A PRELIMINARY ASSESSMENT OF THE POTENTIAL FOR ARTIFICIAL RECHARGE IN EASTERN ARKANSAS

By Daniel J. Fitzpatrick

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MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
2301 Federal Office Building
700 West Capitol
Little Rock, Arkansas 72201

Copies of this report can be purchased from:

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CONVERSION FACTORS

For use of readers who prefer to use metric (International System) units, rather than the inch-pound units used in this report, the following conversion factors may be used:

Multiply inch-pound unit	By	To obtain metric unit
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot per minute (acre-ft/min)	1,233	cubic meter per minute (m^3/min)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
gallon per minute (gal/min)	0.0630	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
inch (in.)	25.4	millimeter (mm)
inch per day (in/d)	25.4	millimeter per day (mm/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

Large withdrawals of water from the Mississippi River Valley alluvial aquifer in eastern Arkansas has resulted in declines in the potentiometric surface of greater than 80 feet within the area west of Crowleys Ridge and in the Grand Prairie area. As a result of these declines and potential ground-water shortages, artificial recharge of the alluvial aquifer is being examined as a potential means of augmenting existing water supply to alleviate expected shortages. Artificial recharge has proven effective in augmenting ground-water supplies in many locales where geohydrologic conditions and economic considerations permit.

The study area is underlain entirely by Quaternary alluvial deposits. The lower part of these deposits, largely made up of sand and gravel, comprise the alluvial aquifer. The upper part of these deposits consists of clay and silt, and serves as a confining unit throughout most of the study area. Recharge to the aquifer occurs mainly as infiltration from rivers and as lateral leakage of water from adjacent geohydrologic units. Direct recharge by infiltration of precipitation is minimal because of the surficial clay and silt deposits that overlie the alluvial aquifer. Regional flow patterns in the alluvial aquifer are toward the south and east. Locally, drawdown of the potentiometric surface has resulted from heavy pumping, chiefly for irrigation.

The effectiveness of various artificial recharge techniques largely depends on local geohydrologic characteristics. Artificial recharge techniques examined in detail in this investigation are recharge through basins and recharge through wells. The greatest potential for recharge through basins exists where the upper confining unit is thin or absent. The only relatively extensive areas where these conditions apply are located west of Crowleys Ridge along the Cache River and Village Creek. In terms of geohydrologic conditions, the potential for well recharge generally exists throughout the study area. Economic considerations are the major limiting factor for recharge through wells.

The cost of an artificial recharge system largely depends on the technique used. Recharge through basins is less costly than recharge through wells, but can be used only where the upper confining unit is thin or absent.

Design criteria of an operational recharge system usually depend on site-specific conditions and local water needs. Design components for a well-recharge site include a pump for injection under pressure, noncorrosive components that come in contact with water, a means for pretreatment of the recharge water, a means for rehabilitating a recharge well after well clogging has occurred, and observation wells to monitor both short- and long-term clogging effects and water-quality changes.

Water needs within the study area, based on projected pumpage estimates with conservation measures imposed for the year 1990, indicated that the amount of augmentation required to maintain a minimum saturated thickness of 20 feet in the alluvial aquifer is approximately 155,000 acre-feet per year in the area west of Crowleys Ridge, and 351,000 acre-feet per year in the Grand Prairie area. Assuming an average recharge rate of 700 acre-feet per year per well, about 220 wells would be required in the area west of Crowleys Ridge and about 500 wells in the Grand Prairie area to satisfy these requirements.

INTRODUCTION

The Mississippi River Valley alluvial aquifer, hereafter referred to as the alluvial aquifer, is the major source of water supply for eastern Arkansas. In 1985, approximately 3,400 Mgal/d (million gallons per day) were withdrawn from the aquifer for irrigation (mainly rice) and aquaculture (Holland, 1987). As a result of heavy pumpage, drawdown cones have developed in some areas of the alluvial aquifer in eastern Arkansas. The largest and deepest of these drawdown cones is centered within Arkansas and Prairie Counties, where drawdown exceeds 80 feet. A second drawdown cone centers around Cross County, where drawdown exceeds 50 feet.

The potential for water shortage and depletion of ground-water supplies has become an increasing concern to farmers in the area, as well as to water managers. State and Federal authorities currently are considering alternate sources of water to augment existing supplies, thus alleviating water-level declines and potential shortage problems. Among the options being considered is artificial recharge of surplus surface water to the alluvial aquifer. Artificial recharge has been shown to be an effective approach to augmenting ground-water supplies in some areas where local geohydrologic conditions permit (Todd, 1980).

Purpose and Scope

The U.S. Geological Survey, in cooperation with the Arkansas Soil and Water Conservation Commission, examined the potential for recharging through artificial means those areas of the alluvial aquifer in eastern Arkansas where large drawdowns have occurred. Specific objectives of this report are to summarize the following:

1. A preliminary assessment of the geohydrologic characteristics of the alluvial aquifer with regard to the potential for artificial recharge of the alluvial aquifer in and around areas where large drawdowns have occurred.
2. A review of artificial recharge techniques from existing literature, and evaluation of selected artificial recharge methods as to their relative feasibility for recharging the alluvial aquifer.
3. A preliminary evaluation of the economic and system design considerations for selected artificial recharge methods.

This discussion will be limited to those areas where relatively large drawdowns in the alluvial aquifer occurred. The study relied on analysis of existing data and published material in evaluating geohydrologic characteristics as well as artificial recharge methods.

Description of Study Area

The study area, as referred to in this report, lies entirely within the Mississippi Alluvial Plain of the Gulf Coastal province in eastern Arkansas, and consists of two subareas (fig. 1). Water levels in both subareas have been drawn down substantially due to pumping. One of the areas, referred to herein as the area west of Crowleys Ridge, includes all or parts of Craighead, Cross, Independence, Jackson, Lawrence, Lonoke, Monroe, Poinsett, Prairie, St. Francis, White, and Woodruff Counties (figs. 1 and 2). The area is bounded by the Fall Line to the west, and Crowleys Ridge to the east. Boundaries to the north and south were chosen for convenience. The second subarea, referred to herein as the Grand Prairie area, includes all or parts of Arkansas, Jefferson, Lonoke, Monroe, Prairie, and Pulaski Counties. The area is bounded by the Arkansas River to the west and south, and the White River to the east. The Grand Prairie area extends northward covering 75 percent of Lonoke and Prairie Counties (figs. 1 and 3).

Land use within the study area is predominantly agriculture. Major crops include rice, soybeans, and cotton. Large amounts of ground water are withdrawn for irrigation (mainly rice). Approximately 2,000 Mgal/d and 60 Mgal/d are withdrawn from the alluvial and Sparta aquifers, respectively (Holland, 1987), for rice irrigation, within the study area.

Previous Investigations

Artificial recharge of the alluvial aquifer with surplus surface water has been considered as a means of augmenting water supplies in eastern Arkansas since at least 1931. In 1952, a proposal was made to establish a pilot study to artificially recharge the alluvial aquifer through the use of horizontal wells. However, this study was not implemented (Engler and others, 1963).

The U.S. Geological Survey began a research study in 1953 with the objective of determining the feasibility of relieving ground-water shortages by injection of surface water through wells. A series of injection tests were conducted under varying conditions to accomplish the stated objective. The results of this investigation are summarized in Engler and others (1963); Johnson and others (1966); Sniegocki (1963a, 1963b, 1964); Sniegocki and others (1963, 1965); and Sniegocki and Reed (1963). Artificial recharge of shallow aquifers through well injection and other techniques are described in Oaksford (1985); Argo and Cline (1985); Wilderer and others (1985); and Huisman and Olsthoorn (1983).

GEOHYDROLOGY OF THE STUDY AREA

The study area is directly underlain by unconsolidated alluvium and terrace deposits of Quaternary age. The Quaternary alluvium consists largely of Pleistocene terrace deposits, with some Holocene flood-plain deposits. The Quaternary alluvium generally ranges in thickness from 100 to 200 feet and is divided into two distinct lithologic zones: an upper zone consisting of clay and silt, and a basal unit primarily made up of sand and gravel.

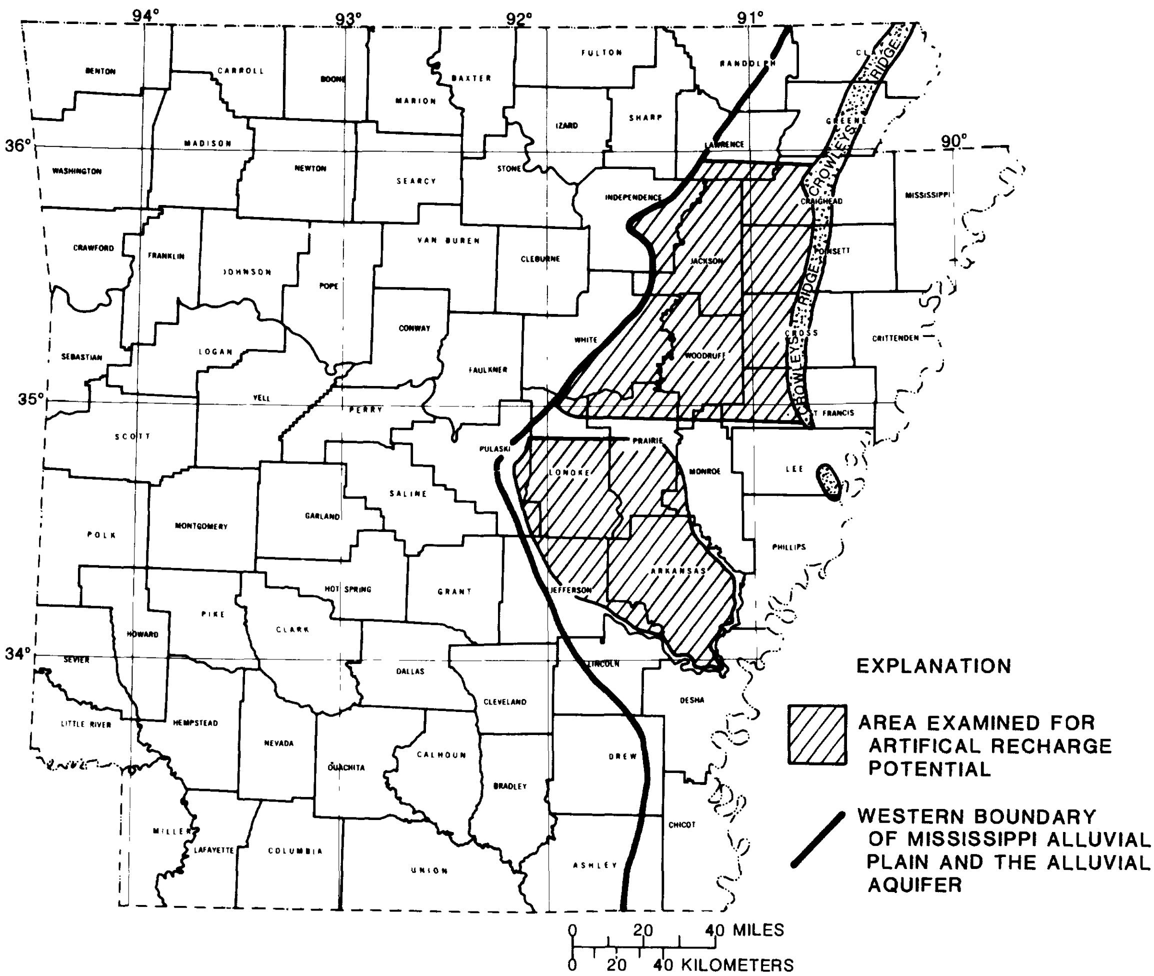

Figure 1.--Location of study area in eastern Arkansas.

