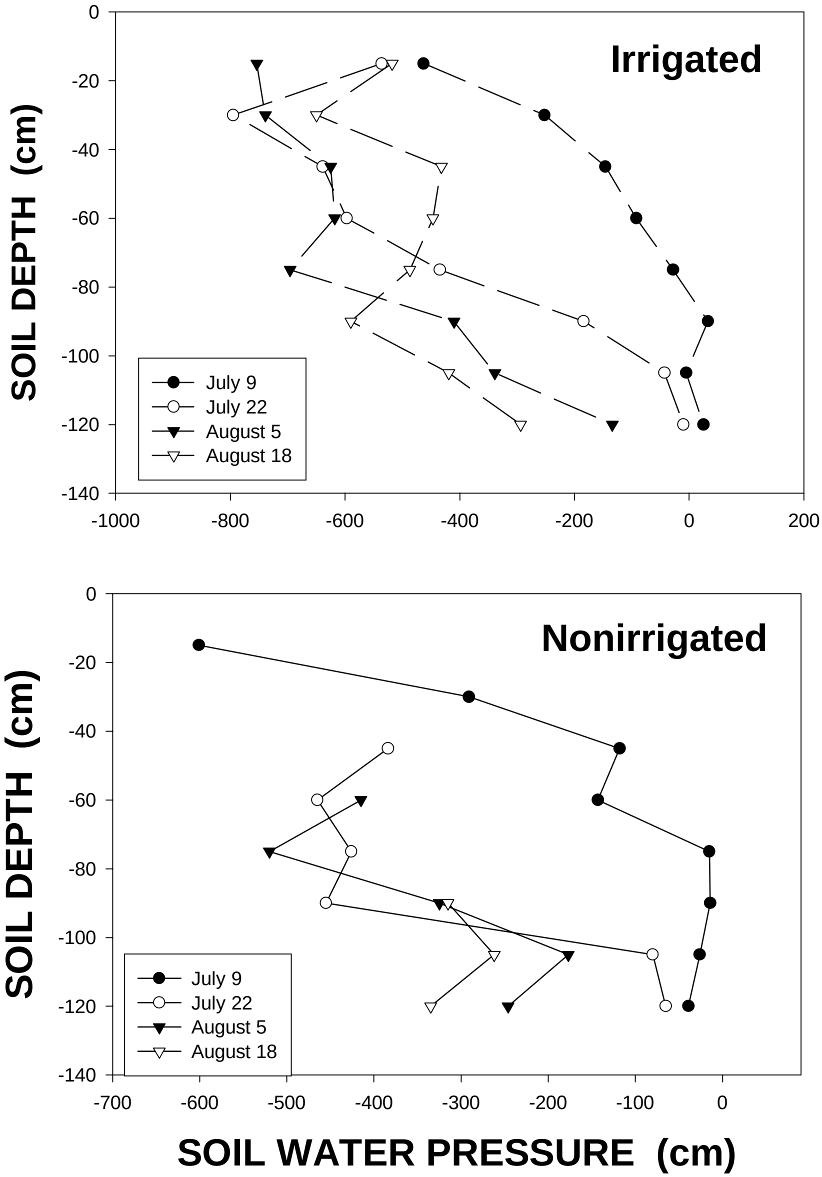


Fig. 25. Soil water pressure in the Crowley (DeWitt) profile at four dates during the growing season.

In the Delta of Arkansas, both drought and excessive amounts of water can occur during the same growing season. Drought stresses result from a deficient water supply in the root zone and from excessive atmospheric demand for water from the leaves. Some drought stress is unavoidable; however, significant drought must be overcome if the crop is to grow and develop at rates governed by its genetic potential. Under field conditions crops obtain the needed water primarily from the soil. Large variabilities occur in the physical properties of the soils in eastern Arkansas, and this results in differing storage capabilities and amounts of water available to the crop. Therefore, water management practices have been developed to overcome significant drought. Aeration stress occurs when water is ponded on the soil surface for prolonged periods of time.

In eastern Arkansas significant volumes of water are extracted annually from the Alluvial aquifer by irrigation of crops. This has led to lowering of the potentiometric surface of the aquifer in some regions. More efficient use of ground water requires the adoption of proper irrigation scheduling and application techniques. Two scheduling methods have been successfully used to schedule irrigations in the field. Tensiometers, installed at a specified depth in the profile, are used to monitor the soil water pressure. Irrigation is applied when the critical pressure is exceeded. For fine-textured soils this pressure is about -500 cm (50 cbars or 50 kPa). 'The Scheduler,' which is a computer-based water balance program, takes advantage of mathematical relationships between air temperature and atmospheric demand as well as known crop demand curves and soil deficits.

