REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM OF THE U.S. GEOLOGICAL SURVEY--BIBLIOGRAPHY, 1978-86

By John B. Weeks and Ren Jen Sun

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DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

Ren Jen Sun, RASA Program Coordinator
Office of Ground Water,
Water Resources Division
U.S. Geological Survey,
National Center, Mail Stop 411
12201 Sunrise Valley Drive
Reston, VA 22092

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CONTENTS

FIGURE

CONVERSION FACTORS

For the use of readers who prefer to use metric (International System) units, conversion factors for inch-pound units used in the report are listed below:

Multiply inch-pound unit	*By*	*To obtain metric unit*
	Length	
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
	Area	
square mile	2.59	square kilometer
	Volume	
acre foot	1,233	cubic meter
billion acre-feet	1,233	cubic kilometer
million acre-feet	1,233	cubic hectometer
	Flow	
foot per year	0.3048	meter per year
inch per year	25.4	millimeter per year
cubic foot per second	0.02832	cubic meter per second
gallon per day	0.003785	cubic meter per day
billion gallons per day	43.81	cubic meter per second
million gallons per day	0.04381	cubic meter per second

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 "Mean Sea Level of 1929."

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ABSTRACT

The Regional Aquifer-System Analysis Program of the U.S. Geological Survey was initiated in 1978. The purpose of this program is to define the regional geohydrology and establish a framework of background information on geology, hydrology, and geochemistry of the Nation's important aquifer systems. This information is critically needed to develop an understanding of the Nation's major ground-water flow systems and to support better ground-water resources management.

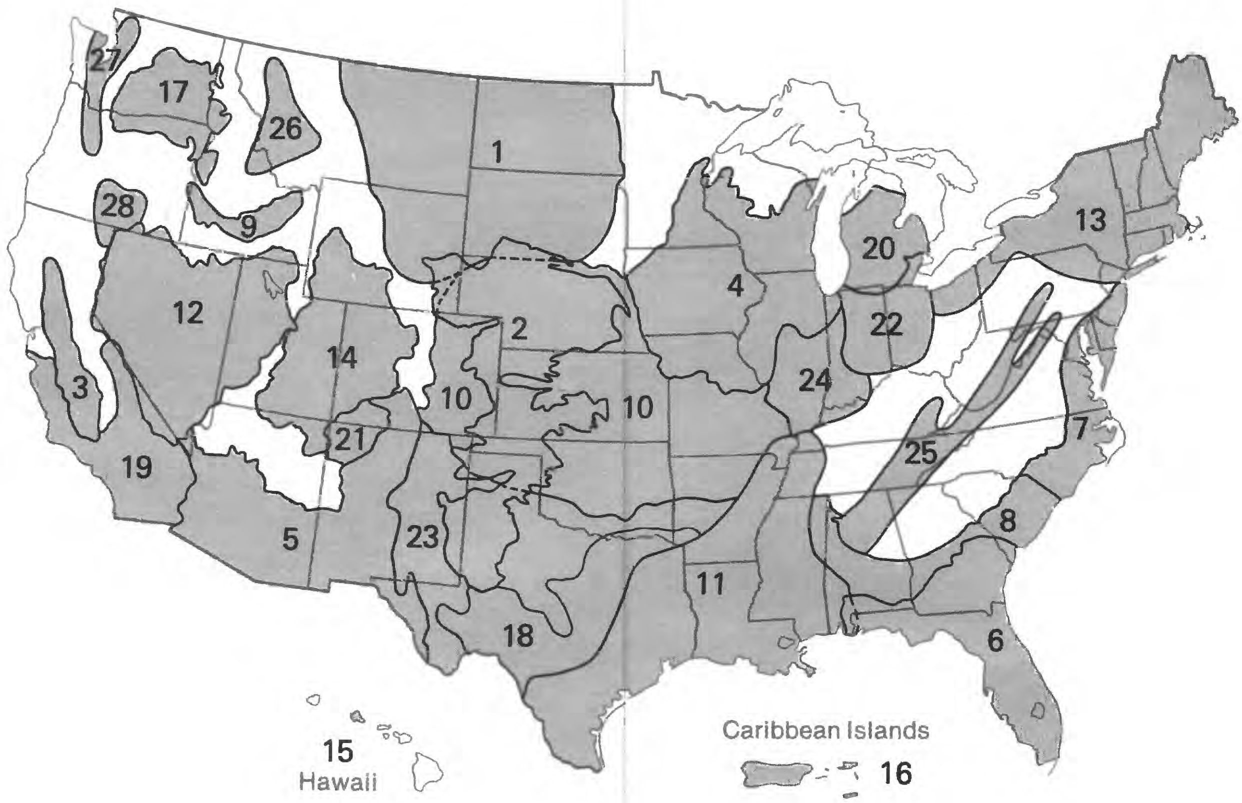
As of 1986, investigations of 28 regional aquifer systems were planned, investigations of 9 regional aquifer systems were completed, and 11 regional aquifer systems were being studied. This report is a bibliography of reports completed as part of the Regional Aquifer-System Analysis Program from 1978 through 1986.