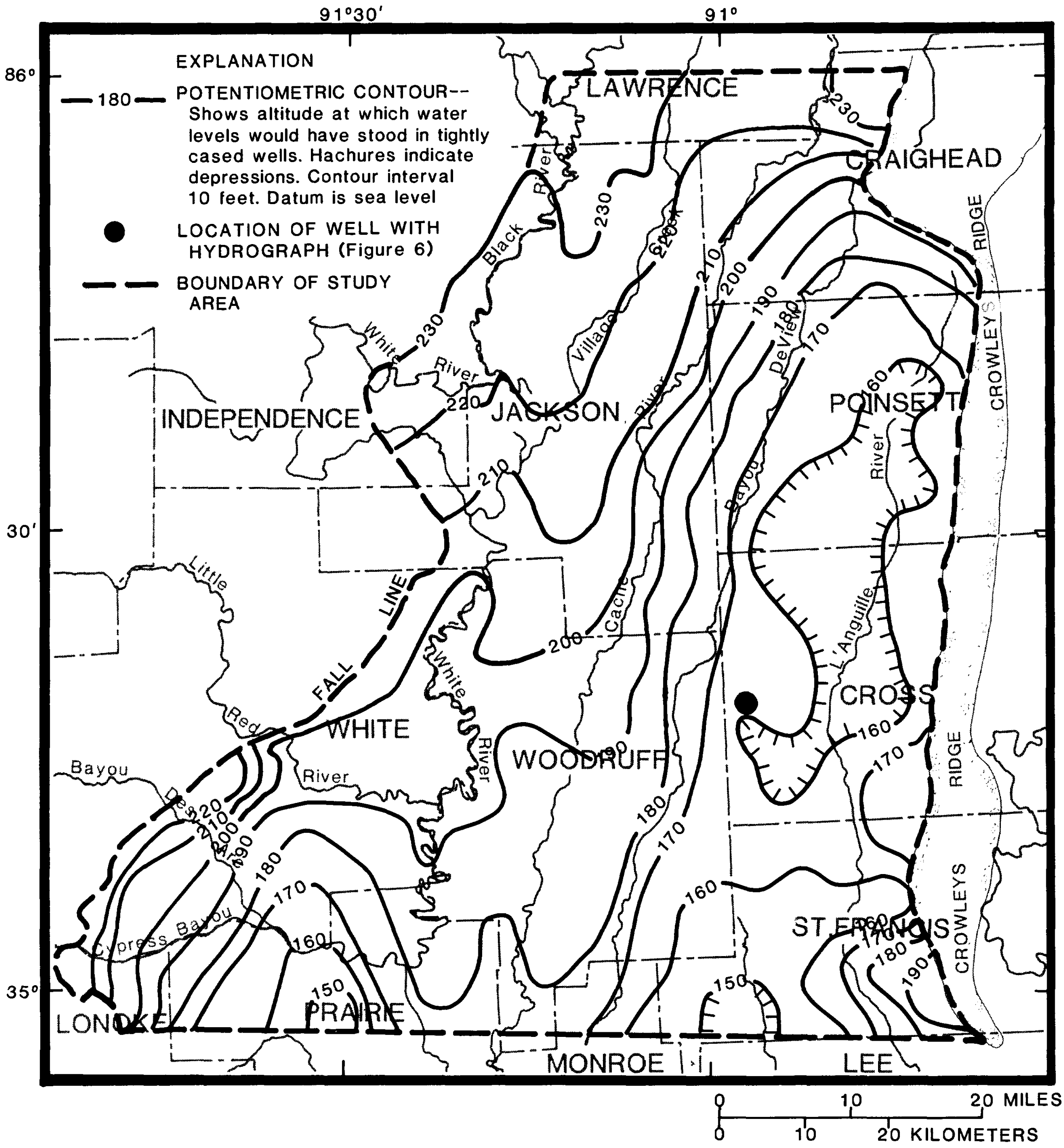

Figure 2.--Potentiometric surface of the alluvial aquifer in the area west of Crowleys Ridge, spring 1985 (modified from Plafcan and Fugitt, 1987).

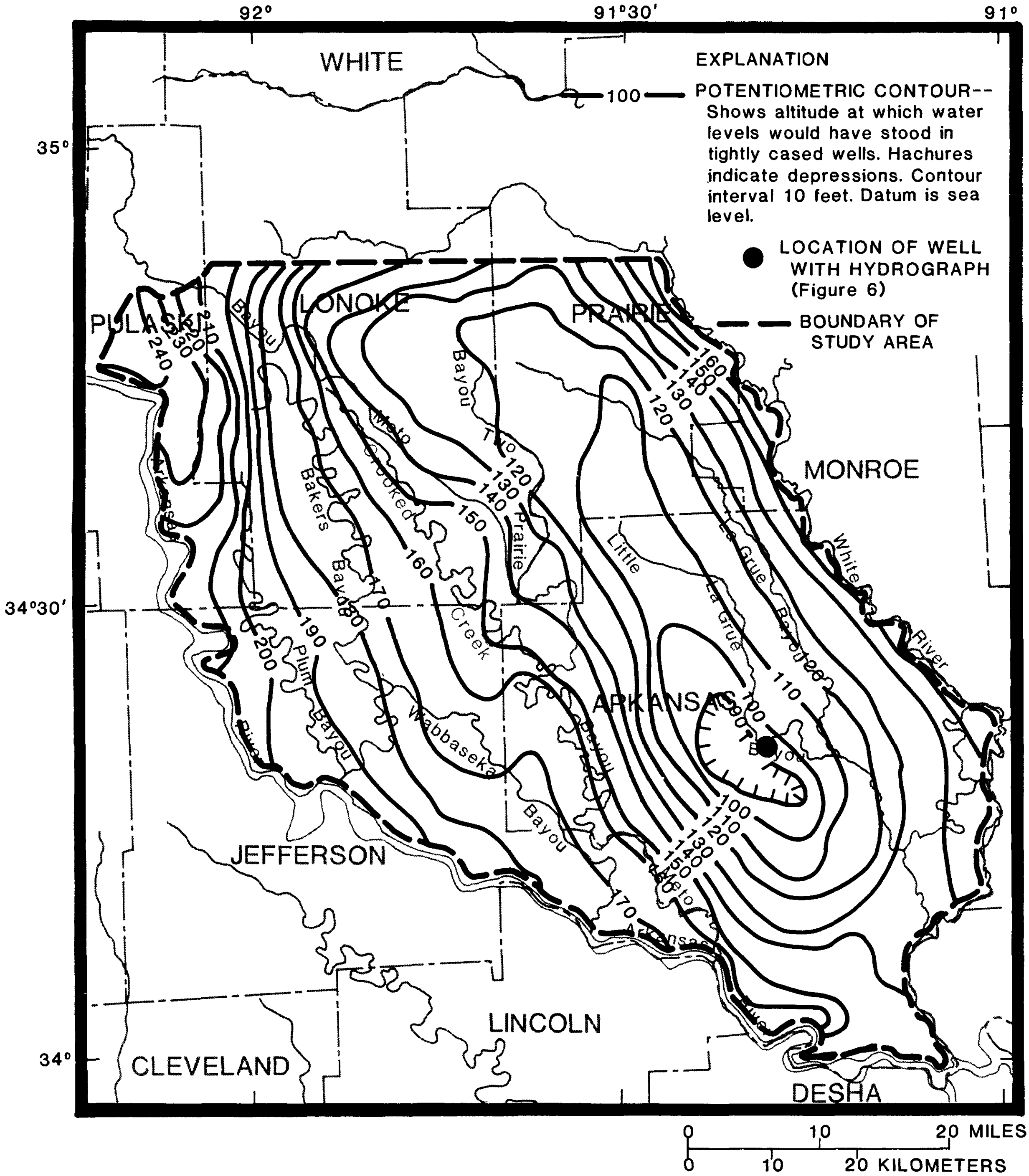

Figure 3.--Potentiometric surface of the alluvial aquifer in the Grand Prairie area, spring 1985 (modified from Plafcan and Fugitt, 1987).

The Quaternary deposits rest upon an eroded, irregular surface of the Tertiary sediments of the Jackson Group, predominantly a clay unit. This surface on the Jackson Group consists of a series of entrenched valleys that are filled with Quaternary alluvium. Geologic units of Tertiary age that underlie the Quaternary alluvium are listed in table 1.

Alluvial Aquifer

The alluvial aquifer generally corresponds to the sand and gravel, or the basal unit, of the Quaternary-age deposits. Although these deposits are made up of both terrace and flood-plain deposits, they are similar in lithologic characteristics and are hydraulically connected to form one continuous aquifer. The aquifer material grades from fine sand to coarse gravel, with the coarsest material generally found at the base of the aquifer. Lenses of clay, silt, or sandy silt are found in places within the aquifer but are rarely continuous (D.J. Ackerman, U.S. Geological Survey, written commun., 1988).

