PLAN OF STUDY FOR THE CENTRAL MIDWEST REGIONAL AQUIFER SYSTEM ANALYSIS IN PARTS OF ARKANSAS, COLORADO, KANSAS, MISSOURI, NEBRASKA, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, AND TEXAS

By Donald G. Jorgensen and Donald C. Signor

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CONVERSION TABLE

For those readers interested in metric units, the factors for converting inch-pound units to the International System (SI) of Units are given below:

Multiply inch-pound units	by	To obtain SI units
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
gallon per minute	0.06309	liter per second

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ABSTRACT

Sedimentary rocks of Paleozoic and Mesozoic age in the central midwest United States commonly are water bearing. A regional-flow pattern, based on preliminary potentiometric data, indicates that slightly saline and saline waters flow generally eastward from Colorado and Nebraska to meet freshwater that flows radially outward from the Ozark area of Missouri and Arkansas. The regional-aquifer system is the major source of freshwater in southern Missouri and northern Arkansas, as well as in small parts of Kansas and Oklahoma. In Oklahoma, Kansas, and Nebraska, the system is the source of water used for oil recovery. Aquifers within the system also are used as depositories for saltwater brines associated with oil and gas production and also as depositories for some industrial wastes.

Future demands for freshwater and further development of energy and metal resources require that the hydrology of the region be studied to define the underground environment and the flow system. Such definitive information will provide a rational basis for decisions concerning protection and management of the aquifers and the water resources. Thus, the U.S. Geological Survey, as a part of the Regional Aquifer System Analysis program, has begun a 5-year hydrologic investigation of the regional-flow system in Kansas, Nebraska, Oklahoma, eastern Colorado, southern Missouri, northern Arkansas, and small parts of Texas, New Mexico, and South Dakota. The study will define the regional-aquifer system and describe the system by such data as water levels, chemical analyses of water samples, and hydrogeologic properties of aquifers. The study will investigate environmental and related problems and will evaluate the effects of future conditions and management alternatives.

ACKNOWLEDGMENTS

This plan of study was organized by the authors with assistance from several persons in the U.S. Geological Survey. Persons significantly contributing to this report, in alphabetical order, are Michael J. Ellis, Anthony J. Gogel, Edward J. Harvey, R. Theodore Hurr, Forest P. Lyford, and Melvin V. Marcher.

INTRODUCTION

The study area is located between the foothills of the Rocky Mountains in Colorado to the valley of the Mississippi River in eastern Missouri and, in general, from South Dakota to Texas. The area includes a large part of the Great Plains and the Ozark Mountains. The Central Great Plains has a nearly flat to gently rolling surface and borders the more rugged area of the Ozark Plateaus (referred to as the Ozark area, fig. 1).

Sedimentary rocks underly the entire region, except at the St. Francois Mountains, as shown in figure 1. The sedimentary rocks, which generally are water bearing, range in thickness from zero at the St. Francois Mountains in Missouri to more than 40,000 feet in the Anadarko Basin in central Oklahoma. The "basement" rocks, which generally are not water bearing, consist of igneous and metamorphic rocks. The buried surface of the basement rocks forms the bottom of the aquifer system in most of the study area.

The limited data now available are not sufficient to determine if a region-wide flow pattern exists in all the aquifers other than in the Ozark area. Flow in relatively small areas associated with subsurface basin features within the study area also may exist. However, a regional-flow pattern in the rocks of Paleozoic age is assumed to be from the west and northwest to the east and southeast and radially outward from the Ozark area if the direction of flow is at right angles to the potentiometeric-surface contours, as shown in figure 2. The water levels in figure 2 are those believed to have existed before development in water-yielding rocks of Cambrian and Ordovician age, and data on water levels in these rocks are based on information from Anthony T. Gogel (U.S. Geological Survey, oral commun., 1980), Horick and Steinhilber (1978), Edward J. Harvey (U.S. Geological Survey, oral commun., 1980), and on other preliminary data. No corrections have been made to adjust water levels for the large differences in density that exist between freshwater and saltwater. The regional-flow system for the aquifers in rocks of Mesozoic age is believed to be from west to east, as indicated by the predevelopment (before 1905) potentiometric surface of the Dakota aquifer (Dakota Sandstone or Group and equivalent rocks) shown in figure 3.

Hydrogeologic properties affecting flow characteristics are believed to differ greatly between the predominantly sandstones, shales, and evaporites of Cretaceous, Jurassic, and Permian age; shales and limestones of Pennsylvanian and Mississippian age; and dolomites of Devonian, Silurian, Ordovician, and Cambrian age. Except in the Ozark area, little is known about the water flow between aquifers, as not all of the aquifers have been defined. It is not known for many formations if they contain aquifers or confining layers.

In the Ozark area, two prominent aquifers are believed to exist; the upper aquifer generally is contained in rocks of Mississippian age. This aquifer yields water to wells at rates of as much as 300 gallons per minute. A second aquifer is contained in rocks of Ordovician and Cambrian age. This aquifer is the principal aquifer in the Ozark area and yields as much as to 1,000 gallons per minute to wells. This aquifer is commonly separated from the aquifer in the Mississippian rocks by the Chattanooga Shale. Another aquifer of less importance also is present at some locations in the Upper Cambrian rocks. This aquifer, if present, is below the principal aquifer and is above the Precambrian basement rocks.