LITERATURE CITED

Ackerman, D.J. 1996. Hydrology of the Mississippi River Valley Alluvial Aquifer, South-Central United States. U.S. Geological Survey Professional Paper 1416-D.

Arkansas Agricultural Statistics Service. 1996. Arkansas agricultural statistics for 1995. Arkansas Agricultural Experiment Station. Report Series 334.

Arkansas Soil and Water Conservation Commission. 1990. Arkansas water plan: Executive summary. 82 pp.

Arkansas Soil and Water Conservation Commission. 1995. 1995 annual ground-water protection and management report. December.

Arkansas Soil and Water Conservation Commission. 1997. Ground water protection and management report for 1996. March.

Arkansas Farm Bureau Federation. 1982. Water: Its use and the implications for Arkansas agriculture. 159 pp.

Ashlock, L.O., R. Klerk and W. Mayhew. 1995. Arkansas 1994 soybean research verification program. Cooperative Extension Service, University of Arkansas.

Batchelor, J.T., and H.D. Scott. 1979. Effects of irrigation on nitrogen and potassium uptake by soybeans. Ark. Farm Res. 28(2):5.

Boerma, H.R., and D.A. Ashley. 1982. Irrigation, row spacing and genotype effects on late and ultra-late planted soybean. Agron. J. 74:995-999.

Boswell, E.H., E.H. Cushing and R.L. Hosman. 1969. Quaternary aquifers in the Mississippi embayment, with a discussion of quality of the water. U.S. Geological Survey Professional Paper 448-E. 15pp.

Bowman, D., P. Raymer and D. Dombek. 1993. Crop performance trials under irrigated and dryland conditions. Agron. J. 85:610-614.

Brown, D.A., V.E. Nash and A.G. Caldwell. 1972. A monograph of the soils of the Mississippi River Valley Alluvium. South. Cooperative. Series Bull. 178.

Bruce, R.R., A.W. Thomas, V.L. Quisenberry, H.D. Scott and W.M. Snyder. 1985. Irrigation practice for crop culture in the southeastern United States. Adv. Irrigation 3:51-106.

Cahoon, J., J. Ferguson, D. Edwards and P. Tacker. 1990. A microcomputer-based irrigation scheduler for the humid mid-south region. Applied Engineering in Agriculture. 6:289-295.

Cline, R.G., and G. S. Campbell. 1976. Seasonal and diurnal water relations of selected forest species. Ecology 57:367-373.

Daniels, M.B., and H.D. Scott. 1991. Water use efficiency of double-cropped wheat and soybean. Agron. J. 83:564-570.

De Angulo, J. 1988. Spatial and temporal variability of a sharkey clay cropped to soybeans. M.S. Thesis. Department of Agronomy. University of Arkansas, Fayetteville.

Dillon, C.A., M. Cochran and T. Windham. 1997. An economic evaluation of irrigated and nonirrigated southern state soybean production. Proc. '94 South. Soybean Conf. Memphis, Tennessee. pp 70-75.

Dombek, D.G., R.D. Bond and S.B. Cain. 1995. Arkansas soybean performance tests - 1994. Variety Testing Publication 2055. Arkansas Agricultural Experiment Station.

Doorenbos, J., and W.O. Pruitt. 1977. Crop water requirements. FAO Irrig. and Drain. Paper 24 (rev.) 156 pp.

Ferguson, J.A., and J.T. Gilmour. 1981. A hydrologic carbonate chemistry model of flooded rice fields. Arkansas Water Resources Research Center Publication No. 78.

Ferguson, J.A. 1979. The effect of selected electric power interruptions on rice irrigation. Arkansas Agr. Exp. Stn. Special Report 74. University of Arkansas, Fayetteville.

Ferguson, J.A., D.J. Pitts and R.E. Baser. 1986. Levee seepage under rice production on clay soils. Proceedings of the 21st Technical Working Group.

Gardner, W.R. 1968. Availability and measurement of soil water. *In:* T.T. Kozlowski (ed.). Water deficits and plant growth. Academic Press, New York, New York. pp. 107-135.

Glinski, J., and W. Stepniewski. 1985. Soil aeration and its role for plants. CRC Press. Boca Raton, Florida.