Thickness of the alluvial aquifer is variable, but generally increases northward. Aquifer thickness in the Grand Prairie area ranges between about 60 and 100 feet. Aquifer thickness in the area west of Crowleys Ridge generally ranges from 100 to 140 feet, except where the aquifer thins out near the Fall Line (Mahon and Ludwig, 1990).

The alluvial aquifer is underlain by a clay confining unit within the Jackson Group, and overlain by a nearly continuous clay confining unit in the upper part of the Quaternary alluvium. The alluvial aquifer generally is confined within the study area, except where heads have fallen below the top of the aquifer.

Transmissivity of the aquifer, a function of the saturated thickness and hydraulic conductivity of the sediments, has been estimated to range generally between 30,000 and 40,000 ft#/d (foot squared per day) within the area west of Crowleys Ridge and between 20,000 and 30,000 ft#/d within the Grand Prairie area (Mahon and Ludwig, 1990).

The value for storage coefficient of the alluvial aquifer, the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head, depends largely on whether the aquifer is in an artesian or water table condition in a given area within the study area. Where the aquifer is artesian, the storage coefficient is estimated to be 1×10^{-4}. Where water levels have declined below the top of the aquifer, the storage coefficient is estimated to be about 0.3 (Mahon and Ludwig, 1990).

Prior to development, flow in the alluvial aquifer generally was toward the south and east and was controlled to a large degree by topography and surface drainage. As a result of development, drawdown cones have formed because of large withdrawals for irrigation within both of the subareas (figs. 2 and 3). Flow in the aquifer in both areas is influenced by the areas of major withdrawals.

Table 1.--Generalized stratigraphic column in the study area

Erathem	System	Series	Group	Formation
Cenozoic	Quaternary	Holocene and Pleistocene		Alluvium and terrace deposits
	Tertiary	Eocene	Jackson	Undifferentiated
			Claiborne	Cockfield Formation
				Cook Mountain Formation
				Sparta Sand
				Cane River Formation
				Carrizo Sand
			Wilcox	Undifferentiated
		Paleocene	Midway	Undifferentiated

Drawdown has been severe in some places in the study area with heads dropping below the top of the aquifer and the saturated thickness being substantially reduced in some places. In the Grand Prairie area, water levels in wells have been drawn down as much as 80 feet below predevelopment levels (Ackerman, 1989). Minimum saturated thickness in the Grand Prairie area is about 20 feet (Plafcan and Edds, 1986). In the area west of Crowleys Ridge, water levels in wells have been drawn down about 50 feet below predevelopment levels (Ackerman, 1989).

Depth to water ranges from less than 20 feet to 100 feet in the area west of Crowleys Ridge (fig. 4) and from less than 20 feet to 120 feet in the Grand Prairie area (fig. 5). In both areas depth to water generally is greatest near the center of the drawdown cones.

Water-level trends within the study area largely have been in response to changes in pumping for irrigation. Water-level trends in the Grand Prairie area and in the area west of Crowleys Ridge are illustrated in figure 6. As shown, the trend throughout both areas generally has been downward. The actual magnitude of the downward trend largely is dependent upon the proximity of the area to major centers of pumping.

Recharge to the alluvial aquifer originates largely as leakage from the upper confining unit and from rivers. Smaller amounts of recharge originate from underlying units. Direct recharge to the alluvial aquifer by infiltration of precipitation generally is minimal due to the presence of the upper confining unit throughout most of the study area. A simulation of regional flow in the alluvial aquifer (D.J. Ackerman, U.S. Geological Survey, written commun., 1990) indicated that recharge from leakage through the upper confining unit generally ranged from about 1.4 to 1.9 in/yr (inch per year) in the 1980's. Larger amounts of recharge would be expected where the clay confining unit is absent. In the same study, recharge from rivers accounted for about 20 percent to more than 30 percent of the total recharge since the 1970's. Major sources of recharge from rivers within the study area are the Cache, White, Black, Arkansas, and Little Red Rivers and Bayou Meto. Much lesser amounts of recharge originate from units beneath the alluvial aquifer.

Discharge from the alluvial aquifer primarily occurs through wells, with lesser amounts occurring through evapotranspiration and leakage to confining units, rivers, and laterally adjacent hydrologic units.

Upper Confining Unit

Throughout most of the study area, the alluvial aquifer is overlain and confined by sediments consisting of clay, silt, and fine sand in the upper part of the Quaternary alluvium. These sediments, herein referred to as the upper confining unit, are relatively impervious and generally impede recharge to the alluvial aquifer. The upper confining unit generally is continuous throughout the study area, although it may be absent locally.

The depositional environments that produced the upper confining unit consisted of (1) braided streams, (2) meander belts, or (3) backswamps (Fisk, 1944, 1947; Krinitzsky and Wire, 1964). Deposition in all three environments was dominated by silts and clays or lenticular clays and sands. Only the braided stream deposits contain significant amounts of sand (Fisk, 1947).

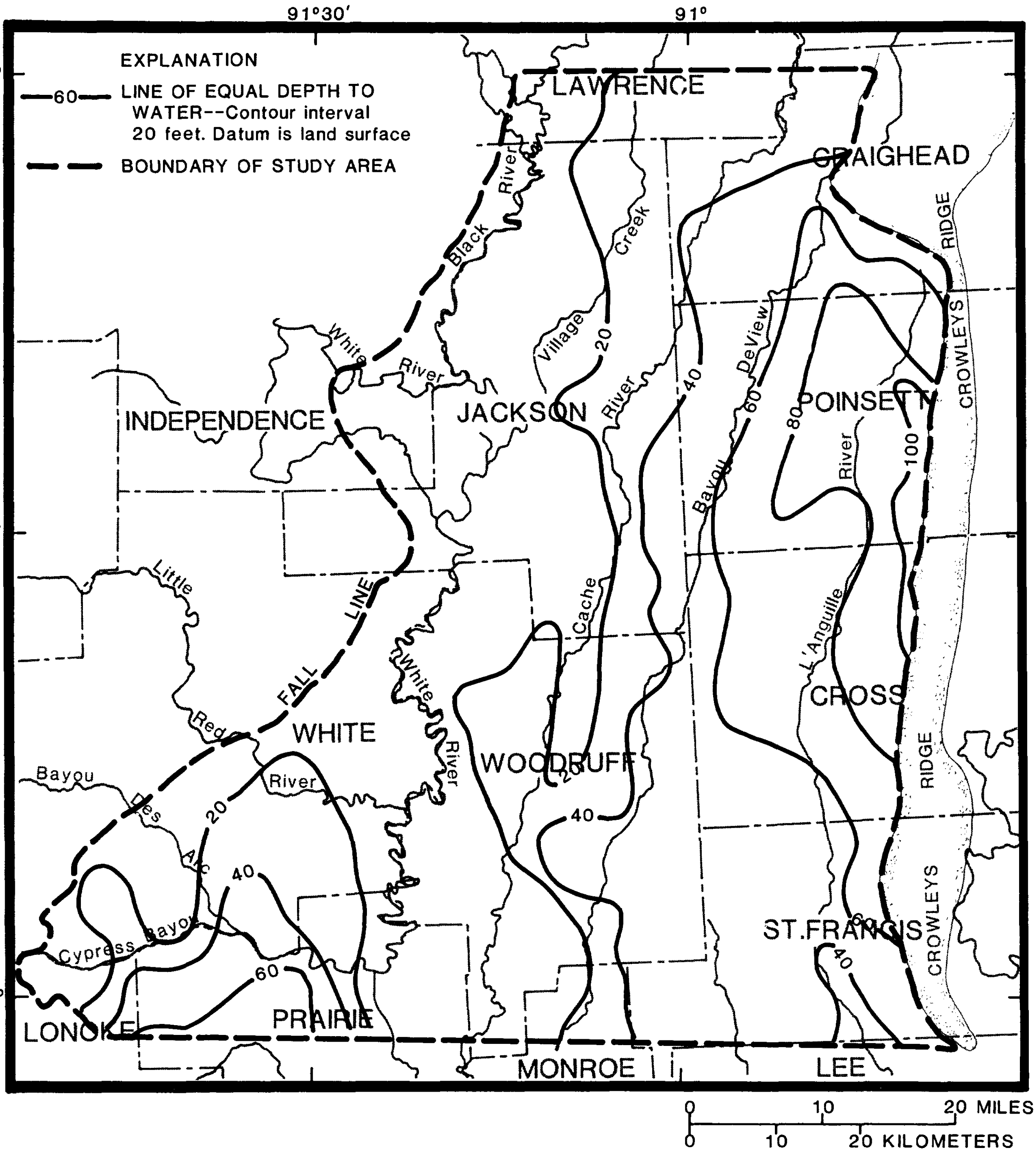

Figure 4.--Depth to water in the alluvial aquifer in the area west of Crowleys Ridge, spring 1985 (modified from Plafcan and Fugitt, 1987).

