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WATER-RESOURCES DEVELOPMENT ALTERNATIVES FOR THE MISSISSIPPI ALLUVIAL PLAIN IN EASTERN ARKANSAS

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ABSTRACT: Effective management of the water resources of the Mississippi Alluvial Plain in eastern Arkansas involves understanding the nature of existing problems, estimating total water demands, predicting how much of the total demand can be provided by the underlying aquifer and available surface-water sources, and deducing how much water must come from alternate sources. Various Federal and State agencies have cooperatively provided hydrologic information for the area to evaluate water-resources development alternatives ensuring that (1) the use of water from the aquifer be maximized while maintaining a minimum of 20 feet of saturated thickness, (2) the use of surface water be maximized where it is currently available, and (3) alternate sources of water (surplus surface water) be identified for use in deficit areas.

Water-resources development alternatives are being evaluated by using digital ground-water flow and optimization models. The optimization model is used to maximize withdrawals from the aquifer and from available surface-water sources, while maintaining a minimum saturated thickness in the aquifer. The validity of predictions in both the flow and optimization models depends on the accuracy of historic and projected water use. Optimization model by-products include estimates of unmet water-use demands and the location of surplus surface water that would be available for transport to and utilization in deficient areas.

(KEY TERMS: eastern Arkansas, Mississippi River Valley alluvial aquifer, ground-water flow model, conjunctive use, optimization model, ground-water management.)

INTRODUCTION

Background

The Mississippi Alluvial Plain is part of the Gulf Coastal Plain and extends southward in a narrow band from near Cairo, Illinois, to the Gulf of Mexico. Total area of the plain is about 30,000 to 35,000 square miles. The land surface is a vast, flatland with one significant topographic feature west of the Mississippi River, namely Crowleys Ridge, that trends north to south and bisects the alluvial plain. Major rivers that drain the alluvial plain are the Arkansas, Mississippi, Ouachita, St. Francis, Tensas, White, and Yazoo Rivers.

The alluvial plain in eastern Arkansas covers about 19,000 square miles and covers all or part of 27 counties. The study area north of the Arkansas River is shown in figure 1. The principal water bearing unit underlying this area consists of a sequence of alluvial sediments and is called the Mississippi River Valley alluvial aquifer. Combined sources of surface and ground water provide irrigation water for agriculture and water to support the large aquaculture industry in eastern Arkansas.

The largest user of water in Arkansas is for hydroelectric power generation and the second largest use is for agriculture. Most of the agriculture occurs in the eastern part of the State. The total use of water for agriculture in 1985 was 4,254 million gallons per day (Holland, 1987), with 91 percent going to irrigate Arkansas' major crops, which are rice, soybeans, and cotton. About 65 percent of the total water used was from ground-water sources, of which about 93 percent was from the alluvial aquifer in eastern Arkansas.

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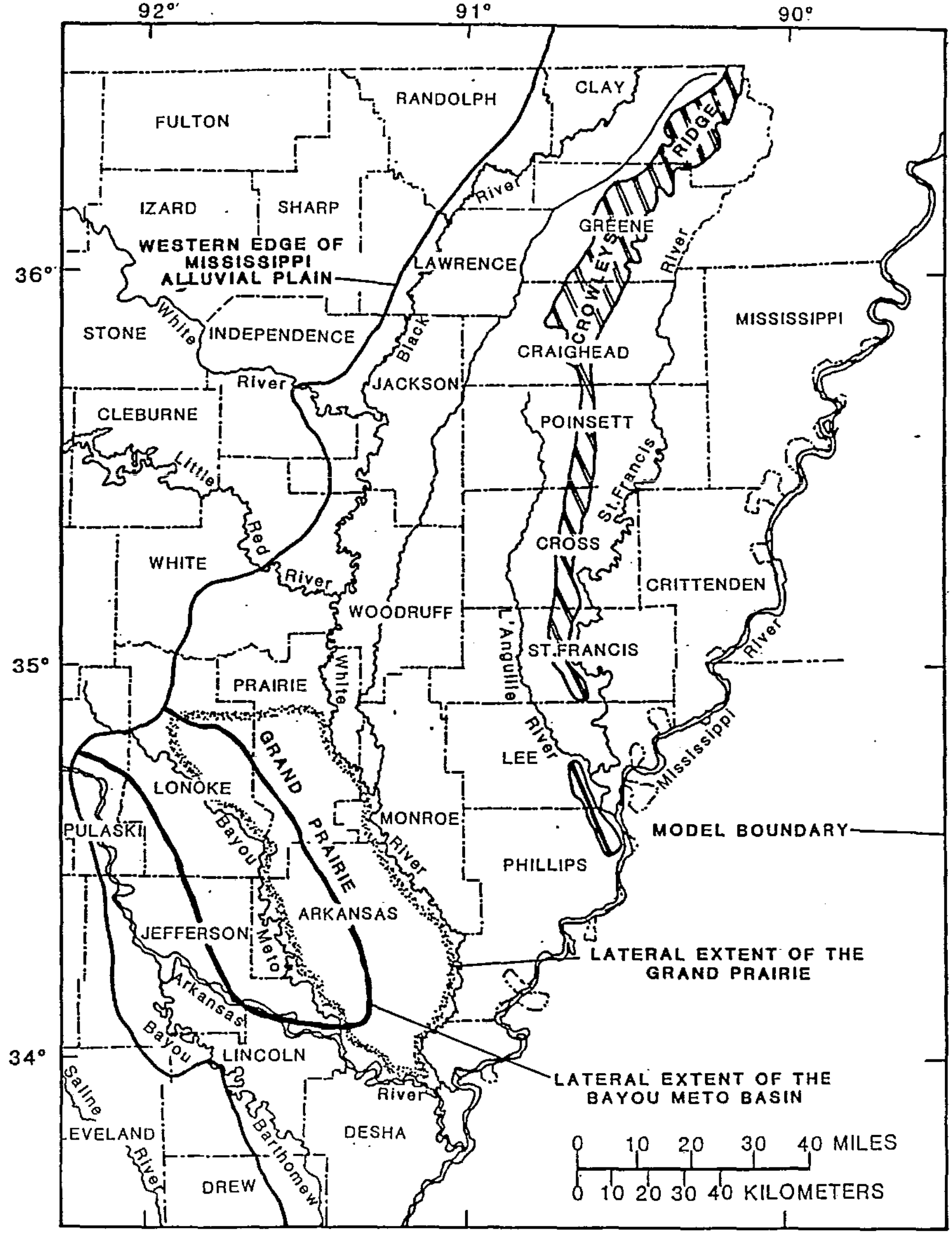

Figure 1.--Location of study area.