The reports resulting from each regional aquifer-system study are listed after an introduction to the study. During 1978-86, 488 reports were completed under the Regional Aquifer-System Analysis Program, and 168 reports which were partially funded by the Regional Aquifer-System Analysis Program were completed under the National Research Program.

INTRODUCTION

The U.S. Geological Survey initiated the Regional Aquifer-System Analysis (RASA) Program during 1978 in response to Federal and State needs for information to support better ground-water management. The objective of the RASA program is to define the regional geohydrology and establish a framework of background information--geologic, hydrologic, and geochemical--that can be used for regional assessment of ground-water resources and in support of more detailed local studies.

A total of 28 regional aquifer systems have been identified for study under the RASA Program (fig. 1). As of 1986, 21 RASA projects had been started. Studies of the following nine regional aquifer systems have been completed: Northern Great Plains; High Plains; Central Valley, California; Northern Midwest; Southwest Alluvial Basins; Floridan; Snake River Plain; Central Midwest; and Great Basin. In some of these projects, where major technical problems or data deficiencies were identified that could not be addressed adequately within the context of the initial investigation (phase I study), follow-up studies (termed RASA phase II studies) have



EXPLANATION

10 — REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM -- Numbering-system for identification purposes only, not intended to imply priority

1, Northern Great Plains
2, High Plains
3, Central Valley, California
4, Northern Midwest
5, Southwest alluvial basins
6, Floridan
7, Northern Atlantic Coastal Plain
8, Southeastern Coastal Plain
9, Snake River Plain
10, Central Midwest
11, Gulf Coastal Plain
12, Great Basin
13, Northeast glacial
14, Upper Colorado River Basin
15, Oahu Island, Hawaii
16, Caribbean Islands
17, Columbia Plateau basalt
18, Edwards-Trinity
19, Southern California alluvial basins
20, Michigan Basin
21, San Juan Basin
22, Ohio-Indiana glacial deposits and carbonates
23, Pecos River Basin
24, Illinois Basin
25, Appalachian Valleys and Piedmont
26, Northern Rockies Intermontane basins
27, Puget-Willamette Trough
28, Alluvial basins, Oregon, California, and Nevada

Figure 1.--Location of regional aquifer systems identified for study under the Regional Aquifer-System Analysis Program of the U.S. Geological Survey.

been undertaken. Except for the Great Basin and Northern Great Plains regional aquifer-system studies, the other seven completed studies have follow-up projects. In addition to the phase II studies, there were 11 on-going studies during 1986: Northern Atlantic Coastal Plain; Southeastern Coastal Plain; Gulf Coastal Plain; Northeast Glacial; Upper Colorado; Oahu Island, Hawaii; Caribbean Islands; Columbia Plateau; Edwards-Trinity, Texas; Michigan Basin; and San Juan Basin. One study, Southern California alluvial basins, was temporarily terminated.

The RASA Program has partially supported the National Research Program (NRP) of the U.S. Geological Survey. The purpose of this support is to build for the future by continued research and development of theoretical and operational procedures for hydrologic investigations. Previous research on analytical procedures developed by the NRP, such as computer models for ground-water flow and mass transport, have made the RASA Program effective. This bibliography includes RASA reports and NRP reports that were partially funded by the RASA Program from 1978 through 1986.