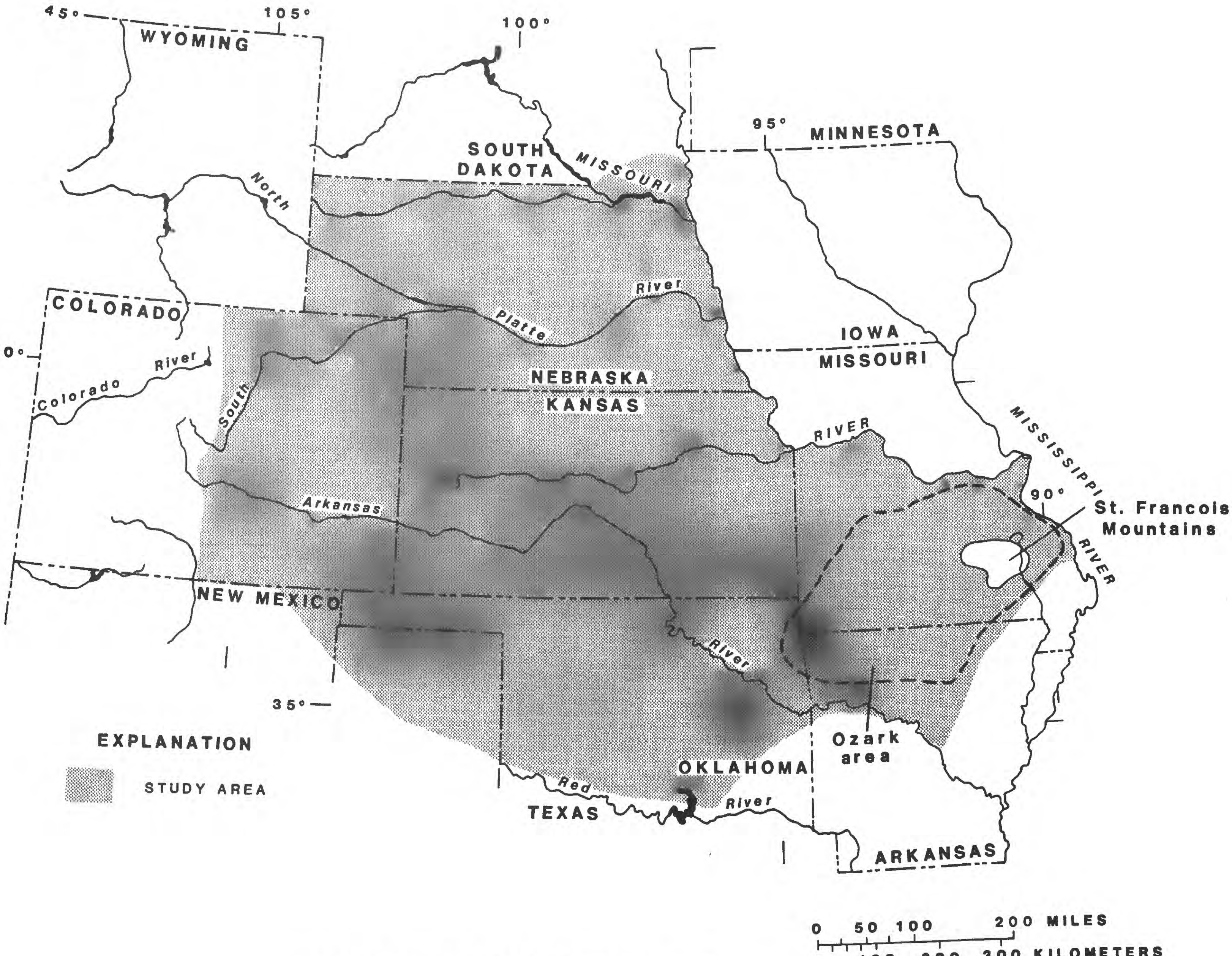

Figure 1.--Location of study area.

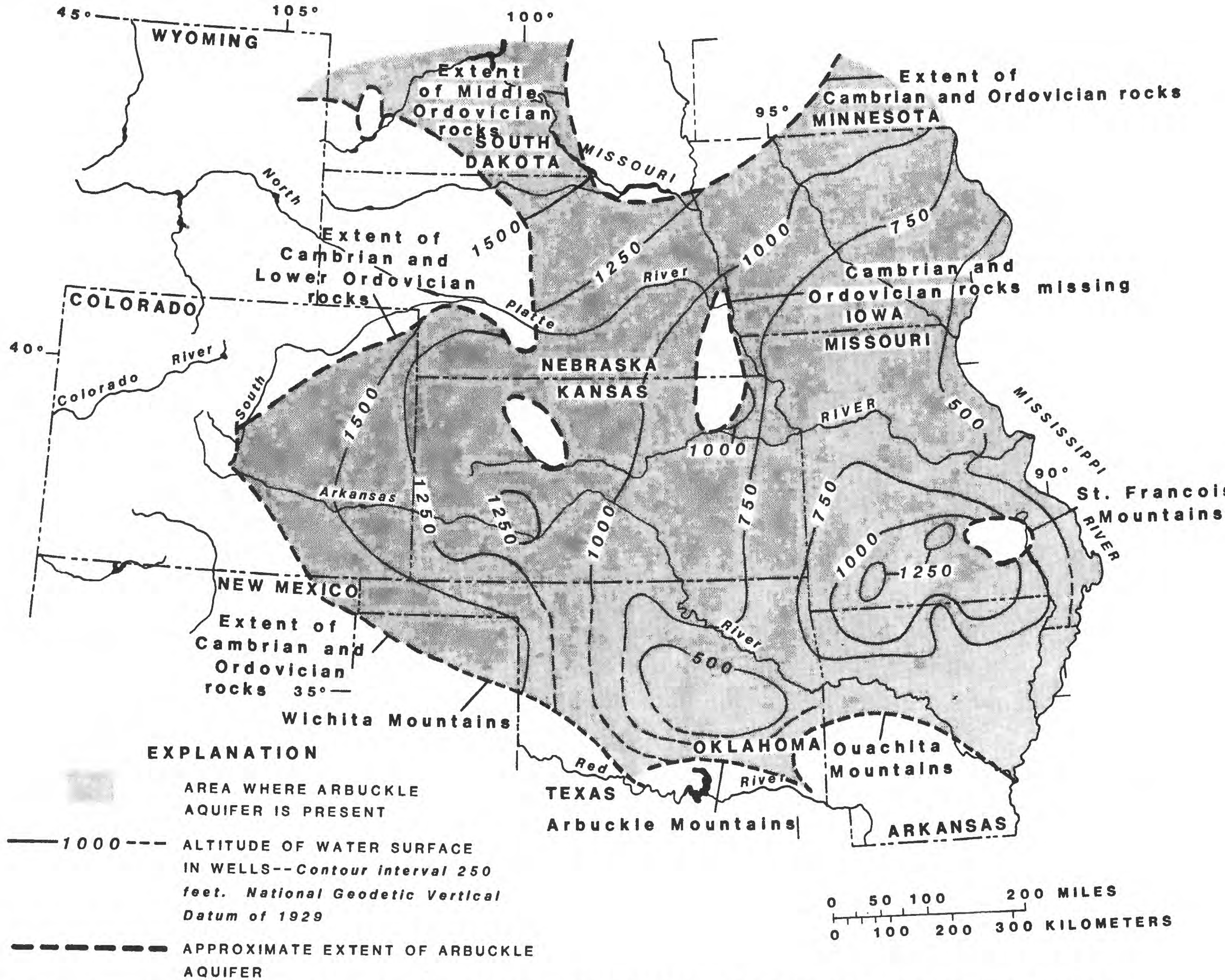

Figure 2.--Assumed predevelopment water levels in wells finished in Cambrian and Ordovician rocks.