As a result of these large withdrawals, the potentiometric surface of the alluvial aquifer has declined substantially, especially during the summer months when irrigation is at its maximum. Natural surface-water recharge increases as a result. For those streams in the modeled area that are hydraulically connected to the alluvial aquifer, the flow gradient is toward the aquifer. In other words, the altitude of the potentiometric surface (hydraulic head) in the aquifer is less than the altitude of the water surface in the stream. As the head in the aquifer drops due to increased withdrawals, the hydraulic gradient between the stream and the aquifer increases and more water moves from the stream into the aquifer. Before describing the current configuration of the potentiometric surface and the resultant flow in the aquifer, it is appropriate to briefly discuss predevelopment conditions.

The only predevelopment potentiometric surface available for the alluvial aquifer is an estimate resulting from model simulations. Broom and Lyford (1981) published a model generated predevelopment potentiometric surface map of the eastern Arkansas alluvial aquifer that showed that water levels in wells unaffected by pumping generally were less than 20 feet below land surface and that the predevelopment surface generally conformed to the slope of land surface. Consequently, ground water would have flowed southward and toward the major rivers such as the Arkansas, Mississippi, St. Francis, and White. The aquifer probably was fully saturated until the onset of pumping in the Grand Prairie (fig. 1).

The earliest records of significant withdrawals are from about 1910 in Arkansas County in the Grand Prairie. Water-level declines in the alluvial aquifer resulting from withdrawals for irrigation were documented in 1929 (Engler and others, 1945). In some areas of the Grand Prairie water levels have declined to such an extent that many irrigation wells have gone dry.

As water levels in the aquifer have declined there have been alterations to the natural flow direction. The use of ground water has become so extensive, that the aquifer no longer discharges to the rivers in many areas, but is recharged by them. As an example, when the aquifer was fully saturated it most likely discharged to the Arkansas River. However, recent model simulations indicate that as a result of substantial water-level declines, water from the Arkansas River was recharging the alluvial aquifer and flowing toward the Grand Prairie at an average rate of about 7,500,000 cubic feet per day in 1987 (D.J. Ackerman, U.S. Geological Survey, written commun., 1988).

The most significant area of water-level decline is in the Grand Prairie between the Arkansas and White Rivers (Plafcan and Edds, 1986) (fig. 2). This was the first area in eastern Arkansas to develop water-level declines that currently extend southward only to the Arkansas River. Although the White River is a major source of recharge to the aquifer along the Grand Prairie's northern border, the water-level declines do extend beyond that river.

Major areas of water-level declines also are developing west of Crowleys Ridge in Cross, Lee, Monroe, Poinsett, and St. Francis Counties; east of the ridge another small cone is developing in St. Francis County (fig. 2). These depressions in the potentiometric surface exist as a result of large withdrawals from the alluvial aquifer.

The areas having ground-water level declines are the areas most in need of water-resources development alternatives. The first step toward the solution of any problem is to recognize that a problem exists and that some remedial action may be necessary. Although water-level declines were acknowledged 60 years ago, only recently has the magnitude and potential consequences of the problem stimulated action on the part of water users, water managers, and water scientists alike.

Purpose and Scope

By the early 1980's substantial water-level declines in the alluvial aquifer were undeniable symptoms of significant ground-water problems in eastern Arkansas. The Eastern Arkansas Water Conservation Project (EAWCP) was started in 1983 by the U.S. Department of Agriculture in cooperation with the Arkansas Soil and Water Conservation Commission and the U.S. Geological Survey. The primary purpose of the project was to provide a detailed evaluation of the water-level declines. Concurrently, the Memphis District of the U.S. Army Corps of Engineers was involved in the Eastern Arkansas Region Comprehensive Study (EARCS) to determine the feasibility of constructing hydraulic structures for surface water diversion and artificial recharge in areas deficient of ground water.