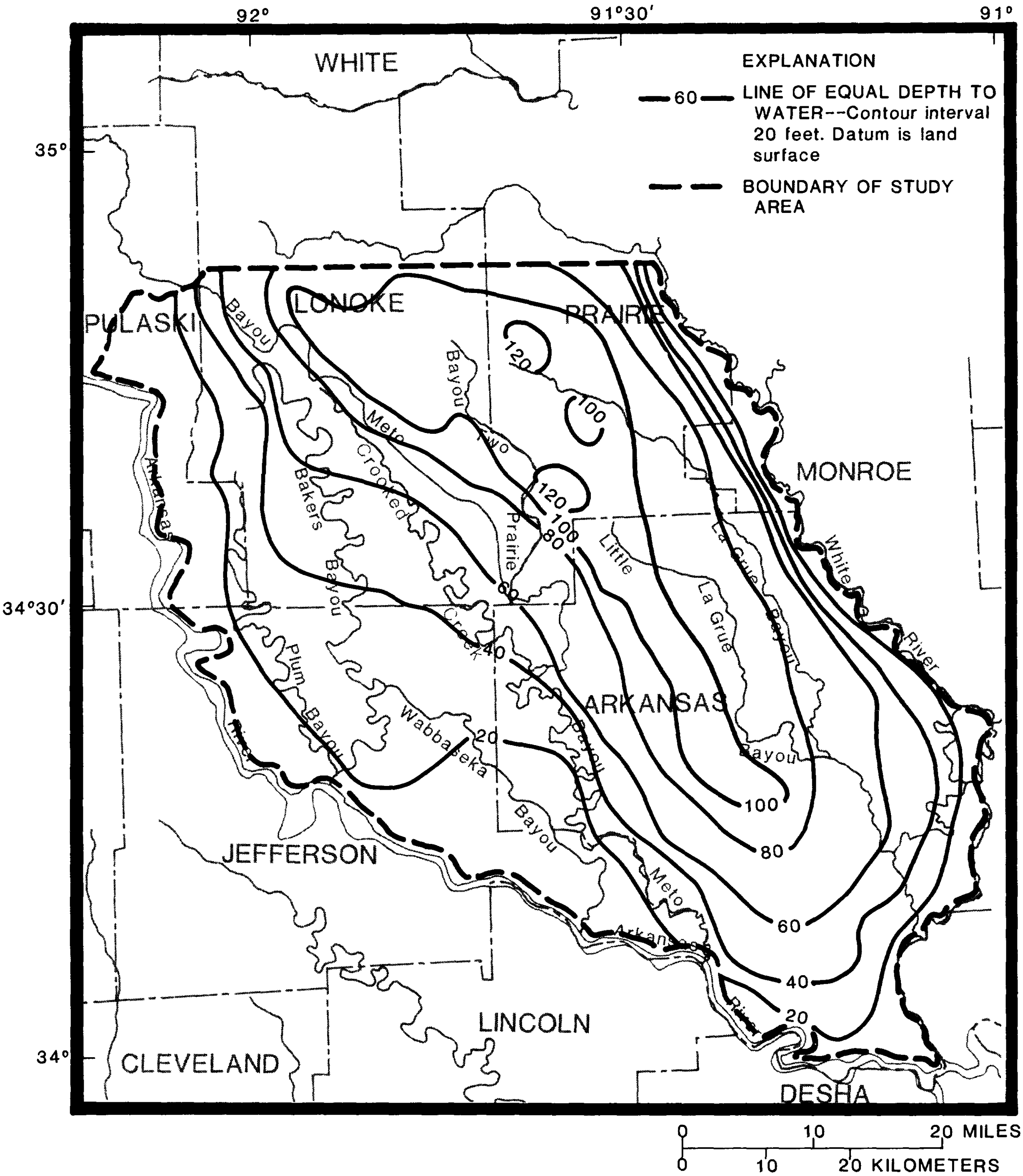

Figure 5.--Depth to water in the alluvial aquifer in the Grand Prairie area, spring 1985 (modified from Plafcan and Fugitt, 1987).

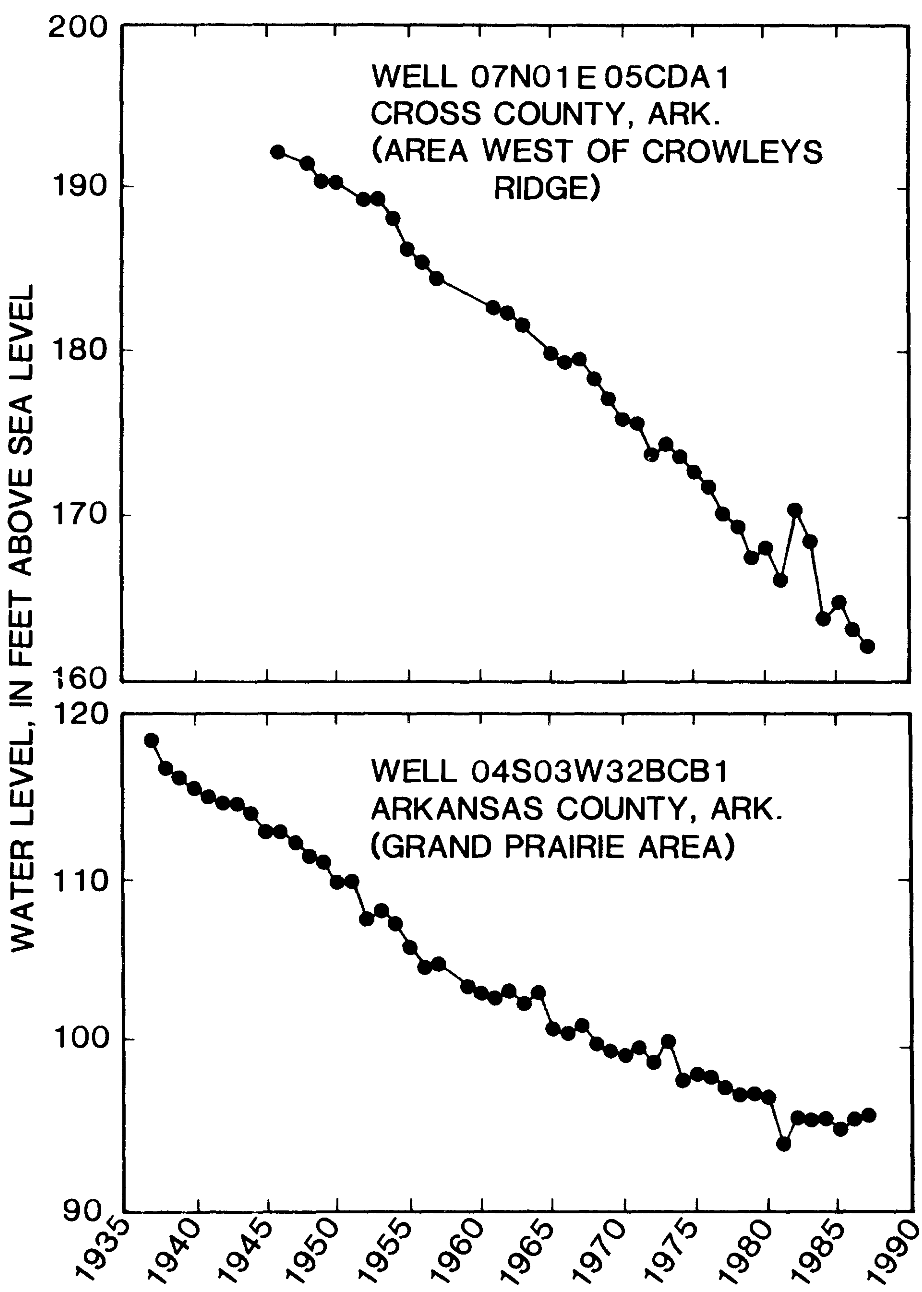

Figure 6.--Hydrographs of water levels in wells located in the area west of Crowleys Ridge (figure 2) and in the Grand Prairie area (figure 3).

The thickness of the upper confining unit within the study area is illustrated in figures 7 and 8. Most clay-thickness data were derived from water well driller's logs supplied by drillers to the Arkansas Geological Commission. Other data used were based on test holes completed through the Quaternary deposits (Krinitzsky and Wire, 1964), geologic maps of the Quaternary deposits (1:62,500), and cross-sectional data from Saucier (1967) and Smith and Saucier (1971).

Maps showing upper confining unit thickness in eastern Arkansas have recently been prepared by Ackerman (1989) and Mahon and Ludwig (1990). Some differences exist between these previous maps and figures 7 and 8. These differences primarily resulted from differences in scale and data aggregation procedures used in these previous investigations. Figures 7 and 8 are less generalized, showing relatively small areas of thinner or thicker confining unit not shown by Ackerman (1989) or Mahon and Ludwig (1990).

Because of the different depositional environments, upper confining unit thickness within the study area is highly variable. In the area west of Crowleys Ridge (fig. 7), it ranges in thickness from less than 10 to more than 40 feet. Thinnest sections of the upper confining unit occur near stream beds, whereas the thickest sections occur near Crowleys Ridge. Thickness of the upper confining unit in most of the area west of Crowleys Ridge (fig. 7) is between 10 and 20 feet.

The thickness of the upper confining unit in the Grand Prairie area (fig. 8) generally is greater than that in the area west of Crowleys Ridge. Upper confining unit thickness in the Grand Prairie area generally ranges from less than 20 to more than 80 feet, with only very small areas having a thickness of less than 20 feet.

POTENTIAL FOR ARTIFICIAL RECHARGE

Artificial recharge has been defined as the process of replenishing ground water through works designed specifically for that purpose (Oaksford, 1985). It is a means of augmenting water supplies in ground-water systems during periods of low demand, or when surface-water bodies contain excess water. Artificial recharge potentially would have the effect of resaturating dewatered parts of the alluvial aquifer, thus increasing the amount of water in storage and aquifer transmissivity. Pumping lift costs also would potentially be reduced due to increased water levels. A number of artificial recharge methods have proven effective depending on site-specific geohydrologic conditions. The following discussion will describe several artificial recharge methods, provide a preliminary assessment of the application of selected methods to the alluvial aquifer in eastern Arkansas, and examine economic considerations and system design.