Griffis, C.L. 1972. Groundwater-surface water integration study in the Grand Prairie of Arkansas. Ark. Water. Resour. Center Publ. No. 11, University of Arkansas, Fayetteville, Arkansas.

Huey, B.A. 1977. Rice production in Arkansas. Circular 476. Cooperative Extension Service. University of Arkansas.

Jackson, J.L., and L.E. Mack. 1982. Arkansas water: Why wait for the crisis? The Winthrop Rockefeller Foundation. Little Rock, Arkansas.

Jung, P.K., and H.D. Scott. 1980. Leaf water potential, stomatal resistance, and temperature relations in field-grown soybeans. Agron. J. 72:989-990.

Keisling, T.C., C.R. Dillon, L.R. Oliver, F.L. Baldwin, L.O. Ashlock and G.M. Palmer. 1995. Assessing the value of pre-plant and post-plant tillage for full season soybeans on clayey and silt loam soils. Southern Conservation Tillage Conference. pp. 69-71.

Kozlowski, T.T. 1968. Water deficits and plant growth. Academic Press. Vols 1-4. New York, New York.

League of Women Voters. 1984. Arkansas ground water fact sheet. 915 Oak Street Conway, Arkansas.

Lutz, J.A., and G.D. Jones. 1975. Effect of irrigation, lime and fertility treatments on the yield and chemical composition of soybeans. Agron. J. 67:523-526.

McGrew, C.A. 1973. Soils of Arkansas. Proc. 28th Annual Meeting Soil Conservation Society of America. Hot Springs, Arkansas.

Nelson, M., W.H. Sachs and R.H. Austin. 1923. The soils of Arkansas. Arkansas Agricultural Experiment Station Bulletin 187.

NOAA. 1982. Monthly normals of temperature, precipitation, and heating and cooling degree days 1951-89. National Climatic Center. Asheville, North Carolina.

NOAA. Climatological data for Arkansas. National Climatic Data Center, Asheville, North Carolina.

Oosterhuis, D.M., H.D. Scott, R.E. Hampton and S.D. Wullschleger. 1990. Physiological responses of two soybean [*Glycine max* (l.) Merr.] cultivars to short-term flooding. Environ. and Exp. Bot. 30:85-92.

Peralta, R.C., A. Yazdanian, P.J. Killian and R.N. Shulstad. 1985. Future quaternary groundwater assessibility in the Grand Prairie - 1993. Ark. Agric. Exp. Sta. Bulletin 877.

Pitts, D.J., J.A. Ferguson, J. DeAngulo and P.L. Tacker. 1987. A comparison of surge flow furrow irrigation to continuous flow furrow irrigation on clay soil. Arkansas Farm Res. 36(4):9.

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resourc. Res. 8:1204-1213.

Sabbe, W.E., and R.E. DeLong. 1997. Influence of phosphorus plus potash fertilizer and irrigation on grain yields of soybean cultivars. *In:* W.E. Sabbe (ed.). Arkansas Soil Fertility Studies: 1996. Arkansas Agr. Exp. Stn. Research Series 455.

Sallam, A., and H.D. Scott. 1987. Effects of prolonged flooding on soybeans during early vegetative growth. Soil Sci. 144:61-66.

Scott, H.D. 1980. Variables involved in irrigation of soybeans. American Soybean Conference. Memphis, Tennessee. pp. 33-35.

Scott, H.D. 1985. Irrigation water management of soybeans. *In:* R. Shibles (ed.). World Soybean Res. Conf. III: Proceedings. Ames, Iowa. pp. 972-979.

Scott, H.D., and J.T. Batchelor. 1979. Dry weight and leaf area production rates of irrigated determinate soybeans. Agron. J. 71:776-782.

Scott, H.D., and D.W. Brewer. 1982. Characterization of nutrient transport coefficients in field-grown soybeans. Soil Sci. Soc. Amer. J. 46:998-1004.

Scott, H.D., J. DeAngulo, M.B. Daniels and L.S. Wood. 1989. Flood duration effects on soybean growth and yield. Agron. J. 81:631-636.

Scott, H.D., J. DeAngulo, L.S. Wood and D.J. Pitts. 1990. Influence of temporary flooding at three growth stages on soybeans grown on a clayey soil. J. Plant Nutr. 13(8):1045-1071.

Scott, H.D., J.A. Ferguson and T.C. Keisling. 1986a. Effects of drought on soybean yields. Ark. Farm Res. 35(1):4.