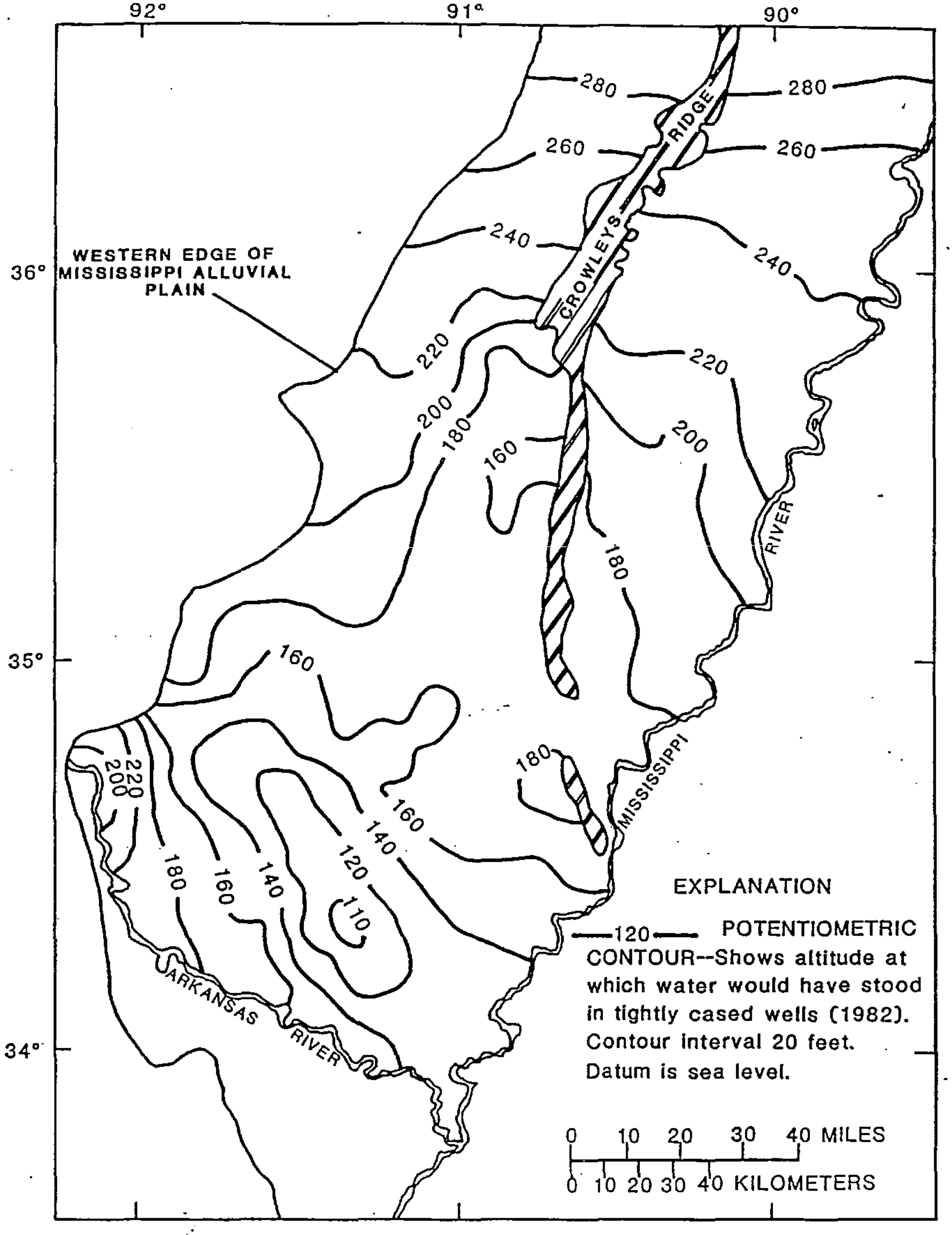

Figure 2.--Potentiometric surface map of the alluvial aquifer, spring 1982.

Initial activities by the Geological Survey in the EAWCP project included training and assisting other agency personnel in the ground-water monitoring program. Data were compiled, analyzed, and technical reports were prepared. As a part of the EARCS project, the Geological Survey developed a computer flow model of the area north of the Arkansas River. The modeled area was overlain with an X-Y grid containing 3x3-mile cell sizes. All model input and output was defined on the basis of the 9-square mile cells. The purpose of the flow model was to accurately represent the flow system and quantify incoming and outgoing fluxes so that parameters from the calibrated flow model could be used as input to a conjunctive-use optimization model being developed by the University of Arkansas (Cantiller and others, 1989). Results of the optimization model were used by the Corps of Engineers to help assess the feasibility of building diversion structures to move available surface water to areas where projected water demands could not be met from existing sources.

The purpose of this paper is to describe activities related to water-resources development alternatives being evaluated in the Mississippi Alluvial Plain in eastern Arkansas. Possible alternatives and their impact upon the flow system are simulated by digital ground-water flow and optimization models. This report also discusses the acquisition of input data from cooperating agencies, and the assumptions and considerations involved in evaluating development alternatives for surface and ground water.

The paper describes the flow and optimization model results for the simulations using 9-square mile cells. The flow and optimization models of the alluvial aquifer compute results based on projected pumpage for 10-year increments from 1990 until 2030. Simulations were made using pumpage values projected from 1980 estimates, both with and without conservation measures. The modeled area extends from southern Missouri southward to the Arkansas River and from the Mississippi River westward to the outcrop of the Paleozoic and Tertiary rocks (fig. 1).

GEOHYDROLOGY

The uppermost water bearing unit underlying the Mississippi Alluvial Plain in eastern Arkansas is the Mississippi River Valley alluvial aquifer. The aquifer underlies all of the study area with the exception of Crowleys Ridge, a remnant of Pleistocene and Eocene loess, silt, and sand deposits that create a prominent topographic feature on an otherwise flat alluvial plain. The ridge constitutes a hydraulic barrier to the flow of ground water in the alluvial aquifer.

The deeper alluvial sediments are composed of coarse sand and gravel fining upward to fine sand. These sediments form the alluvial aquifer. The upper alluvial sediments are composed of clay, silt, and fine sand and form an effective upper confining layer to the alluvial aquifer through most of the project area. Spatial variations in lithology result from the depositional environment that produced the sediments. These lateral and vertical variations produce variability in the infiltration potential of the upper confining unit as well as the transmissive properties of the aquifer.

The spatial definition of the aquifer and the confining unit resulted from evaluation of driller's logs obtained from the Arkansas Geological Commission. The thickness of the alluvium generally ranges from 125 to 200 feet. The alluvial aquifer ranges from 30 to 180 feet in thickness and averages about 100 feet. The aquifer is thickest where the upper confining unit is thin or where depressions occur in the underlying sediments of Tertiary age. The upper confining unit generally is 50 feet or less in thickness but may be as much as 70 feet thick in places, such as in the Grand Prairie.

Many rivers flow across the alluvial plain and exchange water with the aquifer. The flux of water through the riverbeds is dependent on the transmissive properties of the riverbed and the differential between the potentiometric surface in the aquifer and the river stage. Rivers such as the Mississippi and the Arkansas are presumed to have a very high degree of hydraulic connection with the aquifer and, consequently, the water level in the aquifer adjacent to the river is nearly identical to the river stage. The White and St. Francis Rivers are not as well connected hydraulically with the aquifer. Therefore, hydrographs for wells near these rivers reflect attenuated changes in river stage. Field observations and water-level measurements indicate that other smaller streams in the alluvial plain generally have less hydraulic connection with the aquifer. Model simulations indicate that the general direction of the exchange of water is from the rivers and streams to the aquifer and the streams provide a large amount of recharge to the aquifer.

Other sources of recharge to the aquifer include infiltration from precipitation and seepage from adjacent and underlying formations. Precipitation averages about 49 inches annually, some of which seeps through the fine-grained material overlying the aquifer. Infiltration varies within the alluvial plain but overall is probably less than 5 inches annually and less than 1 inch per year in the Grand Prairie. A small amount, less than 5 percent, of the total recharge enters the aquifer from Tertiary and Cretaceous sediments underlying the aquifer and from the Paleozoic sediments flanking the western side of the valley (D.J. Ackerman, U.S. Geological Survey, written commun.).

Hydraulic conductivity in the alluvial aquifer ranges from about 120 to 390 feet per day (ft/d), based on estimates by Krinitzsky and Wire (1964) and Ackerman (1989). The hydraulic conductivity is greatest near the base of the aquifer where the sediment consists mostly of coarse sand and gravel. However, there are no laterally extensive confining units within the aquifer, and the aquifer reacts hydraulically as a single unit.