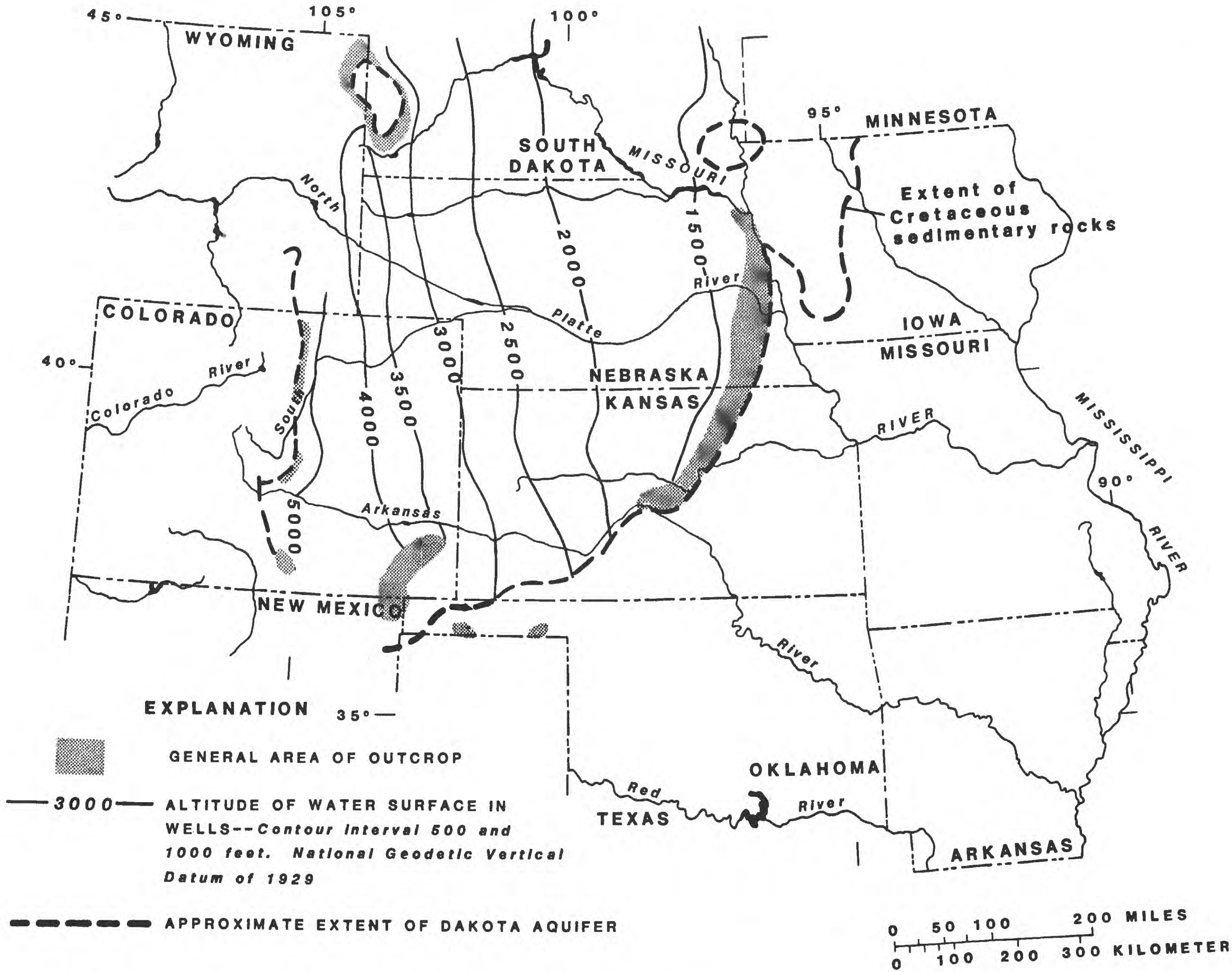

Figure 3.--Approximate water levels in wells finished in the Dakota aquifer, about 1900 (after Darton, 1905).

The quality of water is not known in several aquifers and is little known in several others. Recharge and discharge from the aquifers is not completely known. Some water in Permian rocks, as well as water in other rocks, contains relatively large concentrations of dissolved solids consisting principally of sodium and chloride. It is not known if these brines are static or slowly moving in a regional-flow system. Radium-226 concentrations that exceed maximum levels recommended by the U.S. Environmental Protection Agency for drinking water have been reported in a few analyses of water from Cambrian and Ordovician rocks. Data indicate that the aquifers at great depths have lower hydraulic heads than those in the overlying, shallow aquifers at some locations. The relation is shown, in part, by comparing the potentiometric surface of the aquifer in rocks of Ordovician and Cambrian age (fig. 2) with that of the overlying Dakota aquifer in rocks of Cretaceous age (fig. 3).

Purpose and Scope

The purpose of this report is to describe the problems associated with the use of the regional aquifers in the study area and to present a plan of investigation to accomplish the regional-aquifer system analysis for the study area. The purpose of the Central Midwest Regional Aquifer System Analysis study is to evaluate, to the degree possible, the potential of water contained in the regional-aquifer system for use and management. In general, the aquifers to be studied are contained in rocks of Early Cretaceous age and older and will include the Dakota aquifer and those below. Aquifers that form important elements in the regional-flow system within the study area will be examined. Local-flow systems will not be studied individually, unless they are a hydrologically important part of a regional-flow system.

Problems

Development of energy resources, power generation, increased irrigation, and expanded water supplies for municipal, as well as domestic and industrial, water in the study area is largely dependent on the development of reliable ground-water sources. Protection of the aquifers from contamination and pollution is required if the aquifers are to be developed into a long-lasting water supply.

The potential for contamination of ground-water sources resulting from surface discharges is especially great in the central Ozark area of Missouri and Arkansas. Here, the aquifer in Ordovician and Cambrian rocks is the major source of freshwater. These rocks consist of fractured and karstic dolomites exposed at the surface. Contaminants, such as municipal sewage, leachate from solid wastes, feedlot wastes, petroleum spills, leached fertilizers, and mining-industry wastes, can rapidly enter the aquifer.

The change of land use in the Ozark area may alter drastically the ground-water hydrology in the same area. In particular, deforestation could result in increased erosion, more rapid runoff, less recharge to the aquifer, and degraded quality of water.

A relatively undefined saltwater-freshwater interface exists between the freshwater-flow system of the Ozark area and the eastward-flowing saltwater system. The saltwater-freshwater interface exists in a belt outside and along the Ozark area in western Missouri, southeastern Kansas, and northeastern Oklahoma. During the 1970's, moderate irrigation development and other freshwater pumping have caused concern of possible saltwater encroachment.

New and renewed coal mining in the tristate area of Kansas, Missouri, and Oklahoma could result in degradation of the quality of both ground-water and surface-water resources of the area. Other coal-related activities, which possibly could affect water quality, include coal gasification by a plant process or an in-situ process.

Because of the very rapid increase in the price of metals, even more mining efforts can be expected in the next few years. Renewed mining of zinc may occur in the tristate area and might pose the potential hazard of water-quality degradation. The potential of degradation of water quality is especially great in the tristate area because most ore occurs in the same Mississippian rocks that also contain the upper aquifer in the Ozark area. Historically, mining and processing in the tristate area have resulted in "acid" water that contains excessive cadmium, zinc, and lead concentrations.

Mining activities, especially for lead and barite, are occurring in and near the St. Francois Mountains of Missouri. The lead ore is from Cambrian rocks. These same rocks are sources of ground water in nearby areas. A potential for contamination of the ground water may exist.

Oklahoma and Kansas are very important oil- and gas-producing States. Large quantities of salt brines and saltwater are produced with oil and gas. Most of the brines, irrespective of the yielding formation, are being disposed of by injection into rocks of Ordovician and Cambrian age. At many places in these two States, the water in the Cambrian and Ordovician rocks is less mineralized than the water that is being injected.

Because of the increased price of oil and gas, petroleum-related activity is at record levels. Many old oilfields are being revitalized. Many of the revitalized wells are "stripper" wells and produce exceptionally large quantities of brines in relation to the amount of oil produced. Additionally, many old fields are undergoing secondary- and tertiary-recovery processes, which commonly are "flooding" techniques. The amount of cross-formational flow is unknown. However, preliminary data indicate that petroleum activities have altered the pressure distribution, which increases the potential for cross-formational flow, and the chemical character of the ground water in large areas.

In Nebraska, the quality of water in the Dakota aquifer is extremely variable. At many localities in Nebraska, the water in the Dakota aquifer is potable and is used as a water supply. In areas near the saltwater-freshwater interfaces, however, saltwater movement toward pumping centers has resulted in degradation of quality to such an extent that the Dakota aquifer has been abandoned as a source of municipal water.

Another problem related to irrigation from the Ogallala aquifer (Ogallala Formation and equivalent rocks) is that the Ogallala is being rapidly dewatered in western Kansas, southeastern Colorado, parts of Nebraska, and in the panhandle areas of Oklahoma and Texas. In search of additional water supplies in this area, irrigators are now extending their wells below the bottom of the Ogallala and into water-bearing sandstones of Cretaceous, Jurassic, Triassic, and Permian age. Where these wells are screened in both the Ogallala aquifer and the underlying sandstone aquifers, cross-aquifer flow is induced because the underlying aquifers have hydraulic heads different than the Ogallala. Cross flow is of particular importance because the water from underlying sandstones generally is more mineralized than water from the Ogallala.

In Colorado, a thick section of shale occurs in rocks of Cretaceous age. The shale is considered by some investigators as virtually impermeable and thus may be a suitable depository for wastes. Similarly, several thick salt deposits, occurring in the rocks of Permian age in Oklahoma, Kansas, Nebraska, Colorado, and Texas (fig. 4), are considered to be stable zones of insignificant water movement. These deposits also have been suggested as a depository for wastes. Salt deposits presently are being used for the storage of liquified petroleum gas in Kansas.