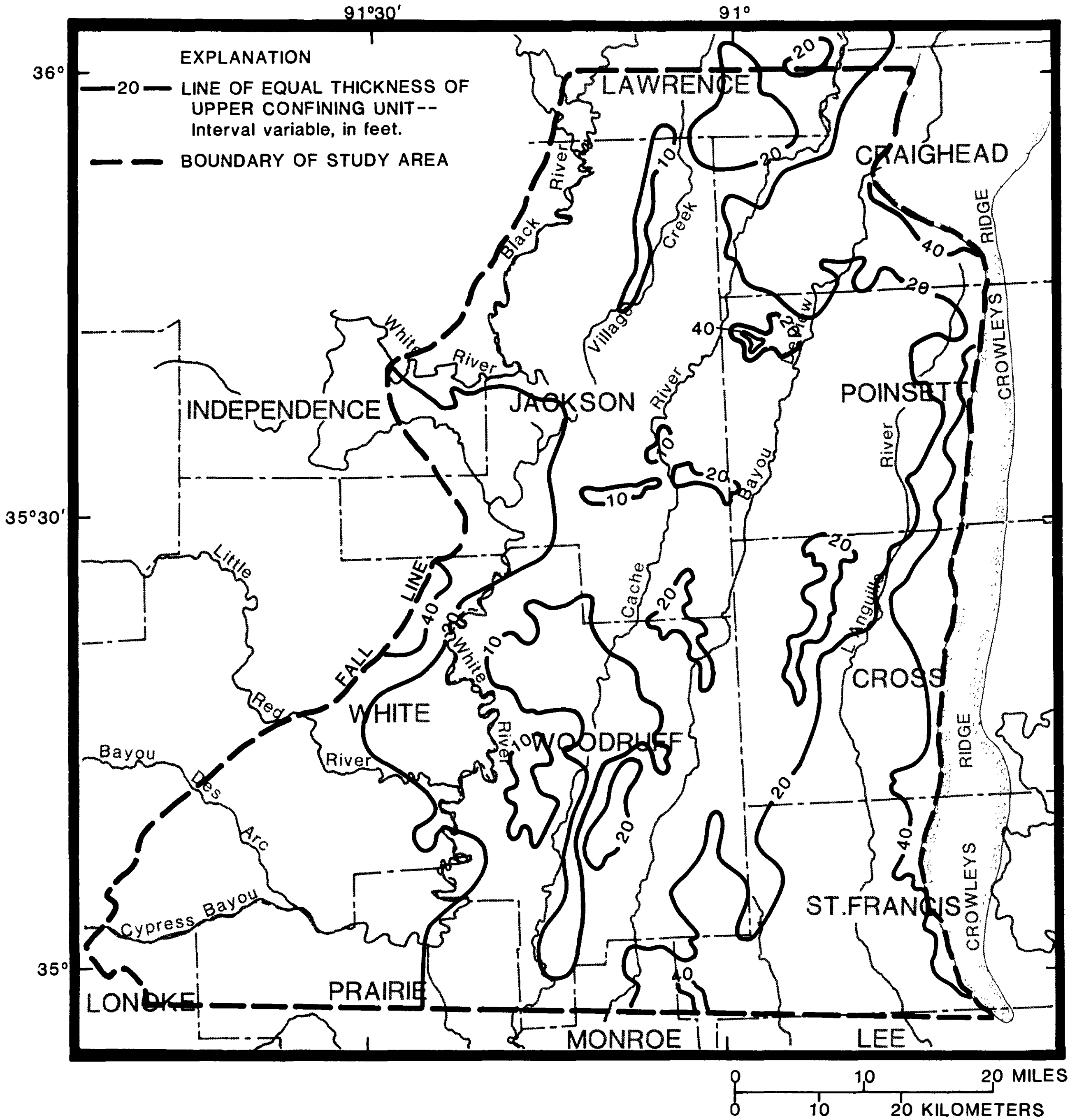

Figure 7.--Thickness of the upper confining unit in the area west of Crowleys Ridge.

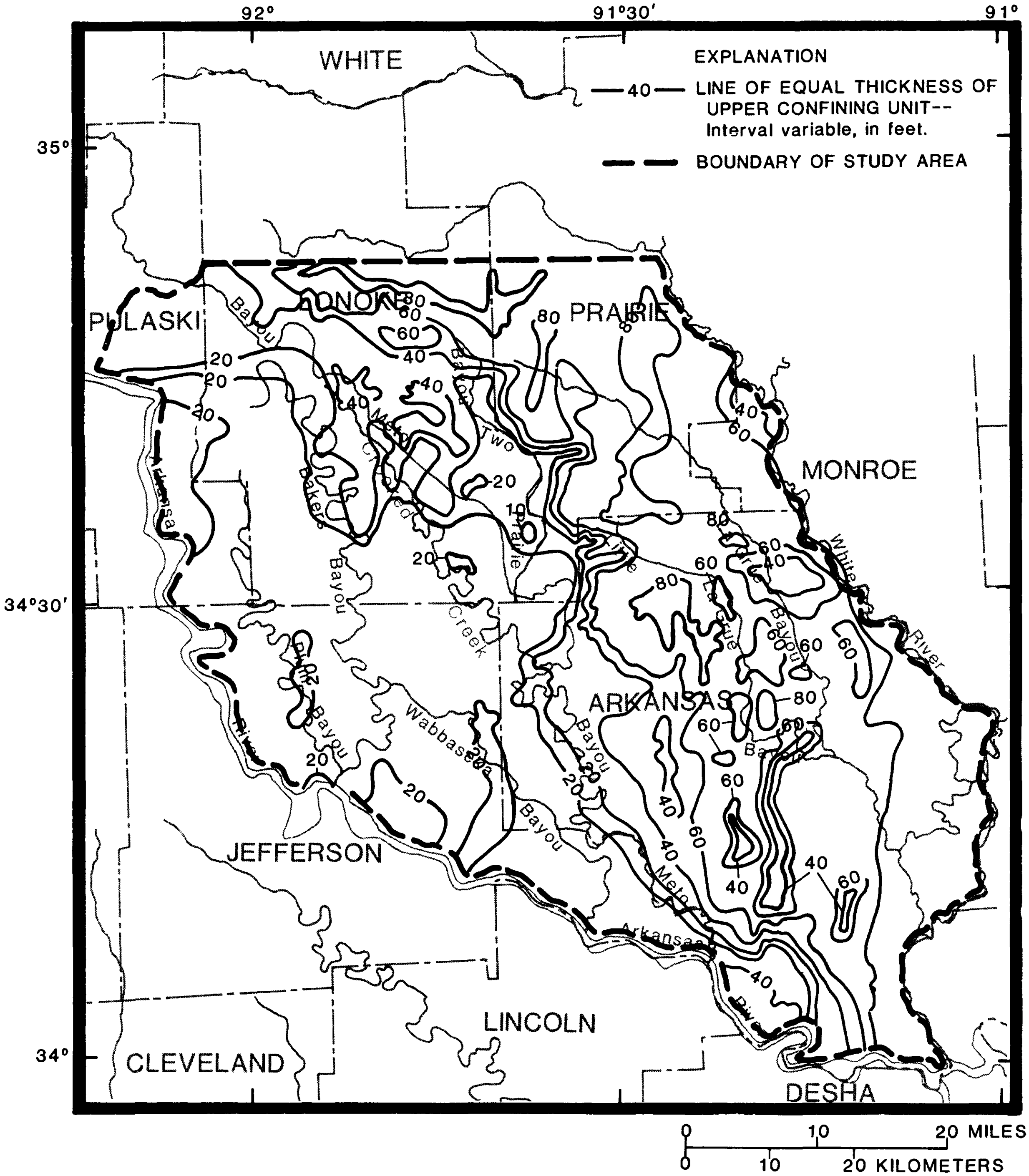

Figure 8.--Thickness of the upper confining unit in the Grand Prairie area.

Artificial Recharge Methods

Artificial recharge can be divided into surface and subsurface categories. Surface or water spreading methods that have proven successful under certain conditions include recharge through basins, flooding, ditch and furrow systems, overirrigation, stream-channel modification, and pits and shafts. Subsurface techniques can be utilized where surface techniques are not applicable, mainly where the aquifer to be recharged is overlain by a confining layer that substantially retards recharge from the surface. Subsurface recharge consists of conducting recharge water directly to the aquifer, chiefly through wells. Because of the greater costs involved, subsurface methods of recharge are utilized only where direct surface methods cannot be applied because of geohydrologic conditions or land availability constraints. Recharge to an aquifer can also be increased through indirect means that include inducing recharge by withdrawing water from an aquifer adjacent to a stream or other surface-water body. Although not strictly regarded as artificial recharge, methods for inducing recharge also are discussed in that they too result in an augmentation of the amount of ground water that can be developed from an area. The following provides a discussion of selected surface and subsurface artificial recharge methods and induced recharge methodologies.

Basins

Infiltration basins are one of the most widely used and favored methods for artificial recharge because they allow for the efficient use of land and require only simple maintenance (Oaksford, 1985). Basins generally are constructed through the placement of dikes and levees, or through excavation. Basins can be constructed singularly to collect local runoff or in series. Multiple basins are sometimes constructed along streams to recharge diverted streamflow, with the upper basin(s) used as a settling pond for silt and other particles. The size and shape of basins largely are governed by local topography, expected flows, and available land. Basins generally are more costly in flat terrains, since natural landforms cannot be utilized for containment and excavation becomes necessary. Some excavation may be warranted in any case in order to extend the bottom of the basins beneath any surface confining layer that might retard recharge rates below acceptable levels. More detailed information on basin construction is given in Oaksford (1985).

Recharge rates in basins vary widely, both between different locales because of geohydrologic factors and within individual basins through time because of clogging. Todd (1980) showed recharge rates at facilities with varying geohydrologic characteristics elsewhere in the United States ranging from about 4 in/d (inches per day) to 9.5 ft/d (feet per day). Basin clogging, resulting largely from the deposition of finer-grained particles, can result in decreases in recharge rates of greater than 6.5 ft/d (Todd, 1980). Periodic basin maintenance, including scraping, disking, or scarifying when dry generally restores basin recharge rates.

A site suitable for artificial recharge using basins, as well as many other direct surface methods, should have the following characteristics (modified from Bouwer, 1978):

1. The surface soil and the zone of aeration must be sufficiently permeable to yield acceptable infiltration rates and prevent the formation of perched ground-water mounds that could cause water levels to rise to the basin bottom.
2. The water table must be sufficiently deep so that the ground-water mound remains below the bottom of the basins, but not so deep that large quantities of recharge water are needed to saturate the zone of aeration before the mounded water table approaches the top of the aquifer.
3. The aquifer must be sufficiently transmissive and extensive to permit lateral movement of recharge water within the aquifer without building up ground-water mounds that rise to the bottom of the basin and cause a reduction in infiltration rates.

Flooding

Recharge by flooding can be utilized where topography generally is flat. The objective of this method is to spread diverted water over a large area in a thin sheet that travels at a minimum velocity so as not to disturb the soil. In general, higher infiltration rates occur where the soil and vegetative cover are undisturbed. In order to control water flow, the recharge area usually is surrounded by ditches or embankments. Advantages in using this technique include the relatively low cost of land preparation and maintenance. Problems related to the flooding method include water containment and evaporation losses. Also, this method is not very effective if the area to be flooded is underlain by a confining unit that retards or prohibits the downward flow of water to the aquifer.

Ditch and Furrow Systems

Using this method, water is diverted through a series of ditches or furrows that are closely spaced, shallow, and flat bottomed. Ditch and furrow systems generally utilize one of three designs: (1) dendritic, where a main canal diverts water into successively smaller canals or ditches; (2) lateral, where smaller ditches extend at 90° angles from a main ditch or canal; and (3) contour, where a ditch meanders back and forth following the general contour of the land. These designs are illustrated and described in more detail in Oaksford (1985). Potential clogging problems are minimized with this method because flow velocities through the system generally are high enough to carry away most suspended material that may occur in the recharge water and act as a clogging agent. This method is most efficient if the bottom of the ditch and furrow system is below any surface confining layer.