NUMERICAL MODEL DEVELOPMENT

Modeling of surface- and ground-water systems by computers has become an integral part of many hydrologic investigations in recent years. Models are an aid to understanding how the aquifer system functions. They allow the investigator to quantify certain parameters that are difficult to measure in the field, and they allow predictions or projections of aquifer conditions into the future.

Two types of digital models were utilized during the study of the alluvial plain in eastern Arkansas: a ground-water flow model and a model to optimize the conjunctive use of ground and surface water. Results of ground-water flow models show water levels in the aquifer on a cell-by-cell basis and, consequently, the direction of flow resulting from the potential gradients between cells can be deduced. Flow models also quantify the volumetric flow rates, or fluxes, across boundaries, between cells, and between rivers and the aquifer. The optimization model uses the framework developed for the flow model to quantify the optimal use of both surface and ground water based on projected water use. Minimum saturated thicknesses or target water levels are sustained indefinitely on a cell-by-cell basis.

Flow in the alluvial aquifer was modeled as being two dimensional, that is, flow was considered in only one layer. The single-layer representation was believed to be adequate for the needs of the study. However, it is a simplification of the generally accepted concept of flow in the system that allows for a small amount of inflow from the Paleozoic and Tertiary sediments underlying the alluvial aquifer.

The lateral boundaries of the model include the Mississippi River on the east, the Arkansas River on the south, and consolidated rocks of Paleozoic age on the west. The Mississippi and Arkansas Rivers are considered to fully penetrate the aquifer. They were modeled using large conductance values to simulate their high degree of natural interconnection with the aquifer and, consequently, they respond as constant-head boundaries. The Paleozoic rocks that form the western boundary of the aquifer are considered to be impermeable and the contact is modeled as a no-flow boundary. Because no natural hydrologic boundary exists at the northern end of the study area, the model grid was extended northward several miles into Missouri and expressed as a constant-head boundary to allow for the assimilation of artificial boundary effects outside the area of interest in Arkansas. The bottom of the alluvial aquifer was modeled as a no-flow boundary because of the assumption that very little flux occurs across the boundary between the alluvium and the underlying rocks.

Flow Model

The modular three-dimensional finite difference ground-water flow model (McDonald and Harbaugh, 1984) was used to simulate the stress-response relation for the alluvial aquifer. The model area consisted of a rectangular grid of 70 rows and 52 columns of cells (fig. 2). The spacing between each cell center in the grid represents a distance of 3.0 miles. The model area includes 3,640 cells of which 1,605 cells are active and represent the alluvial aquifer.

Input data for the model were obtained from several sources including water-level records, drillers' logs, and well records maintained by the U.S. Geological Survey and U.S.

Soil Conservation Service soil-type data bases, all of which are referenced to specified cartographic projections. For this reason, the positioning and orientation of the model grid was computed and plotted by computer program such that the coordinates of each intersection point on the grid were defined in accordance with the desired land net used as a base.

Recharge to the aquifer in interstream areas and from rivers is dependent on the conductance of the sediments and the difference between the river stage and the potentiometric surface in the aquifer. The riverbed conductance is a function of the hydraulic conductivity and thickness of the riverbed material, the width of the wetted riverbed, and the length of the river. Because hydraulic conductivity for riverbeds is seldom measured in the field, estimates were made for the material in the interstream areas and underlying the river. Values of 1×10^{-4} ft/d and 1×10^{-2} ft/d were chosen for the conductivities in the interstream areas and for the rivers, respectively.

Other parameters that describe the aquifers ability to transmit and store water were defined on the basis of available data. The aquifer was assumed to be isotropic because there was no data to indicate otherwise. Model simulations indicate that isotropy is a valid assumption. A storage coefficient value of 0.3 was used uniformly in areas where the aquifer is unconfined and a value of 10^{-6} was used where the aquifer is confined. Because of overdevelopment and dewatering, the aquifer has gone from confined to unconfined in some areas. An average value of 300 ft/d was chosen to represent the hydraulic conductivity of the alluvial aquifer based on similar values chosen by Ackerman (1988), Peralta and others (1985), and Broom and Lyford (1981). The average value was varied nodally during the calibration process, but most values remained within about 5 percent of the original estimated value.

Pumpage from the aquifer was distributed to each cell in the model after eliminating those cells in which the predominant land use (for example forest, urban area, or lakes) precluded the withdrawal of ground water. Withdrawals for a series of seven different stress (pumping) periods were defined. An increase in total pumpage from one stress period to the next reflects a general increase in aquifer development with time.

A model is calibrated to insure that it responds properly to the stress-response relation that exists in the aquifer. The EARCS flow model was calibrated by comparing computed head values for each of the stress periods with observed water-level measurements in 19 long-term observation wells in the study area. The wells were selected to provide for evaluation of results in both overdeveloped and unstressed areas in the alluvial aquifer. Some of the largest differences between observed water levels and computed heads exist in Bayou Meto basin (figs. 1 and 3) where large variations of clay thickness occur and water levels are more sensitive to pumpage distributions.

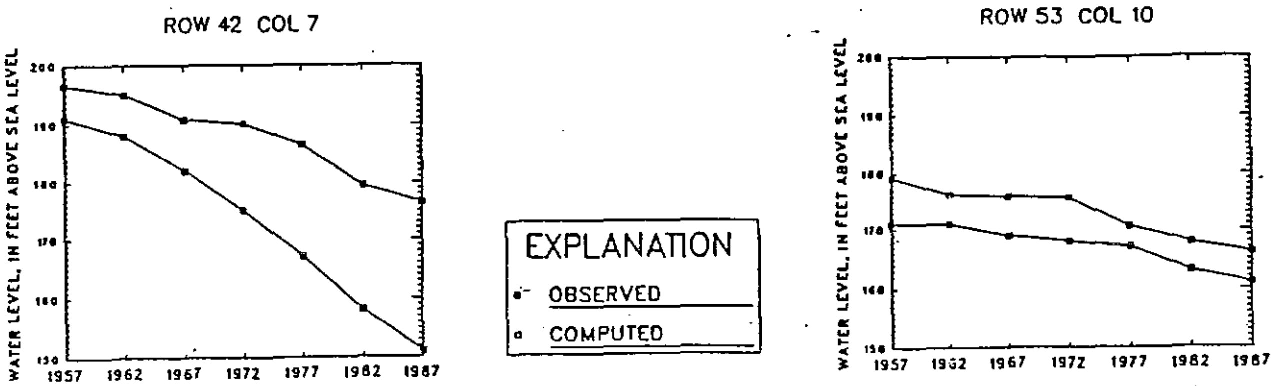

Figure 3.--Model computed and observed heads for Bayou Meto Basin.