It is evident that a knowledge of the occurrence and movement of ground water is imperative to evaluate the effects of waste disposal. It is also necessary to know the sources and discharges of the water, as well as the chemical characteristics, the quantity, rate, and direction of movement, and the aquifer environment.

Objectives

The following objectives of the Central Midwest Regional Aquifer System Analysis have been defined:

1. Describe the hydrologic system, including aquifer designation, hydraulic characteristics of the aquifers, and quality of the water within the aquifers.

2. Create a region-wide data base consisting of selective data on water use, water levels, lithologic logs, geophysical logs, chemical analyses of water samples, and others.

3. Describe historic, present, and future problems associated with the use of water, such as contamination and reliability.

4. Evaluate aquifer or aquifer-system response to future conditions.

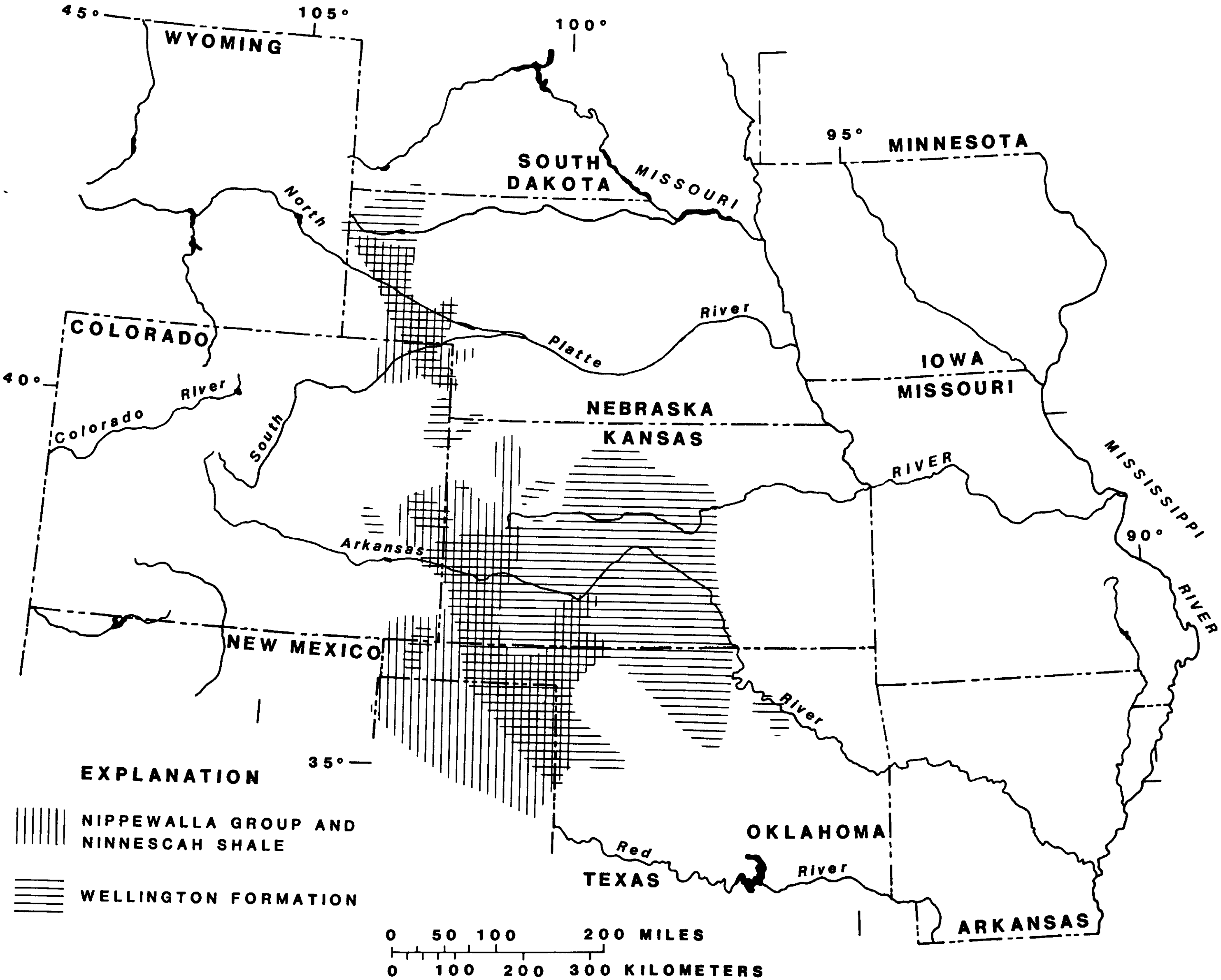

Figure 4.--Location of salt deposits in Permian sedimentary rocks (after McKee, Oriel, and others, 1967).

Approach

The approach for meeting these objectives is as follows:

1. Compile and analyze hydrologic, geologic, and water-quality data.
2. Collect and analyze new data where needed, if feasible.
3. Develop computer models of the aquifers or aquifer systems.
4. Evaluate past and future impacts on the regional-aquifer system resulting from development of ground water.

The approach emphasizes the importance of data necessary to define the hydrologic system and to describe the problems associated with the use of the ground-water resource. The principal sources of data will be U.S. Geological Survey files, existing reports, ongoing studies, as well as information in State-agency, university, consultant, and commercial-service company files. Some additional testing and data collection, such as chemical analyses, packer tests, and geophysical well logs, will be accomplished if needed and if feasible. Most data will be transcribed to a manageable, consistent, machine-readable format. The resultant data files and retrieval system will be an important product of the study and can be updated as new data become available.

Maps, tables, and graphs of data will be used to formulate process models (conceptual models) of the hydrologic system. Computer-modeling techniques will be used to simulate the hydrologic system and to test the process models. Modeling, along with other techniques, also will be used to predict the result of future or proposed changes relating to the use of ground water.

Organization

The 5-year study will be made by the U.S. Geological Survey project team (termed the central staff) located in Lawrence, Kans. Subprojects (District studies) will be made by U.S. Geological Survey District personnel in Arkansas, Colorado, Kansas, Missouri, Nebraska, and Oklahoma. Each District study will be funded by the central project. Contracts and grants may be awarded by either the central staff or by the District personnel.

The central staff will conduct the regional project and coordinate the District studies. The District personnel will provide information for the project and will assist the central staff. Additionally, District personnel will conduct hydrologic investigations that are designed to relate directly to the central project and to meet specific needs of the State in which they are undertaken.

Relation to Other Studies

Much hydrologic information pertinent to this regional assessment has been collected as part of existing cooperative programs between the State or local governmental agencies and the U.S. Geological Survey. Although this project will not be conducted as a cooperative project, efforts will be made to compliment cooperative projects as well as to coordinate and exchange data with cooperative projects. Duplication will be minimized to the degree possible in meeting project goals.

Within the central United States, three other regional aquifer system analyses are underway. These are the High Plains Regional Aquifer System Analysis (Weeks, 1978), the Northern Great Plains Regional Aquifer System Analysis (Dinwiddie, 1979), and the Northern Midwest Regional Aquifer System Analysis (Steinhilber and Young, 1979). Figure 5 shows these ongoing studies. Although all of the other studies shown have a common hydrologic boundary with this study, no duplication of study exists.