Overirrigation

This method basically consists of recharging an aquifer by irrigating land with surface water or treated wastewater during nongrowing seasons. The existing irrigation system is used, thus requiring no additional equipment, construction, or land preparation costs. Overirrigation might result in the leaching of salts as well as soil nutrients from the root zone to the aquifer.

Stream-Channel Modification

The stream channel modification method entails altering a stream channel so that infiltration is enhanced through streamflow detention and through increasing the area over which water can infiltrate. Sometimes a series of earthen check dams or levees are constructed to increase the wetted area as well as the retention time.

The advantages of such methods, where suitable, are that construction and maintenance costs are relatively low, and the method rarely conflicts with other land uses. The principal disadvantage is that these structures are frequently destroyed during high streamflow periods.

Pits and Shafts

Pits and shafts are constructed such that the bottom of the structure penetrates through any relatively impervious surficial material or overlying confining unit to the aquifer. Depth of pits can vary depending on thickness of the overlying confining layer. Slopes generally are steep on pit sides; clogging occurs chiefly at the bottom. Abandoned gravel pits or quarries are commonly employed as recharge pits to minimize excavation costs. However, these structures are not prevalent in the study area.

Recharge Wells

Recharge wells, most commonly injection wells, generally are used in confined aquifers, where ground water is deep, or where geohydrologic or land-use considerations make surface methods impractical. Injection-well construction generally is similar to supply or withdrawal well construction; that is, injection wells usually are cased down to the top of the aquifer or zone to which the injection will take place, with either screen or open hole through the aquifer or desired injection zone. Typically the casing is sealed or grouted to prevent leakage up the outside of the casing during injection. Water is injected into the aquifer under pressure or gravity, with injection rates and pressures largely dependent on well construction, hydraulic properties of the aquifer, and head buildup in the well and aquifer due to clogging during injection.

Effective performance of the recharge well can be severely affected by several factors. These include (1) well clogging caused by an accumulation of suspended solids that are contained in the recharge water, (2) biological growth, (3) chemical reactions between the native ground water or aquifer materials and recharge water resulting in the precipitation of insoluble products or the swelling or deflocculation of clays, (4) precipitation of insoluble products due to aeration, and (5) air entrainment (Sniegocki, 1963b). Many clogging problems can be avoided through pretreatment of the recharge water. The degree of treatment required largely depends on the quality of the recharge water and hydraulic characteristics of the aquifer. Water treatment, however, commonly greatly increases the cost of injecting. Well-clogging effects usually can be corrected by well-redevelopment techniques such as air surging, pumping, and well acidification.

Injection rates are highly variable, largely depending on well construction and aquifer hydraulic-characteristics. Todd (1980) showed average well recharge rates at selected locations in the United States to vary between 0.08 and 13.48 Mgal/d.

Induced Recharge

Recharge is induced when water is withdrawn from an aquifer adjacent to a stream or other surface-water body. Pumping lowers the head in the aquifer, reverses or increases the hydraulic gradient toward the aquifer, and causes movement of water from the strear to the aquifer. This method has proven effective in unconsolidated formations of permeable sand and gravel hydraulically connected to streams (Todd, 1980). Factors affecting the amount induced from surface-water sources include the rate of pumping as it affects the gradient, distance of pumping well from the stream, the degree of hydraulic connection between the stream and aquifer, and hydraulic properties of the aquifer. The principal advantage of induced recharge over direct utilization of the surface water is the improved water quality that results from the filtering effects afforded by the movement of surface water through unconsolidated deposits.

Preliminary Evaluation of the Potential of Selected Artificial Recharge Procedures in Eastern Arkansas

Several factors influence the suitability of any individual method to recharge the alluvial aquifer in eastern Arkansas. Some major controlling factors pertain to the site-specific geohydrologic characteristics of the proposed recharge areas. These include aquifer transmissivity, storage availability, hydraulic gradients, and hydraulic properties of overlying materials. Other considerations not specifically included as part of this discussion include the quality and availability of recharge water, and economic considerations.

The variability of the geohydrologic characteristics of the alluvial aquifer and the overlying upper confining unit allows for the potential for applying various artificial-recharge techniques to exist locally within the study area. The following discussion consists of a preliminary evaluation of the applicability of selected artificial recharge methods to the alluvial aquifer in eastern Arkansas. Methods that are evaluated are basin recharge and well recharge. These techniques do not necessarily represent all possible methods that could be applied locally to the alluvial aquifer in eastern Arkansas, but rather those techniques deemed to have the greatest potential.

Basin Recharge

The preliminary analysis of the suitability of basins to artificially recharge the alluvial aquifer within the study area was accomplished by examining the thickness of the overlying clay confining unit as given in figures 7 and 8. Although other factors contribute to the overall feasibility of using basins, the areal extent and thickness of the confining unit is probably the most critical in terms of potential for artificial recharge. The presence of any substantial thickness of clay at the surface, unless removed, likely would reduce recharge rates to unacceptable levels. Because of large local variations in geohydrologic properties, detailed site-specific investigations of pertinent geohydrologic factors would be required to ultimately determine the feasibility of basins or any of the other surficial methods to recharge the alluvial aquifer in eastern Arkansas.

The greatest potential for recharge using basins or other direct surface methods would be in areas where the confining unit ranges in thickness from 0 to 10 feet. Artificial recharge using surface methods in areas where the thickness is greater than this amount would probably not be feasible. Where the confining unit is less than 10 feet thick, the confining material could be removed as part of the basin construction. Basins or any of the other surficial methods discussed could be used to recharge the alluvial aquifer where the upper confining unit is absent.

The only relatively extensive areas that have upper confining unit thickness of 10 feet or less are located in the area west of Crowleys Ridge along the Cache River and Village Creek (fig. 7). However, confining unit thickness in a much larger area west of Crowleys Ridge is from 10 to 20 feet (fig. 7). Application of surface recharge techniques in this area might be possible but is considered to have low potential because of the expense of removing the confining unit. Maximum thickness of the upper confining unit in the area west of Crowleys Ridge exceeds 50 feet.

Thickness of the upper confining unit is greater within the Grand Prairie area. Maximum thickness in this area exceeds 80 feet. Places where the confining unit is thinnest (10 to 20 feet) within the Grand Prairie area, generally are adjacent to the Arkansas River. Few areas within the Grand Prairie area were found that contained thicknesses of less than 10 feet. In terms of the preliminary assessment, direct surface methods of artificial recharge generally have little potential anywhere in the Grand Prairie area.

Although the data on figures 7 and 8 do not preclude the possibility of localized differences, they do give a general indication of areas with potential for recharge using direct surface techniques. The actual feasibility of a direct surface technique in a given area would require further investigation of local geohydrologic characteristics. Additional data collection requirements might include soil surveys, test drilling, geophysical surveys, measurements of aquifer head relations, relative determinations of hydraulic conductivity, both in the zone of aeration as well as below the water table, and actual testing to determine potential infiltration rates and buildup of ground-water mounds.

Well Recharge

Artificial recharge through well injection generally is utilized where (1) the aquifer is separated from the surface by a confining layer, (2) where the water table is deep, or (3) where topography or land use make artificial recharge using basins or other direct-surface techniques unsuitable. Throughout most of the study area, the presence of a relatively impermeable clay layer makes recharge through wells generally the only potentially viable technique to artificially recharge the alluvial aquifer, particularly in those areas where drawdown is greatest. During well recharge tests performed as part of a pilot study of well recharge to the alluvial aquifer in the Grand Prairie area (Sniegocki and others, 1965), water was injected at rates varying between 37 and 860 gal/min (gallons per minute). Maximum sustainable injection rate at any given area would depend on specific geohydrologic conditions at the site such as transmissivity and head buildup.

In terms of a preliminary evaluation of the suitability of well recharge, the potential for well recharge occurs throughout most of the study area. However, the economics of utilizing well recharge is the principal controlling factor to the overall suitability of artificial recharge as opposed to other alternatives of augmenting water supplies within the study area. Although a detailed economic analysis of well injection within the Grand Prairie area is beyond the scope of this investigation, some discussion on economic aspects follows.

Economic Considerations

In addition to geohydrologic conditions at prospective sites, a major factor in evaluating the suitability of an artificial-recharge technique is the economic cost of project implementation. The total cost of a recharge operation would depend on the cost of recharge as well as the amount of water that could be recovered per unit of recharge water injected. Factors that influence the cost of an artificial-recharge technique include (Abe, 1986):

1. quantity and quality of the recharge water,
2. the recharge technique,
3. the distance from the water-diversion point to the recharge site,
4. the availability and value of land,
5. energy requirements and available power rates,
6. geohydrologic characteristics at the recharge site,
7. institutional constraints, and
8. opportunity costs of storing water.

All of the aforementioned factors would influence, to varying degrees, the cost of prospective artificial-recharge techniques within the study area. The relative importance of these cost factors largely depends on the type of technique used. Basin recharge and most other direct-surface techniques generally are less costly than well recharge, and are the preferred technique when the option for both types of techniques exists. However, within the study area, geohydrologic factors dictate which type of technique, if any, can be used, rather than economic considerations. Economic factors would then come into play in evaluating artificial-recharge techniques against other means of augmenting water supply.

Major cost factors to be considered for basin recharge include conveyance costs, land requirements, and pumping costs. Other costs include basin construction and maintenance. Water treatment, a major cost with well injection, generally is not a consideration, at least to the same extent, with basins. Pretreatment is sometimes required when wastewater or water high in suspended sediment is utilized as a recharge source.

Artificial recharge costs for selected basin infiltration recharge studies in other states are given in table 2. The much greater project costs in Butler Valley, Ariz., and Oceanside, Calif., (table 2) largely are a result of increased costs for water conveyance to the recharge sites (Vaux, 1985; Abe, 1986).

Table 2.--Costs of artificial recharge projects using basins at selected sites

Location	Cost (dollars per acre-foot)
Butler Valley, Arizona[a]	$130-$153
Camp Pendleton, California[b]	$11.50
Hemet, California[b]	$24
Oceanside, California[b]	$107
Phoenix, Arizona[b]	$6
Whittier, California	$11
San Clemente, California[b]	$30

[a]Abe (1986)

[b]Vaux (1985)

The major cost component associated with well recharge is the more advanced water treatment required because of plugging problems inherent in most well injection operations. Other costs of recharge well operation include those involving well construction, water conveyance, well rehabilitation, pumping, and energy consumption. Total costs could vary considerably between locations depending on local conditions at individual sites.