The volumetric budgets for the first and last stress periods of the calibration runs are given in table 1. The simulations show that as aquifer development increased, flow into the aquifer from the rivers increased along with increased flow from recharge and storage. Flow also increased across the constant head boundary on the northern side of the study area.

Table 1.--Volumetric budget for the non-steady-state calibration model at the end of stress period 1 in 1955 and at the end of stress period 7 in 1985, units in cubic feet per day (Mahon and Ludwig, U.S. Geological Survey, written commun., 1989)

RATES FOR STRESS PERIOD 1			RATES FOR STRESS PERIOD 7	
		INFLOW		
STORAGE =	0.89577E+06		STORAGE =	0.12917E+09
CONSTANT HEAD =	0.12717E+08		CONSTANT HEAD =	0.16502E+08
RIVER LEAKAGE =	0.32564E+08		RIVER LEAKAGE =	0.98066E+09
RECHARGE =	0.61314E+08		RECHARGE =	0.17211E+09
TOTAL IN =	0.10749E+09		TOTAL IN =	0.41585E+09
		OUTFLOW		
STORAGE =	0.38130E+08		STORAGE =	0.10778E+06
CONSTANT HEAD =	0.00000		CONSTANT HEAD =	0.00000
PUMPAGE FROM WELLS =	0.43916E+08		PUMPAGE FROM WELLS =	0.40395E+09
RIVER LEAKAGE =	0.11222E+08		RIVER LEAKAGE =	0.42469E+07
RECHARGE =	0.14223E+08		DISCHARGE =	0.75461E+07
TOTAL OUT =	0.10749E+09		TOTAL OUT =	0.41585E+09

A model simulation of saturated thickness for 1982 is shown in figure 4. Although no model cells were found to be critical areas (areas with less than 20 feet of saturated thickness) during model simulation, less than 20 feet of saturated thickness exists at some locations in the Grand Prairie area (Plafcan and Edds, 1986). The lack of critical areas is probably because the potentiometric surface calculated by the model represents an average potentiometric surface for a 9 mi^2 cell and does not account for the large drawdowns caused by a single or several closely spaced pumping wells.

The principal application of the dynamic model in this study is to make use of its predictive capability to project the effects of future increased ground-water withdrawals on ground-water levels. The projections made for this study are based on estimated irrigation-water needs data provided by the U.S. Soil Conservation Service that include projected pumpage data, by cell and by decade, for the period 1990 to 2040 (U.S. Department of Agriculture, 1987). The pumpage for each decade was applied to the model and simulated for 10 years. Heads were calculated at the end of each decade based on the pumpage at the beginning of that decade.

Projected water-needs data were developed on the assumption that 95 percent of all available land, except for wetlands and urban areas, would be placed in production by 2040 and that the land would be irrigated according to a traditional crop-rotation scheme. The projections were based on the distribution and magnitude of 1982 water needs and were increased appropriately each decade to achieve the level of irrigation estimated for the year 2040. Two types of water-needs data were compiled. One type is based on continued use of current irrigation schedules without imposition of any conservation measures. The other type is with imposition of conservation measures and is based on modifications to current irrigation practices. Total pumpage without and with conservation measures imposed are as follows:

	Pumpage x 10^8 (ft^3/d)	
Interval	Without conservation	With conservation
1990-2000	4.0511	3.6734
2000-2010	4.6469	3.8207
2010-2020	5.2081	4.0471
2020-2030	5.7757	4.2289
2030-2040	6.2524	4.4228

Both types of data were used to stress the transient model.