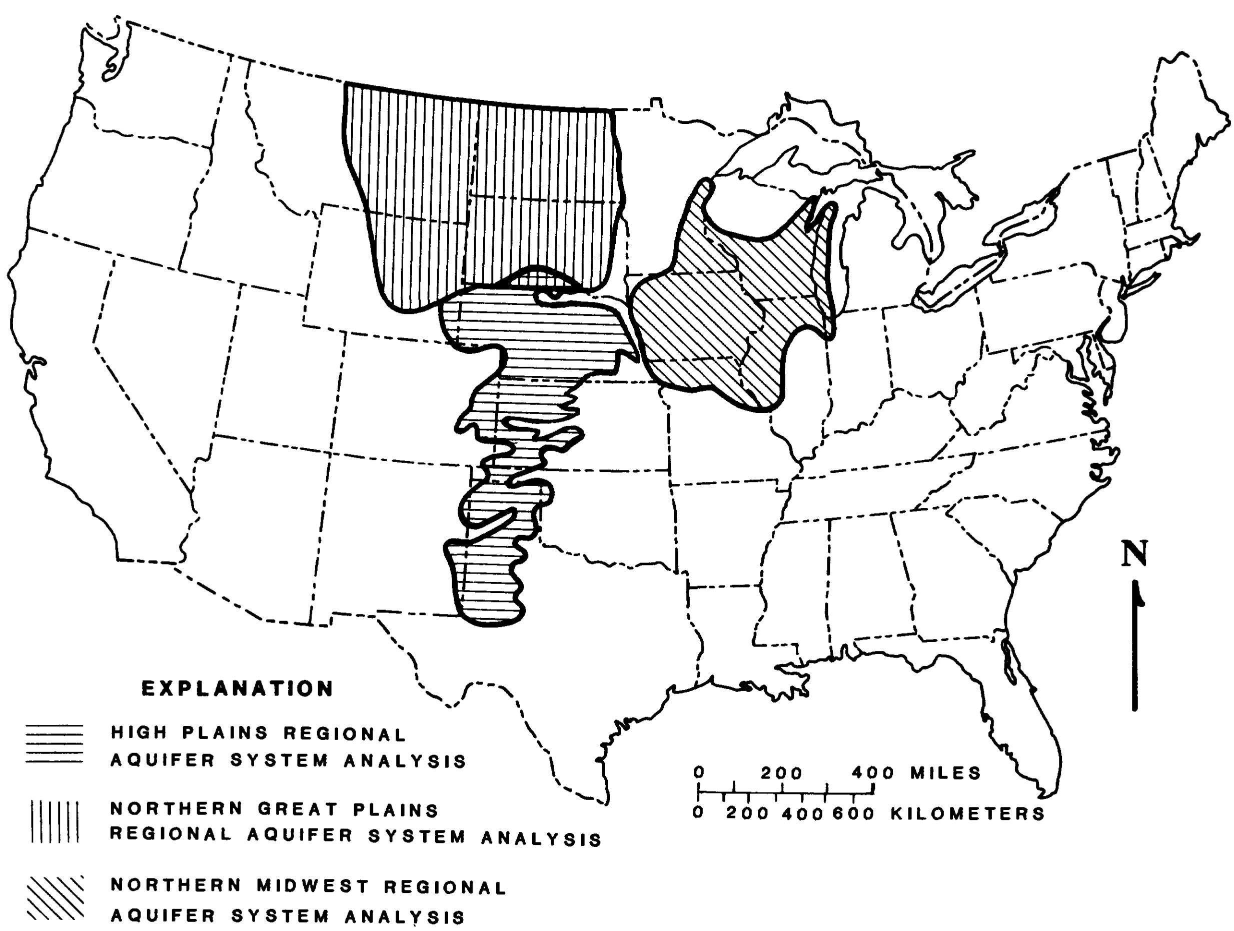

Figure 5.--Location of ongoing regional aquifer system analyses in the central United States.

PLAN OF STUDY

A 1-year project-planning stage (fiscal year 1980) has been scheduled. This project-planning document is a part of the planning phase. The active project is a 5-year study beginning in fiscal year 1981 (October 1, 1980) and ending in fiscal year 1985 (September 30, 1985).

The activities to be accomplished during the 5-year study are listed below:

I. Planning (project planning accomplished during fiscal year 1980)

II. Staffing (staffing begun during fiscal year 1980)

III. Design of data base(s) and graphics
   - A. Point data base
   - B. Computer graphics
     - 1. Select equipment
     - 2. Computer programming

IV. Enter point data
   - A. Well information
   - B. Water levels
   - C. Water chemistry
     - 1. Chemical analyses
     - 2. Temperature
     - 3. Density
     - 4. Resistivity
   - D. Water use
   - E. Lithologic logs
   - F. Geophysical logs
   - G. Aquifer properties
     - 1. Intrinsic permeability
     - 2. Specific storage
     - 3. Porosity
     - 4. Thickness
     - 5. Other

V. Geohydrologic studies
   - A. Initial interpretation
     - 1. Geologic processes
       - a. Sedimentation
       - b. Diagenesis
     - 2. Hydrologic analysis
       - a. Recharge
       - b. Discharge
     - 3. Hydrologic maps
   - B. Revised interpretation(s) of system

VI. Geochemical and water-quality studies
   A. Geochemical-flow processes
   B. Nature and distribution of hydrochemical facies
   C. Assessment of water use as related to water chemistry
   D. Water-chemistry interpretations from geophysical water-resistivity measurements

VII. Additional data collection and special studies
   A. Field collection of data
   B. Lineament mapping using remote sensing
   C. Packer tests in selected wells
   D. Geophysical logging in selected wells
   E. Core analysis and clay mineralogy of existing cores and samples

VIII. Data base of interpretive information for areal investigation of an aquifer
   A. Pressure
   B. Altitude
   C. Thickness
   D. Intrinsic permeability
   E. Water chemistry
   F. Specific storage
   G. Recharge and discharge

IX. Develop management alternatives

X. Model studies
   A. Test process geohydrologic and geochemical model(s)
   B. Calibrate model(s)
   C. Evaluate management alternatives

XI. Publications
   A. Base maps
   B. Report preparation
      1. Summary report
      2. Geochemical
      3. Geologic
      4. Special studies and others
   C. Review of reports

A schedule for the completion of the major work units of the plan of study is shown in figure 6. The plan and schedule may require revision during the course of study. Until the review and compilation of existing data are completed, the need for additional data or special investigations cannot be fully assessed.