A cost analysis of a recharge project in the Grand Prairie area (Sniegocki and others, 1965) estimated the total cost in 1962 of recharge and recovery to be about $50 per acre-foot. At that time, well recharge was determined to be economically unfeasible as a means of solving the problems of ground-water supply (Sniegocki, 1963b). This cost figure is unadjusted for inflation between 1962 and the present time. Cost estimates of other investigations are given in table 3. The considerably higher costs denoted in the studies in Orange County, Calif., Nassau County, N.Y., and El Paso, Tex. mainly are attributed to the more advanced water treatment required for the injection of treated wastewater.

Table 3.--Costs of artificial recharge projects using injection wells at selected sites

Location	Cost (dollars per acre-foot)
Butler Valley, Arizona[a]	$ 248
Palo Alto, California[b]	$ 219
Orange County, California[b]	$ 584
Nassau County, New York[c]	$1,290
El Paso, Texas[d]	$ 612

[a]Abe (1986)

[b]Vaux (1985)

[c]Oliva (1985)

[d]Knorr and Cliett (1985)

System Design Considerations

The design and implementation of an operating recharge system is determined largely by constructing a test site and analyzing appropriate geohydrologic properties as they relate to recharge capabilities, and by examining local water requirements. Required site-specific data largely would depend on the type of recharge technique used. Data needs used in determining design criteria for a basin recharge system include: (1) soil surveys, (2) geophysical surveys, (3) test drilling, (4) hydraulic conductivity of the vadose zone and the aquifer, and (5) potential infiltration rates and buildup of ground-water mounds (Bouwer, 1978). Data needs used in determining design criteria for a well injection system include (1) data on aquifer properties, well depth, screen length, size and setting obtained from test well construction and analysis, and (2) injection rates, head buildup, and water-treatment requirements resulting from injection testing.

A pilot study of well injection at a site in the Grand Prairie area is described in detail in Sniegocki (1963a, 1963b, 1964); Sniegocki and Reed (1963); Engler and others (1963); Johnson and others (1966); and Sniegocki and others (1963, 1965). These discussions include a description of geohydrologic characteristics at the test sites, equipment and system design, testing procedures and results, water quality aspects, and special problems. Because of the similarities in geohydrologic conditions as well as other ambient factors with the study area in this report, much of the design criteria developed in the Grand Prairie study largely would be applicable to these areas. Some modifications would be required where significant variations in geohydrologic conditions occur. Proper engineering design is critical to the long-term success of a well injection system.

Design criteria based largely on the findings of the Grand Prairie study would include the need for all system components that come in contact with water to be constructed of corrosion-resistant materials such as stainless steel or polyvinyl chloride (PVC). Ideally, recharge wells would be constructed to serve the dual function of both recharge and withdrawal. These wells typically range in diameter between 8 and 26 inches. The larger diameter wells are preferred because they afford the opportunity to install accessory equipment and increase the size of the well screen surface area (Sniegocki and others, 1963).

The well casing should be grouted just above the well screen to ensure that the flow of water is from the screen to the aquifer. Recharge through the well can be accomplished by gravity feed as done in the Grand Prairie study, or by injecting under pressure.

A major problem with artificial recharge through wells is well clogging. Major factors causing clogging (Sniegocki, 1963b) include:

a. air entrainment,
b. suspended matter in the recharge water,
c. bacterial contamination of the aquifer by the recharge water and subsequent clogging by bacterial growth, and
d. reactions between the recharge water and the native ground water and aquifer material.

Certain design criteria, specifically injection pressures and rates, can reduce clogging effects in the aquifer and at the well-aquifer interface. For example, air entrainment can be minimized by preventing air from entering anywhere in the line, maintaining pressure in the injection line above atmosphere, and placing the bottom of the injection line at least 8 feet below the water-level surface in the well (Huisman and Olsthoorn, 1983). Air entrainment resulting from cavitation produced by excessive flow can be avoided by matching head loss in the line to the head difference between the pump and water level in the aquifer (Reeder and others, 1976). Optimum injection pressures and rates are influenced to a large degree by local geologic conditions as well as the type and size of the injection line and well casing.

Clogging by suspended material and biological growth can be significantly reduced by pretreatment of the recharge water. Water-treatment methods commonly include processes for coagulation and settling out of suspended solids, chlorination, and filtration. The water-treatment system utilized in the Grand Prairie study is described in detail in Sniegocki and others (1963).

Probably the greatest potential for clogging through chemical interactions is the swelling and dispersion of clay particles, and subsequent reduction of pore space. This occurs when the ratio of calcium (Ca^{2+}) and magnesium (Mg^{+}) ions, to sodium (Na^{+}) and potassium (K^{+}) ions is reduced as a result of the injection. These types of interactions probably can be prevented by selection of another type of recharge water or adding $CaCl_2$ to the recharge water. This process is discussed in detail in Huisman and Olsthoorn (1983). Many of the effects of well clogging that have occurred can be alleviated by physical or chemical means. These include periodically backflushing the well for 10 to 15 minutes, to remove trapped material and growth that have accumulated at the well-aquifer interface. This technique has proven effective in reversing some, but not all, of the cumulative head buildup effects (Sniegocki and others, 1965).

More intensive methods may be necessary to restore a recharge well to its preinjection condition. These methods include scrubbing and the use of water jets to clean the well screen and gravel pack. Chemical cleaning often is required to dissolve deposits and encrustations formed at and near the well-aquifer interface. In the Grand Prairie study, sodium hexametaphosphate was used successfully as a redevelopment agent (Sniegocki and others, 1965). Other chemical agents used for well redevelopment purposes include sodium hypochlorite (NaOCl), calcium hypochlorite ($Ca(OCl)_2$), hydrochloric acid (HCl) and sulphuric acid (H_2SO_4) (Huisman and Olsthoorn, 1983).

Observation wells also are an integral part of an artificial recharge operation, whether the project is operational or experimental (Sniegocki and others, 1963). Observation wells inside and immediately outside a recharge well are required, as these are the areas where the most severe plugging effects are likely to occur. Wells at greater distances also would be required to monitor long-term effects of recharge operations. Sniegocki and others (1963) recommended at least three observation wells for these purposes. All observation wells would be utilized for monitoring water levels and water quality.

A major consideration in the design of an operational artificial recharge system would be the amount and rate of recharge needed to meet some predesigned goal, such as target water levels or water demand. Anticipated water needs within the study area based on computer model simulation by Cantiller and others (1988) are given in figures 9 and 10. Shown in the figures are values of unmet demand in each model cell resulting from simulation of the system with pumping stress based on projected pumpage estimates for the year 1990 by the U.S. Soil Conservation Service. The pumpage estimates assumed that water-conservation procedures would be utilized. The simulation was run until the system reached an equilibrium condition. The values represent the amount of water needed to meet ground-water demands after available ground-water and surface-water supplies are utilized, while maintaining the saturated thickness in the aquifer at an arbitrary minimum of 20 feet.

As shown, unmet demand within any of the 3x3 mile grid cells overlying the study area ranged from 0 to nearly 10,000 acre-ft/yr. The unmet demand in cells in the area west of Crowleys Ridge generally ranged from about 1,500 to 4,000 acre-ft/yr (fig. 9). The total unmet demand in the area west of Crowleys Ridge was about 153,000 acre-ft/yr. Unmet demand in cells in the Grand Prairie area generally ranged from about 2,500 to 5,000 acre-ft/yr (fig. 10). The total unmet demand in the Grand Prairie area was about 352,000 acre-ft/yr.

Areas found to have geohydrologic conditions favorable for basin recharge generally do not coincide with areas having unmet water demand based on the model simulation. Therefore, if the unmet water demand is to be satisfied by artificial recharge, recharge wells offer the only viable option in those water short areas. By assuming an average recharge rate for the study area based on the maximum rate used in the Grand Prairie pilot injection study of 860 gal/min (Sniegocki and others, 1965), the number of recharge sites or wells required to meet all or part of the unmet demand within the study area as shown on figures 9 and 10 can be calculated. An injection rate of 860