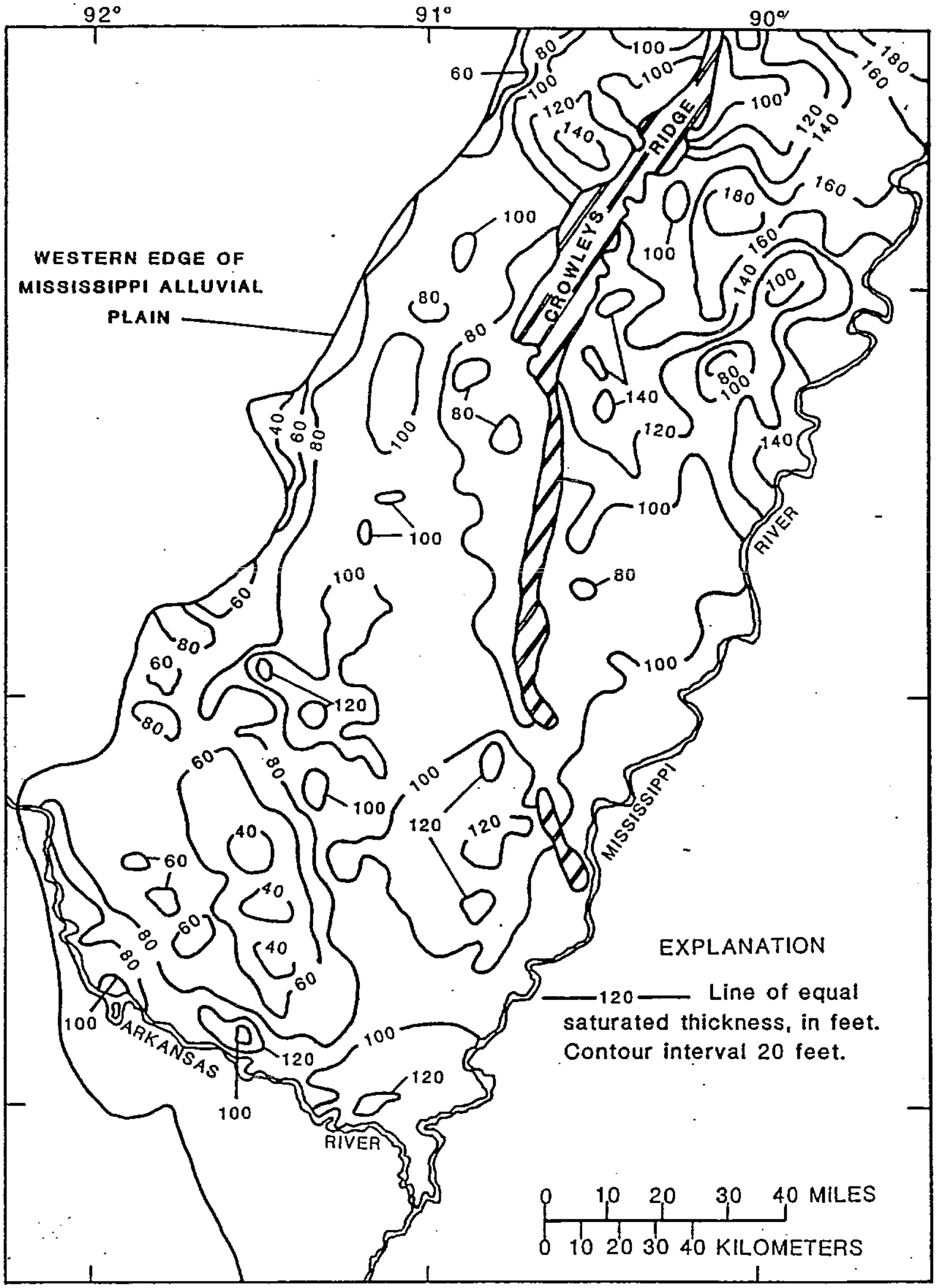

Figure 4.--Saturated thickness of the alluvial aquifer, spring 1982.

The U.S. Soil Conservation Service water-needs projections for 1990 and beyond do not include a breakdown of sources of the irrigation water, such as surface and ground water. Therefore, to apply a more realistic stress, it was assumed for this study that at least the same amount of surface water used in 1982 would be used in future years and the 1982 surface-water use was subtracted, cell by cell, from all projected requirements. Inasmuch as future water needs may be satisfied by the increased use of surface water, the projections developed herein may be conservative, that is, indicate a larger area of critical ground-water levels than may actually exist.

Figure 5 shows the saturated thickness of the aquifer remaining after 10 years of pumping at the rate projected for 2030 with conservation practices in place. The figure also shows the cells in which 20 feet or less of saturated thickness remain. Because of the continued increase in pumpage during the simulation period (1990 to 2040), the number of cells becoming critical increased each decade with and without conservation measures. However, with conservation measures, the number of critical cells was less than without conservation during any given decade. The reduction in the number of critical cells when utilizing conservation measures is particularly evident during the 2030 stress period simulation.

Optimization Model

An optimization model was used in the study in eastern Arkansas to determine the optimal conjunctive use of surface and ground water while maintaining various system variables at acceptable levels (Cantiller and others, 1989). One of the main variables maintained was a minimum saturated thickness of 20 feet in each cell.

The modeling method maximizes the sum of ground and surface water used and applies steady-state equations to approximate water levels within the ground-water system. The approach approximates, within established constraints, the amount of water that can be withdrawn to meet specified demands. Optimal water use is determined within the model by taking into account available ground and surface water and total quantities of water needed. The significance of the sustained yield strategy is that by limiting ground-water withdrawals and using surface-water resources in the amounts prescribed in the optimization model, at least a minimum aquifer saturation will be maintained in every cell for an infinite length of time, ensuring that the optimal ground-water pumpage determined by the model is sustainable.

Geohydrologic parameters from the calibrated ground-water flow model were used as input for the optimization model. These data include hydraulic conductivity, interstream and river leakage, and boundary conditions. Estimates of surface-water use and total water use are also input data for the optimization model.

Two sets of scenarios were run during the optimization of pumpages, each set with and without conservation measures imposed. Each scenario was based on a different application of a lower bound for pumping (Cantiller and others, 1989). The scenarios are listed and described below:

WITH CONSERVATION

* CMA - lower bound on pumping equals the municipal and industrial demand
* CON - lower bound on pumping is zero

WITHOUT CONSERVATION

* SMA - lower bound on pumping equals the municipal and industrial demand
* SUB - lower bound on pumping equals the municipal and industrial demand in the first decade after which the lower limit equals the optimal pumping strategy of the preceding decade

Municipal and industrial demand was decreased by about 10 percent to account for the imposition of conservation measures and accounts for no use of surface water. Total agricultural demand was reduced between decades on an increasing basis, starting with approximately 10 percent in 1990 and ending with approximately 30 percent in 2030. Demand was not reduced uniformly over the total model area but was reduced by county and, consequently, on a cell-by-cell basis dependent on the anticipated magnitude of the ground-water problem. These reductions reflect the planning by the conservation districts and the State to irrigate more efficiently and utilize surface-water resources.