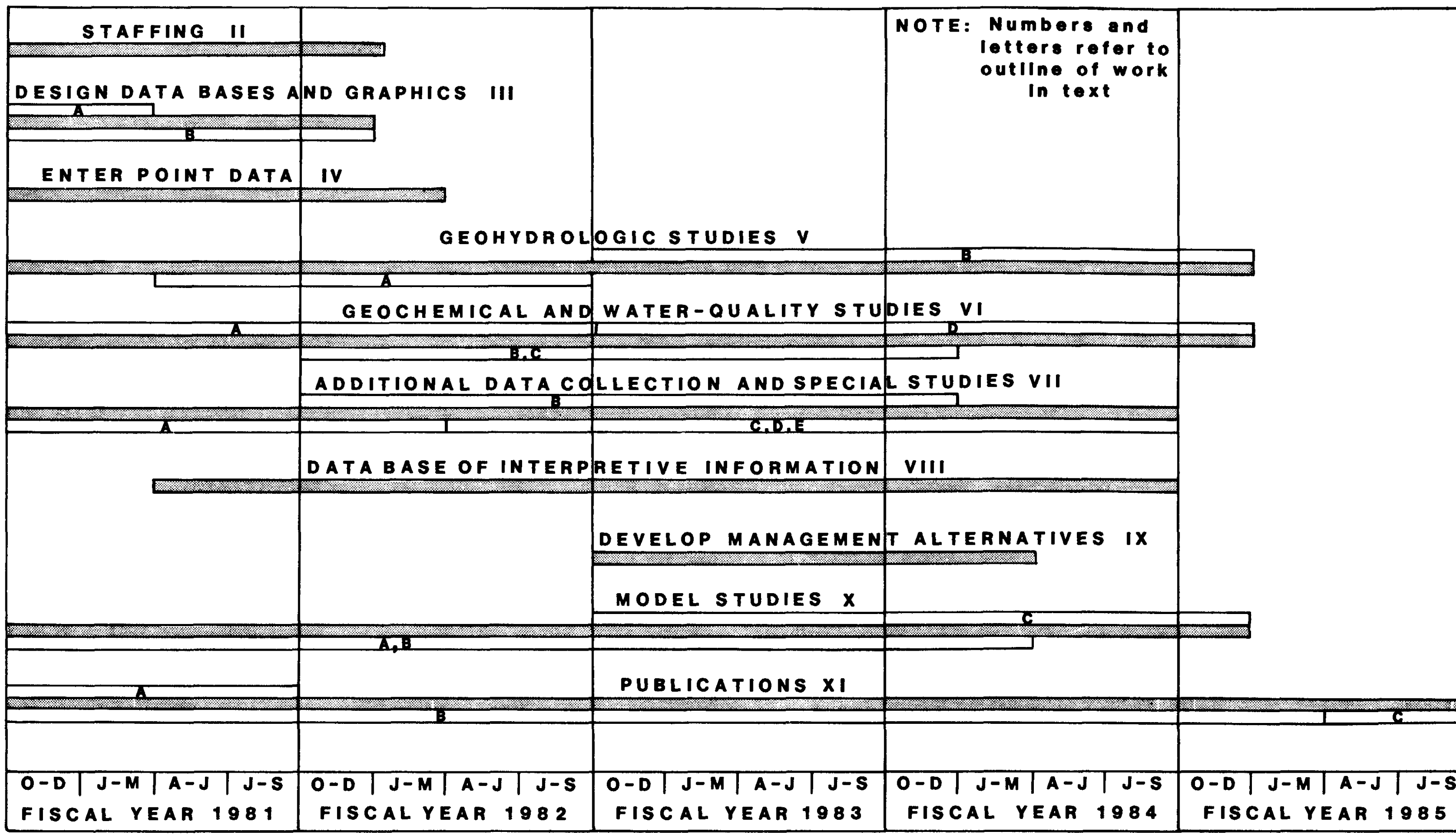

Figure 6.--Schedule of major work items.

Planning and Staffing

The personnel requirements for the Central Midwest Regional Aquifer System Analysis have been determined. The project staff for the central team, as well as the District teams, will be assembled during fiscal year 1981. Work plans in detail beyond that presented in this report will be completed during the first year.

Development of Data Bases

Included in the development of data bases for this project is the concept of digitized data, allowing computer storage for use in a data-management system. A well-designed data-management system allows efficient access, easy editing, additions, and deletions, as well as easy modification of existing files to create more useable files. The last feature is very important for use of the data by others for additional purposes.

Data bases will be of two types. The first type will consist of measured point data, such as location, altitude, depth to water, and others. The second type of data base will be interpretive data needed for modeling or areal assessment, such as matrices of specific-storage values that were obtained by interpolation from points of known specific storage.

Existing hydrologic information will be reviewed and evaluated. Data from all sources (investigative reports, data reports, U.S. Geological Survey files, files of Federal agencies, State and local government agencies, service company files, and others) will be evaluated for accuracy, detail, format, cost, and completeness.

Point data will be entered and stored in existing digitized-data files, such as GWSI (Ground Water Site Inventory), on U.S. Geological Survey computers. Project files, such as files needed for modeling, will be created from the digitized-data files. Project files will be "housed" on the Kansas District computer. A data-management system will be used to manage all project data files. All Districts already have the capability to enter data into digitized-data files. Additionally, the Districts will be equipped to address the project files housed in Kansas computer.

Hydrologic Framework

Information, such as hydraulic head, water quality, lithology, and hydrologic characteristics, will be used to aid in defining conceptual models of the aquifers and the hydrologic system. After defining the systems and the aquifers, maps and digital matrices for spatially distributed hydrologic-framework parameters will be created for the hydrologic units of the system. Simulation of the system, as conceived in the process model, will be done using digital models. If simulation results are unsatisfactory, a revised process model will be developed. New maps and matrices will be created to show the new hydrologic framework, and the process model will be retested. This procedure will be repeated until testing indicates that an adequate process model has been defined. The above procedure will require easy utilization of the point-data files to allow generation of data matrices that describe the hydrologic framework.

Porosity, Permeability, and Lithology

Porosity, permeability, and lithologic composition of near-surface aquifers will be determined primarily from existing aquifer tests, drilling samples, and geophysical logs. Information on porosity, permeability, and lithologic composition could be determined by extensive coring and drill-stem testing over the areal extent of the aquifer system. This procedure is not economically feasible. However, some core-sample information is available from the petroleum industry, the mining industry, and the Federal government. Some additional information may be obtained from existing unanalyzed core samples. Techniques using data from geophysical logs to calculate porosity, permeability, and mineral composition of the rock matrix are available and will be used in this study. Drill-stem tests conducted by the petroleum industry yield valuable hydrologic information that includes intrinsic permeability and pressure.

Information from core samples, geophysical logs, and drill-stem tests will be combined with concepts concerning sedimentation and diagenesis to formulate theories relating to the areal distribution of porosity and permeability of formations in the subsurface. This approach will be important because much of the stratigraphic section is buried deeply. Diagenesis both creates and destroys porosity and permeability at various stages. For example, important processes that create permeability include fracturing, dolomitization of limestone, and dissolution of carbonate such as rock matrix, fossils, or calcite cement. Other processes, such as cementation of secondary minerals, often fill pores spaces and reduce permeability.

Recharge and Discharge

Sources of water in the various aquifers will be determined to the degree possible. Estimates of recharge resulting from precipitation on an outcrop of the aquifer may be made from evapotranspiration models. Historical water-use data, including data from the petroleum industry, will be used to estimate recharge and discharge to the aquifers. Estimates of recharge and discharge to and from streams and aquifers will be made by analysis of streamflow records. Other techniques of estimating water flow will be developed for the project. Geologic controls will be used to define boundary conditions.

Geochemical Studies

The unusual potentiometric relations (under pressuring) between different aquifers, along with the anomalous chemistry of water found in these aquifers, strongly suggest that geochemical processes are operating in the systems. The cause for these anomalies will be investigated. Geochemical investigations will use computer programs such as WATEQ, BALANCE, and PHREEQE to identify and test possible geochemical processes. Isotopic geochemistry may be used if feasible. Maps and cross sections that show horizontal and vertical distribution of hydrochemical facies will be used to interpret geochemical relationships.

Special Studies

Special studies may include geophysical logging, "spinner" surveys in wells, and packer tests in shallow wells. Preliminary inspection of the amount of data in the study area indicates that large areas exist where little information is available. Most of these areas of sparse data are in that part of the study area where the aquifers are several thousand feet below the land surface. The cost of obtaining this important data by test drilling is far beyond the funding level of this project. Therefore, the possibility of making use of drill holes from unsuccessful commercial oil tests for logging, drill-stem tests, and any other pertinent data collection will be investigated.

Studies to determine geohydrologic parameters may be undertaken. Lineament mapping and other techniques may be used, especially in the parts of the study area where important hydrologic units are at or near the land surface.

Numerical Models

Use of a computer for numerical models of aquifer systems will be an important part of the study. As previously stated, numerical models will be used to evaluate process models of the aquifer systems. New numerical models may be developed to simulate flow from uncommon geochemical processes that result in the movement of water and changes in water quality. The need for development of new models will be apparent only after the aquifers in the study area have been delineated to a moderate degree. Additionally, numerical models also will be used to test alternative plans of water use.