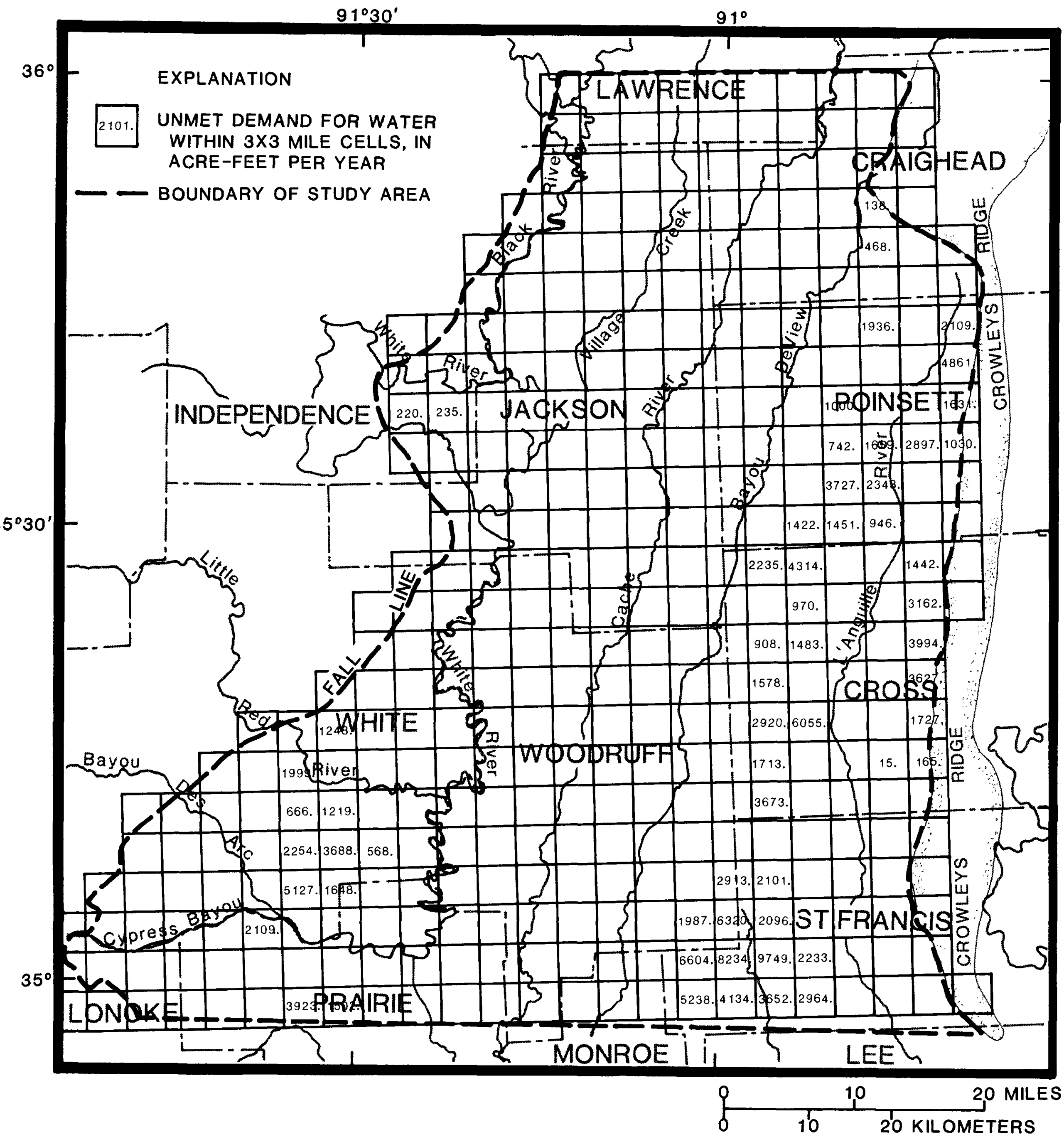

Figure 9.--Projected unmet water demand resulting from pumpage estimates for 1990 for 3X3 mile cells in the area west of Crowleys Ridge (modified from Cantiller and others, 1988).

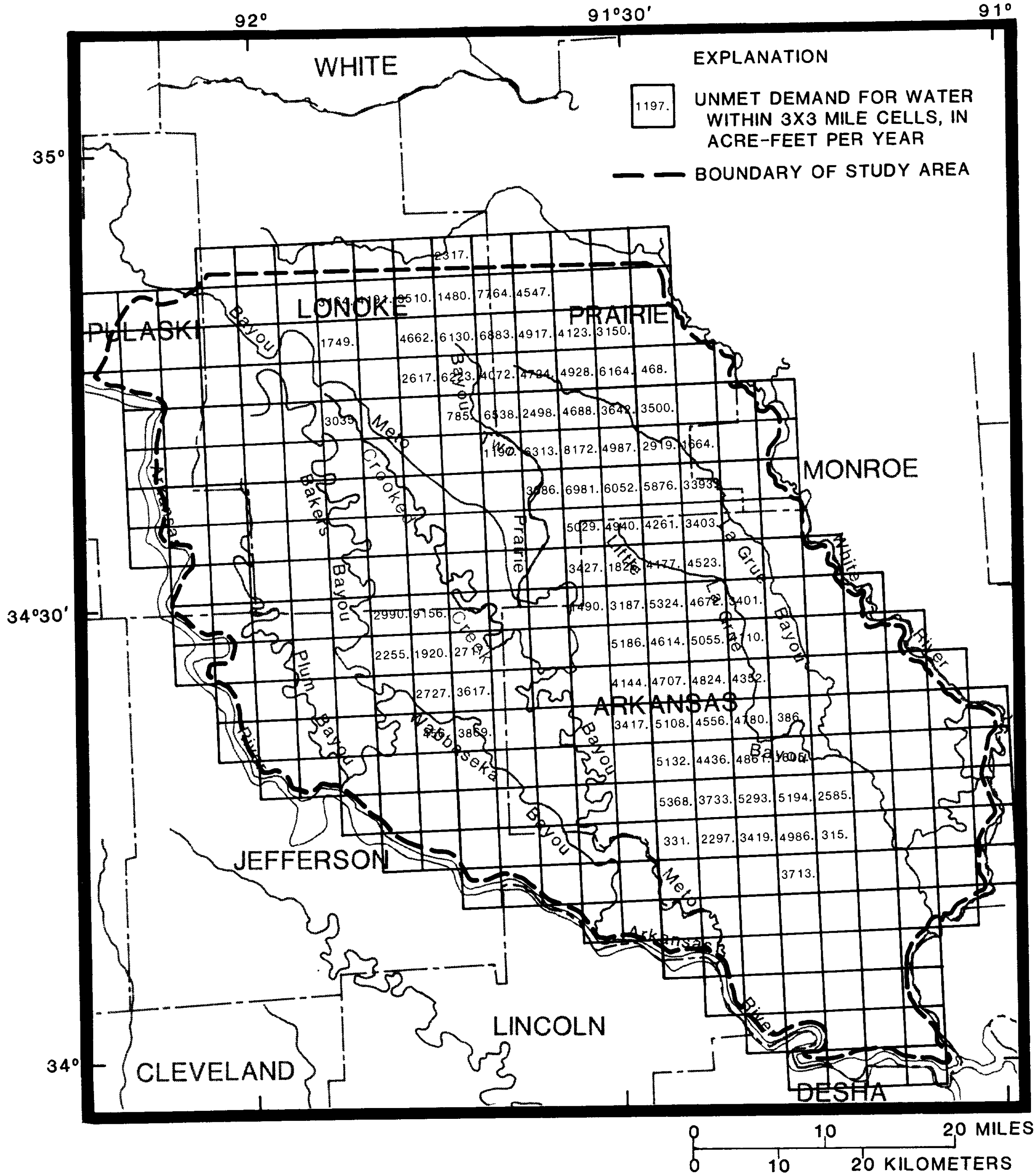

Figure 10.--Projected unmet water demand resulting from pumpage estimates for 1990 for 3X3 mile cells in the Grand Prairie area (modified from Cantiller and others, 1988).

gal/min or 0.00264 acre-ft/min (acre-foot per minute) corresponds to about 1,400 acre-ft/yr (acre-foot per year) if injected continuously over a 12-month period, or 700 acre-ft/yr if injected continuously for a 6-month period. Injection would take place during all or part of the nonirrigation season (October through April) when an excess of surplus surface water is more likely to occur.

Based on an injection rate of 700 acre-ft/yr, a total of 220 wells would be required in the area west of Crowleys Ridge to meet the total unmet water demand (fig. 9). Based on the same average injection rate, a total of 500 wells would be required in the Grand Prairie area to meet the total unmet water demand (fig. 10). The number of wells required to meet the unmet water demand could be lowered if recharge took place for more than 6 months per year or if the recharge rate was increased. The injection rate would vary, because it is largely a function of geohydrologic properties at the recharge site, well construction, injection pressure and head buildup. The recharge wells would be most efficient if they are placed so that minimum interference of the head buildup between wells occurs, and local water requirements are met.

SUMMARY

The alluvial aquifer is the major source of water supply for irrigation in eastern Arkansas. Heavy pumpage over the years has resulted in significant declines in the potentiometric surface of the alluvial aquifer of as much as 80 feet, most prominently in the Grand Prairie area and in an area west of Crowleys Ridge. The potential for water shortages and the depletion of ground-water supplies led State and Federal authorities to consider alternate sources of water to augment existing supplies where needed. One of the options under consideration is artificially recharging the alluvial aquifer. Artificial recharge has proven effective in augmenting ground-water supplies in many locales where geohydrologic conditions permit.

Recharge methodologies examined in this report for their applicability to the alluvial aquifer within the study area are recharge through basins and through wells. In terms of a preliminary analysis, the major controlling factor as to the suitability of basins as well as other direct surface techniques for recharge in eastern Arkansas is the presence and thickness of the upper confining unit. The greatest potential for the use of basins is where the upper confining unit is thinnest or absent. The only relatively extensive areas where the upper confining unit is either absent or less than 10 feet thick are the areas west of Crowleys Ridge along the Cache River and Village Creek. These are probably the only major areas within which a potential for recharge using basins exists. Upper confining unit thickness elsewhere within the study area is highly variable and exceeds 80 feet in places. Actual feasibility of artificial recharge through basins in a given area would require further investigation of geohydrologic characteristics. Artificial recharge through wells generally is an option when recharge through direct-surface techniques is not feasible. In terms of geohydrologic considerations and in the context of a preliminary analysis, the potential for well recharge generally exists throughout the study area.

A major consideration in terms of determining the feasibility of an artificial recharge technique is the economic cost of project implementation. The total cost of any recharge operation would depend on the cost of recharge

and the amount of water that could be recovered per unit volume of recharge water injected. Recharge through basins is less costly than recharge through wells, and thus is the preferred method, where applicable. Major costs pertaining to well recharge include water treatment, well construction, water conveyance, well rehabilitation, pumping, and energy consumption.

The appropriate design of an artificial-recharge system is critical to the long-term success of that system. Design criteria are usually determined by first constructing a test site and analyzing appropriate local geohydrologic properties, and examining water needs as part of implementation of an operational recharge system. Data needs largely would depend on the type of recharge technique used.

Design criteria for a well-recharge system include the use of non-corrosive components that come in contact with water. Recharge wells can vary in size, with larger diameter wells being the preferable. Recharge can be by gravity feed or by injecting under pressure. Strategically located observation wells are necessary to monitor water-quality changes and well clogging, probably the most significant problem of any well-recharge system.

The principal design element in reducing clogging is the pretreatment of the recharge water to remove suspended matter. Other design elements in reducing clogging include the use of appropriate injection pressures and rates and the selection of a chemically compatible recharge water. A means for alleviating or reversing the actual effects of well clogging also is a necessary part of a well-recharge system. The techniques for reducing clogging include physical means such as backflushing, or scrubbing, and chemical means such as well acidizing.

A major consideration in the design of an operational recharge system would be the amount of recharge needed to meet some predesigned goal, such as target water levels, or water demand. Based on pumpage projections for the year 1990, the amount of water required from additional sources to maintain a minimum saturated thickness of 20 feet in the alluvial aquifer is a total of 153,000 acre-ft/yr in the area west of Crowleys Ridge, and 352,000 acre-ft/yr in the Grand Prairie area. Assuming an average recharge rate of 700 acre-ft/yr/well, about 220 wells would be required to meet the projected demand in the area west of Crowleys Ridge, and about 500 wells to meet the projected demand in the Grand Prairie area.

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