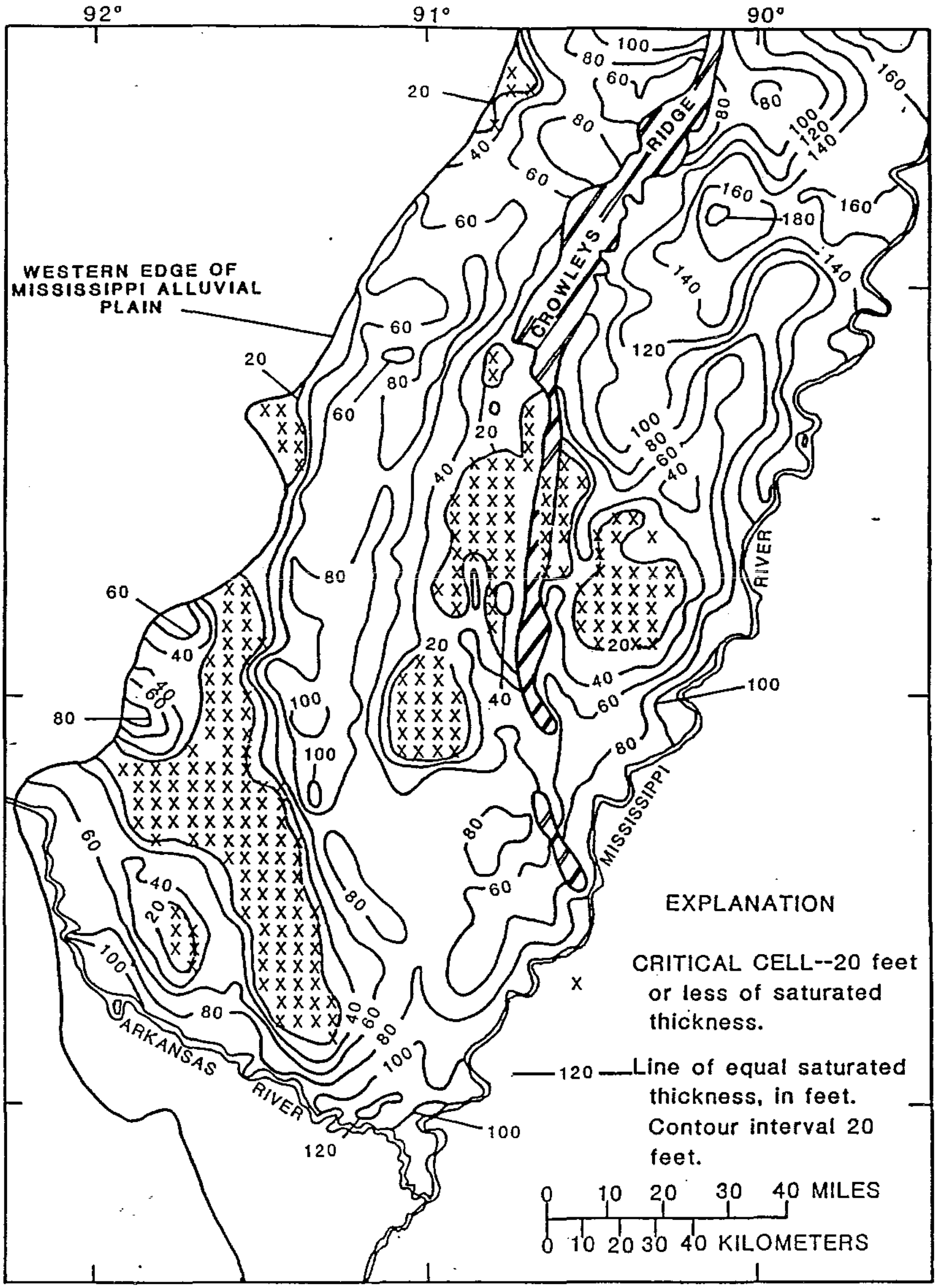

Figure 5.--Saturated thickness and critical cells resulting from 2030 pumpage for 10 years with conservation measures imposed.

The scenario that used pumpage with conservation measures imposed and municipal and industrial pumpage as a lower bound is considered to be the most realistic in terms of future ground-water use. The results of that optimization are given in table 2. Ground-water demand is the sum of demand from the alluvial aquifer and from the aquifers underlying the alluvium. This demand is attributed to projected agricultural, municipal, and industrial water-use needs. Only that part of ground-water demand associated with the alluvial aquifer was considered appropriate stress for the model. Tertiary and Cretaceous aquifer demands were assumed to remain constant and were not modeled. Optimization model simulations indicate that all of the projected water demand from the alluvial aquifer can not be satisfied. The remaining unmet demand must be supplied by water imported to deficient areas. Therefore, in table 2., the sum of the optimized sources equal the demand from the alluvial aquifer. Stream/aquifer flux in the AQUIFER VOLUME BALANCE refers to all vertical movement of water, except for pumping, and includes deep percolation at non-river cells and the exchange between the aquifer and the river at river cells. Recharge is the flux of water across the northern boundary. In the RIVER VOLUME BALANCE, stream-aquifer flux is the vertical flux of water at river cells only. Surface water refers to the quantity of surface water diverted to agricultural lands. This includes diversion from reservoirs as well as rivers.

Figure 6 shows a somewhat quantitative plot of the volume of unmet water demand in each cell resulting from the imposition of projected water demands for year 2030. These areas of unmet demand occur even after ground-water and surface-water withdrawals have been optimized to meet as much of the demand as possible. It is to these areas that water needs to be imported in order to completely meet projected water demands. Model derived values in grid rows 1-10 may have been influenced by the artificial northern boundary. They should not be considered with the same confidence as values in rows 11-86. Prominent areas of unmet demand occur in the same areas as the critical areas in the saturated thickness illustration.

The linking of a classical simulation model with state-of-the-art optimization techniques is an important tool for water-resources managers in Arkansas. When evaluating the probable impacts of projected future stresses, this eliminates the need of trial-and-error iterations in which pumpage is adjusted until the response of the aquifer is within acceptable limits (reasonable saturated thicknesses are maintained). The optimization technology allows the analyst to set acceptable "constraints" on the system before the simulation begins and the quantity of water that can be withdrawn without violating these constraints is automatically optimized. In addition, the withdrawal of supplementary water from surface-water sources may be optimized to help meet the total projected water demands in the modeled area. That part of total water demand that cannot be met from sources within the modeled area is also delineated on a cell by cell basis.

CONCLUSION

Water management has become essential in eastern Arkansas and the need for good scientifically sound water-resources development alternatives is greater than ever before. Ground-water levels in the Mississippi River Valley alluvial aquifer have been declining since ground-water development for irrigation began in the 1930's. Alternate sources of irrigation water, such as surface-water sources, need to be considered to sustain irrigated agricultural acreage while maintaining minimum levels of ground-water saturation. Water-development alternatives that provide for the optimal use of both surface and ground water in the Mississippi Alluvial Plain of eastern Arkansas have been analyzed.

The U.S. Geological Survey developed a digital ground-water flow model and the University of Arkansas used this model to develop an optimization model to determine the optimal conjunctive use of both surface and ground water. The grid for the models was developed jointly by several Federal and State agencies. Data, such as land use, pumpage, and aquifer definition were supplied by these same agencies and applied as model input.