Reports

The final interpretive report for the Central Midwest study will be published by the U.S. Geological Survey. The report will consist of several chapters. The principal interpretations resulting from the study will be included in one chapter. Other chapters will include geochemistry and the geohydrologic framework. Results of special studies, such as geohydrology of a particular aquifer or of a particular area, also may be incorporated as chapters in the report.

DISTRICT STUDIES

Each District will complete their part of the plan of study and perform the necessary work of that part of the study within individual States. Additionally, the Oklahoma District will coordinate collection of data with the Texas and New Mexico Districts for the small parts of the study area located in Texas and New Mexico. The Nebraska District will coordinate an effort in that part of the study area located in South Dakota with the South Dakota District. Each District will participate in all aspects of the project to the degree possible, except for the design of data bases and computer graphics. Districts are encouraged to accomplish work with the assistance of State and local agencies and to undertake cooperative projects that use data and information gained from this study.

Because of differences in the amount of available data and the detail of previous studies, the approach to the study will vary between Districts (States). The following sections outline the work plans for each of the Districts in the project area. The schedule for completion of work items by each of the Districts is the same as that of the central team and is shown in figure 6. Successful completion of all studies requires that all work items be completed on schedule.

Arkansas

Numerous rock units yield water to wells throughout the study area in Arkansas. Some of the aquifer units are at or near the surface and thus are susceptible to contamination from surface activities. The major water-producing rock units are the Roubidoux Formation and the Gunter Sandstone Member of the VanBuren Formation, both of Ordovician age. These units are used extensively for public and industrial supplies by communities and industries in the Ozark area. Other rock units of Ordovician and Cambrian age may be important aquifers, but present knowledge is inadequate for their evaluation. All the aquifer units dip steeply southward to the Arkansas River valley. It is not known if the rock units are aquifers at great depths or if they contain freshwater.

Discharge to streams is the principal means of discharge from the aquifers in the Arkansas Ozark area. Potentiometric "highs" exist near the Arkansas-Missouri border. The highs apparently indicate areas of recharge. The method of recharge to the aquifers is not well known.

Project plans for Arkansas include entering water-quality data into WATSTORE (a computer-data file for chemistry of water) in addition to assembling data for other data files. A selective well and spring inventory, including water sampling and water-level measurements, will be required in some areas where little or no information now exists.

Analysis of discharge records for streams that drain the Ozark area will be made to determine the quantity of water (base flow) that comes from or is lost to the different aquifer units. This is especially important because the south-flowing Arkansas River tributaries, along with the White River, are major discharge areas to the aquifer system.

Maps showing hydrologic properties and water quality for the important water-bearing units will be prepared. Digital models of these aquifers will be made. Interpretive reports based on the results of the investigations will be made and published as a part of the Central Midwest Regional Aquifer System Analysis report. In particular, the Arkansas District, in cooperation with the Missouri District, the Oklahoma District, and the Kansas District, will conduct a detailed report on the hydrology of the Ozark area.

Colorado

In Colorado, four rock units are thought to have sufficient water-bearing potential to warrant consideration. These are: (1) The Manitou Dolomite of Ordovician age, (2) the Lyons Sandstone of Permian age and the Fountain Formation of Pennsylvanian and Permian age, (3) the Dockum Group of Late Triassic age, and (4) the Dakota Group of Cretaceous age.

Eastern Colorado is underlain by bedrock aquifers of Mesozoic and Paleozoic age, some of which extend from the Front Range of the Rocky Mountains eastward into Missouri and Arkansas. In southeastern Colorado, these rocks form a major aquifer system that, in some areas, is the only source of agricultural and domestic water supplies. The Central Midwest Regional Aquifer System Analysis is of special importance to Colorado as little is known about the regional aspects of the geology, hydrology, and water chemistry of these aquifers or the effects of new water-resources development in the aquifers.

The geologic structure of eastern Colorado has two primary features. The first is the Denver structural basin, which is located along the eastern edge of the Rocky Mountains and extends from Pueblo north to beyond the Colorado-Wyoming State line. Depth to Precambrian rocks exceeds 15,000 feet in parts of the Denver Basin, and rocks of Paleozoic through Mesozoic age are buried at great depth. These rocks are not known to be significant aquifers in this area and appear to contain excessively mineralized water. Near outcrops and in some less deeply buried areas, these rocks contain aquifers that are important sources of potable water.

The second primary structural feature of eastern Colorado is a structural high that occurs along the Las Animas arch located near the eastern and southern borders of the State. In an approximately 10,000-square-mile area in the southeastern part of the State, Upper Triassic rocks and Lower Cretaceous rocks crop out or subcrop. These rocks contain major aquifers that yield as much as 3,000 gallons per minute of water to wells, with dissolved-solids concentrations of 200 to 1,800 milligrams per liter. These aquifers are the subject of broad-scale public interest in Colorado due to a large number of water-rights applications that have been made in this area. Presently the underlying aquifers are being developed because water levels in the overlying Ogallala aquifer are rapidly declining.

Investigation of the hydrology of aquifers in Cretaceous and Triassic rocks will be undertaken in coordination with similar studies by the Oklahoma and Kansas Districts as a part of the Central Midwest Regional Aquifer System Analysis. The sources of recharge and discharge to the aquifers in these rocks is of special interest not only in evaluating reliability of the aquifers but in regard to contamination resulting from wells finished in several aquifers having water of different chemical compositions.

A report describing the hydrology, including modeling results of the aquifers in Lower Cretaceous and Upper Triassic rocks, will be included as part of the final interpretive report. Other reports, which describe detailed work of special interest to Colorado, will be prepared for local release.

Kansas

Numerous rock units are known to be water bearing in Kansas. These include rocks of Ordovician and Cambrian age that contain the Arbuckle aquifer (Arbuckle Group). Analysis of the limited amount of data presently available is inconclusive as to whether water flow is within numerous local water-circulation areas, if there is a predominant regional east-west flow, or if there is a combined flow pattern that includes both flow within local areas and regional flow. In general, however, water in the aquifer is believed to flow from west to east and becomes increasingly mineralized as it moves eastward. In southeastern Kansas, the freshwater flowing westward from the Ozark area meets the saltwater flowing eastward across the State. Most rocks above the Ordovician, such as the Silurian, Devonian, and Mississippian, are water bearing; however, the exact hydrologic relationships among the aquifers are unknown.

Rocks of Early Pennsylvanian age generally are considered to be confining layers, although they are reported to contain both water and oil. Rocks of Permian age contain water-bearing zones in some parts of Kansas, and these rocks are the principal reservoir rocks for the extensive Hugoton gas fields. However, extensive salt deposits, which are considered impermeable to water, also exist in the Permian rocks. The relation of water-bearing rocks of Permian age to the overlying water-bearing rocks of Cretaceous age is poorly understood.

Owing to the heretofore easy availability of ground water from the Ogallala aquifer, little interest was focused on other potential aquifers. However, in consideration of the water-supply problems now occurring in western Kansas, attention now is being focused on these aquifers for additional water. Presently, in southwestern Kansas, aquifers below the Ogallala are being considered as a supplemental source of water for irrigation. Specifically, aquifers in rocks of Cretaceous, Jurassic, and Permian age are being considered.

Most hydrologic information about the aquifers that underly the Ogallala in western Kansas is obtained from the oil industry. In eastern Kansas, most data are obtained from water-well records and from the oil industry.

Kansas District project plans include work that will be accomplished in support of this project, as well as work that will meet more specifically the objectives of the District program.