The results of RASA and NRP investigations are released through publications of the U.S. Geological Survey as Hydrologic Investigations Atlases, Open-File Reports, Water-Resources Investigations Reports, Water-Supply Papers, and Professional Papers; some reports are published in proceedings and journals of scientific organizations or by cooperators and contractors. Upon completion of each RASA study, Professional Papers are published that summarize and synthesize the results of the study. The Professional Paper associated with each project is divided into chapters designated by letters, with the letter A reserved for a general chapter that summarizes and integrates the major project findings. All of the Professional Papers derived from RASA studies will be identified by a Professional Paper number between 1400 and 1429.

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REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM BIBLIOGRAPHY

This report provides a brief introduction to the 21 RASA studies as of 1986. The introduction to each RASA study is followed by a list of reports completed during that study. From its inception through 1986, 488 reports were completed under the RASA Program. Two of these reports, which are listed below, explain and summarize the Regional Aquifer-System Analysis Program. The remaining 486 reports are listed in the following sections of this report.

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Northern Great Plains

The area of the Northern Great Plains regional aquifer-system study is about 250,000 square miles and includes North Dakota and parts of South Dakota, Montana, Wyoming, and Nebraska (fig. 1). The northern Great Plains mostly is underlain by sandstone, shale, and some evaporite deposits. Ground water generally flows northeastward across the study area. The source of recharge is precipitation in topographically high areas. Ground water mostly discharges into topographically low areas of eastern North Dakota and South Dakota and occurs as outflow into Canada. Some ground-water discharge also occurs as diffuse upward leakage into overlying aquifers.

Flow characteristics vary significantly between the predominantly carbonate aquifers of Paleozoic age (such as the Madison Limestone) and the predominantly clastic aquifers of Mesozoic age (such as the Dakota Sandstone) and Cenozoic age. Potential for flow among aquifers exists near recharge and discharge areas and in the interior part of the study area, where hydraulic heads vary significantly between aquifers.

Development of ground-water supplies in the northern Great Plains will be needed for the growth of energy resources, power generation, industrial expansion, increasing irrigation, and domestic and municipal water use. Historically, streamflow has satisfied most of the water needs; however, surface water is fully appropriated in much of the area, and it is not always a dependable source because streamflows are extremely variable. Long-term, large-scale water needs require the development of ground water.

A study of the Madison Limestone aquifer was initiated in 1975 to address the problems of water supplies associated with development of coal resources and the proposed coal-slurry pipelines in the Fort Union coal region. The Northern Great Plains regional aquifer-system study was started in 1978 for the purpose of studying the aquifer system underlying the northern Great Plains; the Madison Limestone aquifer study was merged into the Northern Great

Plains regional aquifer-system study. The study was completed in 1982 and it resulted in 62 reports listed in the following bibliography. Reports prepared during the Madison Limestone aquifer study prior to the Northern Great Plains study are not included in this bibliography.

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High Plains

The High Plains aquifer (fig. 1) underlies 174,000 square miles of flat to gently rolling terrain in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The region has abundant sunshine, moderate precipitation (16 to 28 inches annually), and highly productive soils when adequate water is available. Ground water from the High Plains aquifer is the primary source of water in this area of few streams. More than 90 percent of all water used in the High Plains is obtained from the High Plains aquifer. About 95 percent of all water pumped from the aquifer is used for irrigation. Because of a plentiful supply of suitable quality ground water, irrigation has transformed the High Plains into one of the Nation's major agricultural areas.

The High Plains aquifer consists mainly of near-surface sand and gravel deposits. The Tertiary Ogallala Formation, which underlies about 80 percent of the High Plains, is the principal geologic unit in the aquifer. The saturated thickness of the High Plains aquifer averages 200 feet, and the maximum thickness is about 1,000 feet in central Nebraska. Ground water generally flows from west to east and discharges naturally to streams and springs and by evapotranspiration in areas where the water table is near land surface. Infiltration of precipitation and seepage from streams are the principal sources of recharge to the aquifer.

In 1980, about 3.25 billion acre-feet of drainable water was stored in the aquifer. Approximately 66 percent of the water in storage was in Nebraska, and 12 percent was in Texas. New Mexico, the State with the smallest water resource in the High Plains, had only 1.5 percent of the volume of water in storage. The total volume of water in the High Plains aquifer in 1980 had decreased about 5 percent or 166 million acre-feet since ground-water development began. Although the decrease in total volume of water seems small, it has significantly affected ground-water supplies in local areas. As of 1980, the original volume of water stored in the aquifer had declined 23 percent in Texas, 16 percent in New Mexico, 8 percent in Kansas, and smaller amounts in the other States. Consequently, the most severe problems resulting from depletion of the aquifer have occurred in Texas, New Mexico, and Kansas where irrigation developed earliest.