The ground-water flow model was stressed using pumpage estimates both with and without conservation measures imposed for five decades beginning in 1990. The simulations were dynamic in that the responses to stresses were determined at a specific period of time. Both simulations developed large areas of critical cells where aquifer saturated thickness was less than 20 feet. However, the simulations employing pumpage with conservation

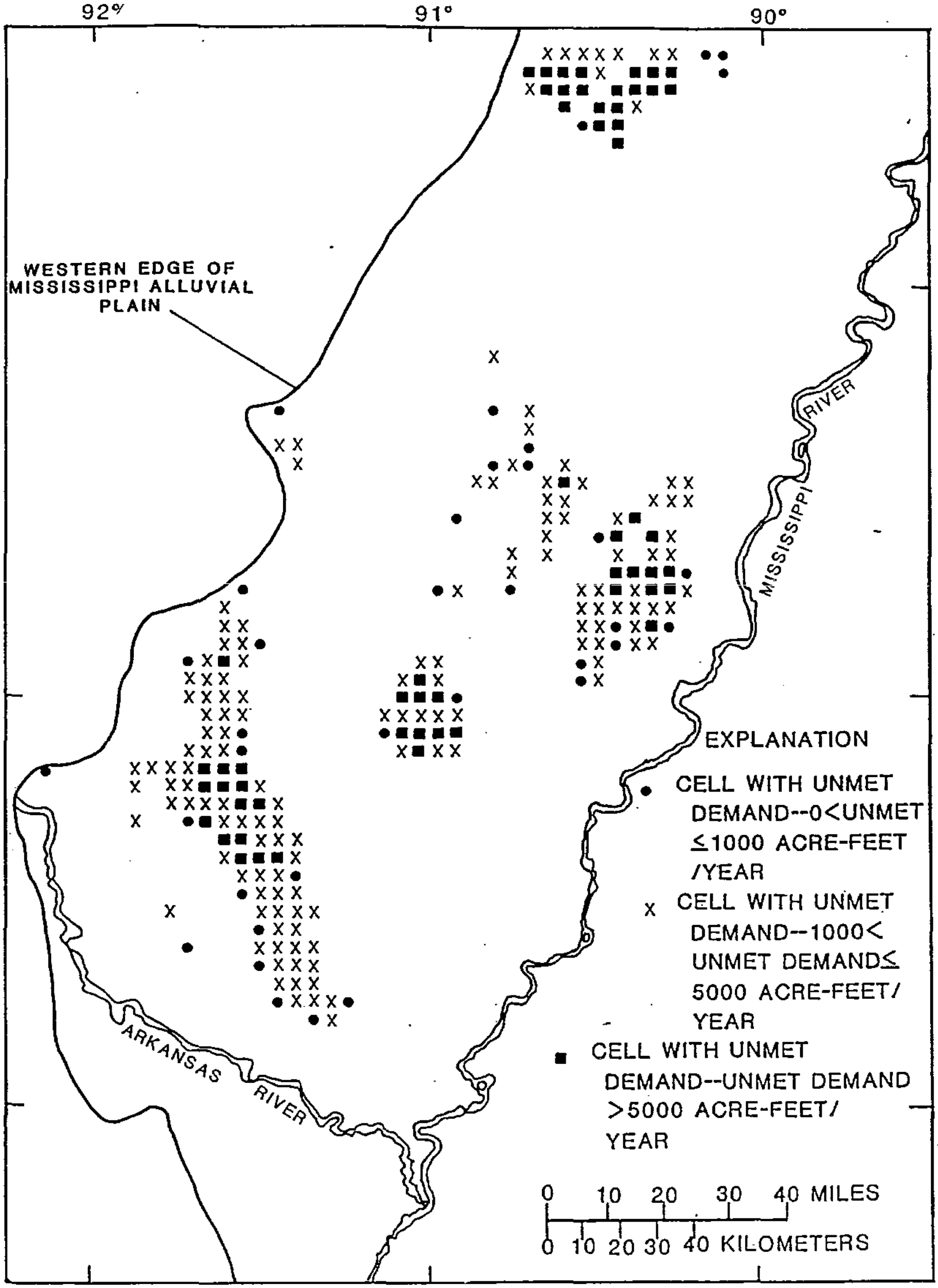

Figure 6.--Cells with unmet demand resulting from 2030 pumpage estimates with conservation measures imposed.

Table 2.--Summary of values for optimal solution of the scenario with conservation measures imposed and the lower bound of pumpage equal to municipal and industrial pumpage (CMA), units in acre-feet per year (modified from Cantiller, 1989)

	1990	2000	2010	2020	2030
DEMANDS					
Ground-water	5,581,116	5,848,938	6,117,345	6,479,769	6,760,397
Alluvial aquifer	5,521,538	5,789,354	6,117,761	6,389,712	6,700,813
Tertiary and Cretaceous aquifers	<--------------------		59,585		-------------------->
USAGE					
Agricultural	5,543,013	5,807,979	6,133,983	6,435,096	6,712,399
Municipal and industrial	38,103	40,959	43,362	44,673	47,998
OPTIMIZED SOURCES					
Ground water	3,697,917	3,947,121	4,197,644	4,394,633	4,610,769
Surface water	1,104,789	1,148,284	1,201,084	1,249,541	1,293,949
Imported water	718,832	693,949	719,033	745,538	796,095
AQUIFER VOLUME BALANCE					
Ground-water pumping	3,697,917	3,947,121	4,197,644	4,394,633	4,610,769
River/aquifer flux	3,643,880	3,893,010	4,143,480	4,340,420	4,556,670
Recharge	54,041	54,112	54,165	54,212	54,097
RIVER VOLUME BALANCE					
River influent	<-------------------		384,216,700		------------------>
Overland inflow	<-------------------		101,250,900		------------------>
Surface water	703,828	747,323	800,123	848,580	892,988
River/aquifer flux	1,056,660	1,148,940	1,243,110	1,316,700	1,403,490
System effluent (x 10^8)	4.837071	4.835713	4.834244	4.833023	4.831711

measures showed fewer critical cells. The principal areas where projected ground-water problems are expected to occur are in the Grand Prairie, west of Crowleys Ridge centered in St. Francis and Cross Counties, and east of the ridge centered in Crittenden County. The area west of Crowleys Ridge could extend northward to Craighead County if conservation measures are not imposed on pumping.

The optimization model uses a conjunctive-use, sustained-yield strategy, which means that the model provides an optimal solution using combined surface and ground water, and that the stresses can be sustained until the system reaches equilibrium or steady state. The model used the calibrated framework from the flow model to govern its hydraulic reponses to the imposed stresses. An optimal use of water was determined in each cell based on the projected water use, available surface water, and the saturated thickness of the aquifer in that cell. A constraint used in the model was that the saturated thickness of the aquifer be greater than or equal to 20 feet at all times. When sufficient ground and surface water were not available in a cell, the model computed an "unmet demand", the amount of water needed from some other source to meet the demands in that cell for that stress period. Results of these models may be used by water managers to plan for better utilization of water for the needs of eastern Arkansas.

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