Scott, H.D., J.A. Ferguson and L.S. Wood. 1987. Water use, yield, and dry matter accumulation by determinate soybean grown in a humid region. Agron. J. 79:870-875.

Scott, H.D., J.A. Ferguson, R.E. Sojka and J.T. Batchelor. 1986b. Response of Lee 74 soybean to irrigation in Arkansas. Ark. Agri. Exp. Stn. Bull. 886.

Scott, H.D., and D.M. Oosterhuis. 1989. Soil-plant-water relations of waterlogged soybeans. World Soybean Res. Conf. IV: Buenos Aires, Argentina. 1:238-243.

Shulstad, R.N., J.A. Ziegler and E.D. Cross. 1978. Arkansas state water plan: Water and related land resources. Arkansas Soil and Water Conservation Commission in cooperation with the Arkansas Water Resources Research Center and the Arkansas Agricultural Experiment Station. Special Report No. 61.

Smith, E.T., Jr., D.T. Fugitt and L.A. Hansen. 1997. A review of water use in Arkansas by aquifer and county. Arkansas Soil and Water Conservation Commission. June.

Spooner, A.E. 1961. Effects of irrigation timing and length of flooding periods on soybean yields. Arkansas Agricultural Exp. Stn. Bull. 644.

Stolzy, L.H., and R.E. Sojka. 1984. Effects of flooding on plant disease. *In*: T.T. Kozlowski (ed.). Soil flooding and plant response. Academic Press, New York, New York. pp. 221-264.

Thompson, L., and C.E. Caviness. 1969. Soybean irrigation on clay soils. Arkansas Farm Res. 18(3):4.

Turner, N.C., and G J. Burch. 1983. The role of water in plants. *In:* I.D. Teare and M.M. Peet (eds.). Crop-water relations. John Wiley and Sons. New York, New York.

Turner, F.T., and W.H. Patrick, Jr. 1968. Chemical changes in waterlogged soils as a result of oxygen depletion. Ninth International Congress of Soil Science 4:53-65.

Unger, P.W., and B.A. Stewart. 1983. Soil management for efficient water use: An overview. *In:* H.M. Taylor and W.R. Jordan (eds.). Limitations to efficient water use in crop production. Amer. Soc. Agron. Chpt. 10A, pp. 419-460.

USDA-ERS. 1996. Irrigation water use, 1994. Agricultural Resources and Environmental Indicators updates. AH-705 Number 8, August.

USDA-SCS. 1981. Land resource regions and major land resource areas of the United States. Agriculture Handbook 296.

USDA-SCS. 1993. Soil survey manual. Soil Survey Division Staff. U.S. Department of Agriculture Handbook N. 18.

van Doren, D.M., Jr. and D.C. Reicosky. 1987. Tillage and irrigation. *In:* J.R. Wilcox (ed.). Soybeans: Improvement, production and uses. Second Edition. American Society of Agronomy, Madison, Wisconsin.

Vories, E. 1997. Personal communication. Northeast Research and Extension Center, Keiser, Arkansas.

Conversion Table

U.S. to Metric			Metric to U.S.		
to convert from	to	multiply U.S. unit by	to convert from	to	multiply metric unit by
length			length		
miles	kilometers	1.61	kilometers	miles	.62
yards	meters	.91	meters	yards	1.09
feet	meters	.31	meters	feet	3.28
inches	centimeters	2.54	centimeters	inches	.39
area and volume			area and volume		
sq yards	sq meters	.84	sq meters	sq yards	1.20
sq feet	sq meters	.09	sq meters	sq feet	10.76
sq inches	sq centimeters	6.45	sq centimeters	sq inches	.16
cu inches	cu centimeters	16.39	cu centimeters	cu inches	.06
acres	hectares	.41	hectares	acres	2.47
liquid measure			liquid measure		
cu inches	liters	.02	liters	cu inches	61.02
cu feet	liters	28.34	liters	cu feet	.04
gallons	liters	3.79	liters	gallons	.26
quarts	liters	.95	liters	quarts	1.06
fluid ounces	milliliters	29.57	milliliters	fluid ounces	.03
weight and mass			weight and mass		
pounds	kilograms	.45	kilograms	pounds	2.21
ounces	grams	28.35	grams	ounces	.04
temperature			temperature		
F	C	5/9(F-32)	C	F	9/5(C+32)

UofA

UNIVERSITY OF ARKANSAS

DIVISION OF AGRICULTURE