National concern about the economic impact of declining water supplies in the High Plains resulted in the beginning of a regional study of the High Plains aquifer in 1978. The objectives of the study were to provide (1) hydrologic data needed to evaluate the effects of continued ground-water development, and (2) computer models for evaluating aquifer response to changes in ground-water development. The study was conducted in two phases. During phase I (completed in 1982), the geohydrologic framework of the aquifer system was evaluated, and computer models of ground-water flow were developed. During phase II (completed in 1986), irrigation returnflow was evaluated, 1980-to-2020 pumpage was estimated using irrigated acreage and water use projections made by the U.S. Department of Commerce, and aquifer response to future pumpage was evaluated using computer models. The study resulted in 109 reports listed in the following bibliography.

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Central Valley, California

The Central Valley of California (fig. 1) includes approximately 20,000 square miles. The northern part is drained by the Sacramento River, and the southern part is drained by the San Joaquin River. The aquifer system of the Central Valley is composed of a heterogeneous mixture of continental alluvial materials derived from the surrounding mountains. Thickness of the sediments averages about 1,500 feet in the Sacramento Valley and 2,900 feet in the San Joaquin Valley.

The climate of the Central Valley is arid to semiarid, with average annual precipitation ranging from 14 to 20 inches in the Sacramento Valley, and 5 to 14 inches in the San Joaquin Valley. Under predevelopment conditions, potential evapotranspiration exceeded precipitation by as much as 40 inches per year. Consequently, large quantities of water are needed for irrigation.

In addition to the agricultural use of ground water, nearly every city in the San Joaquin Valley uses ground water as the principal source for municipal and industrial supplies. Fortunately, ground water is available everywhere in the Central Valley, even where little rain normally falls or little surface water exists. Annual pumpage in the Central Valley has increased from about 362,000 acre-feet during 1912-13 to about 15 million acre-feet during the drought year, 1977. In parts of the Central Valley, pumping has caused water-level declines of nearly 400 feet.

About 50 percent of the thickness of continental sediments in the Central Valley is composed of deposits of clay and silt. As water levels decline in aquifers, water stored in the pores of the layers consisting of fine-grained materials starts to drain into the adjacent aquifers where heads have been reduced. As a result, the land surface may subside due to compaction of the fine-grained sediments. By 1970, subsidence exceeded 29 feet at one point in the San Joaquin Valley, and over 5,000 square miles of land surface in the Central Valley had subsided more than 1 foot.

Because of these problems, water managers need accurate and consistent information on the behavior of the ground-water flow system in the Central Valley and on the potential impact of development on the aquifer system. To provide such needed information, the U.S. Geological Survey started a study of the regional ground-water flow system in the Central Valley in 1978. The study is being conducted in two phases. During phase I (completed in 1982), the geohydrologic framework of the aquifer system was evaluated and computer models of ground-water flow and land subsidence were developed. Phase II of the Central Valley study is evaluating the aquifer system in the San Joaquin Valley where geochemical investigations are being conducted in cooperation with the U.S. Bureau of Reclamation. As of December 1986, 31 reports which are listed in the following bibliography, were completed.

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Northern Midwest

The Northern Midwest regional aquifer-system study (fig. 1) was designed to investigate the hydrogeology, ground-water availability, and chemical quality of water in an aquifer system consisting of rocks of Cambrian and Ordovician age in parts of Illinois, Indiana, Iowa, Minnesota, Missouri, and Wisconsin (fig. 1). The study area is about 161,000 square miles, and its boundaries are the physical or hydrologic limits of the aquifer system.

The aquifer system contains three distinct aquifers--St. Peter-Prairie du Chien-Jordan aquifer, Ironton-Galesville aquifer, and Mount Simon aquifer. The aquifers consist primarily of sandstone, and they are separated by shale, shaly dolomite, or siltstone confining units. Where the Maquoketa Shale is present, the shale and the underlying dolomite and shale strata of the Galena Dolomite and Decorah, Platteville, and Glenwood Formations form a major confining unit that overlies the three aquifers.