Investigations in the Kansas District will include a study of the hydrology of the aquifers in rocks of Cretaceous to Permian age, which exist below the Ogallala aquifer in southwestern Kansas. This study will be done in conjunction with similar studies by the Oklahoma and Colorado Districts. Investigations of lineaments, as well as depth to saltwater, also are planned.

Projects that will meet more specifically the objectives of the Kansas District program include a study of the hydrology and degree of hydrologic connection between the Arbuckle aquifer and overlying units in western Kansas and the investigation of the hydrology of the freshwater part of the Arbuckle aquifer in southeastern Kansas. Also, with the renewal of petroleum-industry activity in eastern Kansas, valuable new data should become available. These data will be used to investigate the hydrologic relationship between the Arbuckle and overlying units in this part of the State.

Aquifers in Cretaceous rocks contain highly mineralized water in some areas. Conversely, these aquifers are known to contain potable water in other areas. Definition of the hydrology of these Cretaceous aquifers and an understanding of the hydrologic relationship between them and subcropping sandstone aquifers in rocks of Permian age are important areas of study in the Kansas District program.

Planned reports include a compilation of the geohydrologic data relating to Kansas. A series of maps, cross sections, and other reports, that discusses ground-water use, structure, lithofacies, porosity, transmissivity, and hydraulic conductivity of geohydrologically important units will be prepared or updated as circumstances dictate. Also, a statewide map depicting the base of freshwater deposits and a map indicating areas of extensive fracturing or lineation development will be prepared. A report on the geohydrology of the aquifer below the Ogallala aquifer in southeastern Colorado, southwestern Kansas, western Oklahoma, northern Texas, and northeastern New Mexico will be a part of the final interpretive report.

Missouri

The study area in Missouri includes the Ozark area (Salem and Springfield Plateaus) and the Osage Plains. Rocks of Ordovician and Cambrian age are the most important aquifer in the State. The aquifer is especially vulnerable to contamination because it is at or near the land surface in the central Ozark area.

A ground-water divide trends southwestward from the St. Francois Mountains through the southwest corner of the State and into Arkansas, as shown in figure 2. The general direction of water movement is southward from the divide and eastward from the St. Francois Mountains to the Mississippi River. North of the divide, the water moves northward toward the Missouri River.

The Missouri River and its alluvial valley may be an area of discharge from the regional-aquifer system in some areas and a source of recharge in other areas. The relationship of the freshwater flow of the Ozark area and the saltwater flow along the Missouri River is not presently known.

Much detailed data on springs are available from previous projects. A current project that concerns a "sole-source" designation of the aquifer for the U.S. Environmental Protection Agency will summarize important data relating to potential contamination of the aquifer. Because of limited petroleum exploration, few geophysical logs are available, and accordingly, few data can be obtained from petroleum-industry sources. However, many lithologic logs of water wells are available from the Missouri Department of Natural Resources.

The Missouri District's plans include the collection of a limited amount of additional data, the numerical modeling of the aquifer(s) early in the project to test process models, the detailed analysis of streamflow records in reference to gains and losses to the aquifers, and the locating of the freshwater-saltwater interface in western Missouri. Numerical modeling of important aquifers in Missouri in reference to water-use alternatives also will be an investigative effort.

Publications will include a report of investigations emphasizing the merged aquifer data from the Missouri parts of the Central Midwest Regional Aquifer System Analysis as well as the Northern Midwest Regional Aquifer System Analysis. Also, a detailed report on the hydrology of the Ozark area in conjunction with the Arkansas District, the Oklahoma District, and the Kansas District will be prepared for inclusion in the final interpretive report.

Nebraska

Rocks of Paleozoic and Mesozoic age underlie all of Nebraska, and aquifers in these rocks are the source of much of the water used for domestic, municipal, industrial, and agricultural purposes in the eastern part of the State. In the western three-fourths of the State, the Ogallala aquifer is used almost exclusively for water supplies, and no hydrogeologic evaluation has been made of the water-bearing formations that underlie the Ogallala. However, problems with the quantity and quality of water in the Ogallala aquifer are developing, and a definite need for information on deeper aquifers now exists.

The Nebraska District's plans include some efforts to locate additional water-well data and to collect new data in the eastern part of the State. These efforts will be commensurate to the funding available and may include the measurement of water levels, the collection of samples for chemical analysis, and the running of borehole geophysical logs in selected wells. Most of the data pertaining to the deep aquifers in the western three-fourths of the State will be obtained from the petroleum industry, and a major effort will be required to collect these data and determine which are useful.

Three regional studies (the High Plains, the Northern Great Plains, and the Northern Midwest Regional Aquifer System Analyses) are being made currently (1980) in areas adjacent to Nebraska, and the evaluation and interpretation of data in Nebraska will be coordinated with these studies.

Investigations in Nebraska will have as their primary objective the definition and description of important aquifers. Numerical-modeling techniques will be used in the investigation of individual aquifers if sufficient data are available and if the effort is warranted. Results of the investigations will be summarized in map reports. Special emphasis will be placed on investigations of the Dakota aquifer, and the boundary of the investigation of this aquifer will be extended to include the southeastern part of South Dakota. Results of the investigations of the Dakota aquifer will be published as a part of the final interpretive report.

Another investigation of importance to the Central Midwest Regional Aquifer System Analysis will be an evaluation of stream-aquifer relations. The Missouri River and most of the streams that are tributary to the river are, at least partly, hydraulically connected with some of the aquifers included in the Central Midwest study area. The general relation between these streams and regional ground-water flow and water quality will be determined.

Oklahoma

Rocks that will be studied in Okalahoma range in thickness from about 1,000 feet in northeastern Oklahoma to more than 40,000 feet in the Anadarko Basin of central Oklahoma. Freshwater aquifers are in the Ordovician Roubidoux Formation of the Arbuckle Group, the Pennsylvanian Vamoosa and Ada Formations, the Permian Garber Sandstone and Wellington Formation, the Dog Creek Shale, the Blaine and Rush Springs Formation, and the Elk City Sandstone. Water quality ranges from freshwater to saturated brines. It is not known if water in the brine area is moving. For example, it is not known if the lower hydraulic heads in central Oklahoma (fig. 2), which are associated in general with very saline brines, indicate a discharge area or if the low potentiometric surface is due largely to the density of the brine.

Important coal deposits in northeastern Oklahoma may be developed further in the future. Contamination of the ground water resulting from coal mines is a possible problem.

The relationship between important freshwater aquifers, which are in rocks of Cambrian to Late Cretaceous age, and the regional-flow system is uncertain. Generally, the base of the freshwater is less than 500-feet deep, but it may be as much as 2,000-feet deep. It is thought that two principal zones of the aquifer system may exist. The lower zone may be in the dominantly carbonate rocks of Mississippian age or older. The second zone of the regional-aquifer system maybe in the predominantly clastic rocks of Pennsylvanian, Permian, Jurassic, and Cretaceous age.

Investigations in Oklahoma will include study of aquifers in rocks of Cretaceous to Permian age below the Ogallala aquifer in the panhandle areas of Oklahoma and Texas, as well as in northeastern New Mexico. This particular investigation will be coordinated with similar study efforts in Colorado and Kansas. Numerical-modeling techniques as part of an investigation of an individual aquifer will be used if adequate data exist and if warranted.

Another important investigation is the hydrologic relationship of water-bearing deposits on the flanks of the Arbuckle, the Wichita, and the Amarillo Uplifts, which form the southern boundary of the study area, to the regional-aquifer system.

Publications will include an initial detailed planning report and atlas-type reports for important aquifers. Reports of investigations of other special studies will be published as parts of the final interpretive report.

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