The Cambrian-Ordovician aquifer system is a leaky-artesian system, and movement of ground water is partly controlled by internal confining units of low permeability. In the outcrop area, water-table conditions prevail in shallow parts of the aquifer system and where the system is thin. Much of the recharge in upland areas discharges to streams through local flow systems which are no more than a few miles in length. The remainder of the recharge moves slowly downward to deeper formations and downgradient to the regional ground-water flow system.

The Cambrian-Ordovician aquifer system supplies a major part of the water needs in the study area. The aquifer system is used extensively for industrial and rural water supplies in the six States. Many metropolitan areas depend on the aquifer system for all or part of their water supplies. Hydraulic heads in the aquifer system have declined hundreds of feet since the late 1800's in the heavily pumped Chicago-Milwaukee area and to a lesser extent in other major metropolitan areas. Projections of future water needs indicate continuing or increasing demands, and, therefore, continuing water-level declines are expected.

The purposes of the Northern Midwest regional aquifer-system study were to evaluate the water-supply potential of the Cambrian-Ordovician aquifer system and develop computer models capable of evaluating regional aquifer response to changes in ground-water development. The study began in 1978 and was completed in 1984. It resulted in 21 reports that are listed in the following bibliography.

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Southwest Alluvial Basins

There are many alluvial basins in the southwestern United States. Some of these basins were selected for study under the RASA Program to understand the occurrence, movement, and quality of ground water in the alluvial-basin aquifer systems. The results of the study of selected basins indicate that certain hydrologic and geologic information can be transferred to other alluvial-basin aquifer systems. The Southwest Alluvial-Basins regional aquifer-systems study (fig. 1) was started in 1978 and completed in 1984. Geographically, the study was divided into two parts:

(1) Study in parts of Colorado, New Mexico, and Texas

The study of aquifer systems underlying the southwest alluvial basins in parts of Colorado, New Mexico, and Texas included a total area of 70,000 square miles. The basins are bounded on the north, east, and west mainly by Quaternary and Tertiary volcanics and Mesozoic and Paleozoic rocks. The southern boundary of the study area is not defined by structural or hydrologic boundaries but was arbitrarily placed at the Mexico-United States International Boundary.

Alluvial sediments in the basins were derived from the surrounding highlands and mountains. The alluvial sediments are composed of flood-plain deposits and sediments of the Quaternary and Tertiary Santa Fe Group. The Santa Fe Group is a rock-stratigraphic unit that consists of unconsolidated to moderately consolidated lenticular deposits of gravel, sand, and clay interbedded in some places with volcanics. Precipitation in the uplifted mountainous blocks east and west of the basins is the source of the surface water which eventually recharges the aquifers near the base of the mountains where infiltration rates are high. The other source of recharge is seepage from the Rio Grande. Most municipal and industrial wells in the study area are completed in the Santa Fe Group.

For this part of the Southwest Alluvial Basins regional aquifer-systems study, computer models of ground-water flow in four basins were developed and 20 reports were prepared. The reports are listed in the following bibliography.

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(2) Study in southern and central Arizona and parts of adjacent States

The study of aquifer systems underlying the alluvial basins in southern and central Arizona and parts of California, Nevada, and New Mexico includes an area of about 82,000 square miles. The area contains 72 basins that are virtually separate hydrologic entities. The boundaries between basins mainly correspond to surface-water drainage divides, ground-water divides, or areas of minimal interbasin connection. The study area is characterized by sharply rising mountains that separate wide, flat basins filled with varying amounts of alluvial deposits. These deposits form the major aquifers and store large amounts of water.

The basins were formed 10 to 15 million years ago. Movement along high-angle normal faults down-dropped the basins in relation to the mountain masses. The result was a series of generally northwest-trending basins. Basin subsidence was a gradual process that was accompanied by deposition of locally derived sediments within the internally drained basins. The basins are filled with alluvial deposits that range in thickness from a few thousand feet to more than 10,000 feet. In almost all basins, the general vertical sequence of sedimentary units is, in ascending order, sediments deposited before the formation of the Basin and Range topography, lower and upper basin fill, and stream alluvium. Each of the hydrogeologic units has different physical, geologic, and hydrologic properties largely because of differences in the depositional environment and source area of the sedimentary material.

The basins of the study area were grouped into five categories on the basis of geologic and hydrologic properties. The groups are: (1) southeast, (2) central, (3) west, (4) Colorado River, and (5) highland. The character of the sediments filling the basins and the important flow components are similar within a category. Computer models were used to analyze ground-water flow conditions for selected basins in each catagory. For this part of the Southwest Alluvial-Basins regional aquifer-systems study, 34 reports were prepared. The reports are listed in the following bibliography.

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Floridan

The Floridan aquifer system is one of the major sources of ground water in the United States. This highly productive aquifer system underlies all of Florida, southeastern Georgia, and small parts of adjoining Alabama and South Carolina (fig. 1), a total area of about 100,000 square miles.

The Floridan aquifer system includes several Tertiary carbonate formations that are hydraulically connected in various degrees to form a regional aquifer system. However, locally there are significant differences in hydrologic properties, water chemistry, and flow. The aquifer system is a sequence of hydraulically connected carbonate rocks (principally limestone with some dolomite) that range in age from late Paleocene to early Miocene. The rocks vary in thickness from a featheredge in outcrop areas to more than 3,500 feet in coastal areas. The aquifer system generally consists of an upper and lower aquifer separated by a less-permeable confining unit of highly variable properties. In parts of northern Florida and southwestern Georgia, there is little permeability contrast within the aquifer system. Thus, in these areas, the Floridan acts effectively as one continuous aquifer.

Ground-water development of the Floridan aquifer system has proceeded unevenly with large withdrawals concentrated in a few areas. A total of about 3.4 million acre-feet per year (3 billion gallons per day) is withdrawn from the aquifer system, and, in many areas, the aquifer system is the sole source of freshwater. A considerable area of the Floridan aquifer system remains highly favorable for development of large ground-water supplies. This favorable area is largely inland and is characterized by high transmissivity as well as minimal development as of 1980. The major constraint on future development is degradation of water quality. The possibility of saltwater encroachment in coastal areas and upconing of deep saltwater in some inland areas are important factors to consider for future development.

The objectives of the Floridan regional aquifer-system study, which began in 1978, were to (1) describe the geohydrologic framework and geochemistry of the Floridan aquifer system, (2) analyze the regional flow system, and (3) assess the effects of large withdrawals of ground-water from the aquifer system. The study was conducted in two phases. During phase I (completed in 1983), the regional flow system was described and modeled using a "coarse-mesh" regional flow model and four subregional flow models. The regional flow model was used to understand the major features of the flow system. The four subregional flow models were used to focus on the areas of greatest ground-water development. During phase II (completed in 1986), detailed investigations of local aspects of the aquifer system were conducted including a petrographic study in central Florida and a study of saltwater movement at Hilton Head Island, South Carolina. The study has resulted in 33 reports which are listed in the following bibliography.

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Northern Atlantic Coastal Plain

The northern Atlantic Coastal Plain is a gently rolling to flat region of about 50,000 square miles that extends along the Atlantic coast from Long Island, New York, to North Carolina (fig. 1). It is underlain by a wedge of predominantly unconsolidated sediments that thickens from a feather edge in the outcrops to 8,000 feet along the coast of Maryland and 10,000 feet at Cape Hatteras, North Carolina. The sediments consist mostly of sand, silt, clay, and gravel of Jurassic to Holocene age. Limestone occurs principally in North Carolina.

This sedimentary wedge forms a complex aquifer system in which the sand, gravel, and limestone function as aquifers, and the clay and silt act as confining units. The sediments can be subdidvided into several aquifers and confining units based on the predominant lithologies, depositional environments, and ages of the sediments. Lateral facies shifts that were caused by marine transgressions and regressions determine the distribution of the aquifers and confining units.

Recharge to the northern Atlantic Coastal Plain aquifer system is derived from precipitation and occurs chiefly in upland and interfluvial areas. It ranges from 10 to 25 inches per year, but most of this flows only through the shallow unconfined parts of the system and discharges to local streams that dissect the Coastal Plain. A small amount of the precipitation, generally less than 1 inch per year, recharges the deeper confined aquifers. Under natural conditions, discharge from the deeper aquifers is primarily upward across the confining units into shallower aquifers and ultimately into the sea or coastal estuaries, sounds, and bays. Saltwater underlies freshwater in the eastern part of the Coastal Plain. Areas of shallow saltwater generally coincide with areas of natural ground-water discharge.

Withdrawal of water from this system, principally for municipal and industrial use, has grown from about 100 million gallons per day in 1900 to about 1,200 million gallons per day in 1980. Pumping from the confined aquifer system has caused widespread water-level declines that have significantly altered ground-water recharge and flow patterns.

The Northern Atlantic Coastal Plain regional aquifer-system study was started in 1979. The study has developed computer models of ground-water flow in the northern Atlantic Coastal Plain. The regional aquifer system was simulated using a multilayered finite-difference flow model that includes ten aquifers and nine confining units. Four subregional models also were developed for better resolution. These models are being used to aid in the understanding of the aquifer system, its response to pumping, and the relations between freshwater and saltwater within the aquifer system. As of December 1986, 16 reports, which are listed in the following bibliography, were completed.

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Southeastern Coastal Plain

The southeastern Coastal Plain aquifer system underlies an area of about 130,000 square miles in South Carolina, Georgia, Alabama, Mississippi, and adjacent areas of northern Florida and southwestern North Carolina (fig. 1). Rainfall ranges from 44 to 64 inches on the coastal plain. The southeastern Coastal Plain aquifer system is located between three adjacent regional aquifer systems: the northern Atlantic Coastal Plain to the northeast, the Floridan to the south and southeast, and the Gulf Coastal Plain to the west.

The southeastern Coastal Plain aquifer system consists of a thick wedge of unconsolidated to poorly consolidated clastic and carbonate rocks of Jurassic to Holocene age. These rocks extend seaward from the inner Coastal Plain margin to the Atlantic Ocean, Gulf of Mexico, or Florida peninsula. Except where they are covered by younger strata, the aquifers and confining units that comprise the southeastern Coastal Plain regional aquifer system crop out in adjacent bands from Mississippi to South Carolina. In outcrop areas, most of the water that enters the aquifer system is discharged to nearby streams and rivers. Only a small part of the water moves downdip where the major part of the regional aquifer system is confined by thick clay, chalk, and shale. The aquifer system is underlain in most places by relatively impervious metamorphic, sedimentary, and igneous rocks of Paleozoic and early Mesozoic age.

The sediments of the southeastern Coastal Plain are the product of cyclical advance and retreat of ancient seas. The fluctuating depositional conditions, resulting from an ever-shifting shoreline, caused the lithology and hydraulic properties of these sediments to differ greatly from place to place. These variations significantly affect the occurrence and flow of ground water.

Pumpage from the southeastern Coastal Plain aquifer system has caused large regional water-level declines and degradation of ground-water quality because of saltwater encroachment. The Southeastern Coastal Plain regional aquifer-system study was started in 1979 to examine these problems. The clastic sediments that comprise the southeastern Coastal Plain regional aquifer system have been grouped into seven major hydrogeologic units. Regional and subregional computer models of the aquifer system are being used to simulate ground-water flow, to help estimate predevelopment potentiometric surfaces and hydraulic properties of the aquifers and confining units, and to test the validity of the conceptual model of the hydrogeologic framework. As of December 1986, 31 reports were completed. The reports are listed in the following bibliography.

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Snake River Plain

The Snake River Plain is an area of about 15,600 square miles that extends across southern Idaho into eastern Oregon (fig. 1). The Snake River descends 2,930 feet along its 502-mile course through the study area. The surface of the plain decreases in altitude from about 6,000 feet above sea level in the northeast to 2,100 feet in the west. Average annual precipitation on much of the plain is less than 10 inches, one-third to one-half of which falls during the April through September growing season. Most water available to the plain originates as snow on surrounding mountains which are as much as 12,000 feet above sea level. Annual precipitation in the mountains is as much as 60 inches. For study purposes, the plain was divided into eastern and western parts on the basis of geology and hydrology. The area of the eastern plain is 10,800 square miles, and the area of the western plain is 4,800 square miles.

The eastern plain is basically a downwarp. Most of the fill consists of Quaternary basalt. Near the margins, unconsolidated sedimentary rocks overlie and are intercalated with the basalt. The tops of basalt flows are typically broken and have large hydraulic conductivities. Consequently, thick sections of basalt, which include many flows, store and yield large quantities of water. In places, the basalt aquifer may be several thousand feet thick; however, the upper 200 to 500 feet are thought to be the most permeable. In much of the eastern plain, the regional aquifer system is unconfined. About two-thirds of the ground water discharged from the eastern plain is through a series of springs that flow to the Snake River, including 11 of 65 springs in the United States that discharge an average of more than 100 cubic feet per second.

The western plain is a graben bounded by well-defined high-angle faults. Quaternary and Tertiary sedimentary rocks of variable thickness are the predominant fill material. In the Boise River valley, most water is obtained from unconfined alluvial sand and gravel. Elsewhere, rocks are predominantly fine grained; included sand and gravel aquifers are largely confined. Ground-water discharge to the Snake River in the western plain is small relative to that in the eastern plain.

The economy of southern Idaho is based largely on agriculture which is dependent on an adequate supply of good-quality water for irrigation. In the past, most water for irrigation was obtained from the Snake River. By 1984, ground water was also a major source of water for irrigation. As water use increases, so does competition for the right to use water.

The Snake River Plain regional aquifer-system study began in 1979. Its purpose was to provide a better understanding of the hydrologic system in the Snake River Plain so that future demands for water could be better managed. The study was conducted in two phases. During phase I (completed in 1984), computer models of the eastern and western parts of the Snake River Plain were developed and used to simulate long-term regional hydrologic changes. During phase II (continuing), computer models of ground-water flow are being developed for areas where detailed information is needed to better understand the hydrologic system. As of December 1986, 22 reports, which are listed in the following bibliography, were completed.

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Central Midwest

The Central Midwest regional aquifer-system study includes 370,000 square miles in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1). The sedimentary rocks underlying the study area, except in parts of Missouri, are generally water-yielding formations and range in thickness from a featheredge where they pinch out in Missouri to more than 40,000 feet in central Oklahoma. The igneous and metamorphic basement rocks that underlie the water-yielding formations generally do not yield significant quantities of water to wells. Therefore, the surface of the basement rock effectively forms the base of the ground-water flow system in the study area.

Hydraulic properties of the various rocks in the study area differ greatly. These rocks include Cretaceous and Jurassic sandstone and shale; Permian evaporites, shale, and limestone; Pennsylvanian shale and Mississippian limestone and shale; and Ordovician and Cambrian dolostone, limestone, and sandstone. In much of the study area, the water-yielding rocks are deeply buried, and ground-water related data are scarce except for data collected incidentally by the petroleum industry. Because the cost of collecting additional hydrologic data in the deep subsurface is prohibitive, special efforts and techniques were used to evaluate and analyze existing data.

The purpose of the Central Midwest regional-aquifer study is to provide hydrologic information needed for planning and managing development of the system and to evaluate the impact of development on the system. Potential development of the aquifer system could include fresh-water supply, saline-water supply, materials storage, waste disposal, and geothermal potential. Potential impacts of development on the system could include declining water supply, deterioration of water quality, and contamination resulting from some surface or subsurface activity. Although interpretation of regional hydraulics could have potential implications regarding oil and gas occurrence and development, the oil and gas resource itself is not being appraised. The investigations of the Central Midwest regional aquifer-system study began in 1980. As of December 1986, 19 reports were completed. The reports are listed in the following bibliography.

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Gulf Coastal Plain

The Gulf Coastal Plain regional aquifer-system study includes an area of about 230,000 square miles onshore in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Mississippi, Missouri, Tennessee, Texas, and all of Louisiana (fig. 1). The study area also includes 60,000 square miles offshore between the coast and the edge of the continental shelf, because the aquifers extend beyond the coast line beneath the Gulf of Mexico. The study is limited to the Coastal Plain sediments of Tertiary and younger age except for an area in the Mississippi embayment where Upper Cretaceous sediments supply ground water in parts of several States. The bottom of the aquifer system is at the top of the Paleocene Midway Group or at the top of the geopressured zone. The sediments are thin in and near the outcrop areas but attain thicknesses of several thousand feet downdip. None of the individual aquifers is continuous throughout the study area; some cover only a few hundred square miles. Some of the aquifers in sediments of Eocene age are present in as many as eight of the ten States and supply large quantities of fresh ground water for municipal, industrial, and agricultural use.

The sediments within the study area are composed predominantly of alternating beds of sand and clay with some interbedded gravel, silt, lignite, and limestone. The sediments that comprise the individual aquifers and associated confining units are exposed at land surface in narrow bands several miles wide that roughly parallel the present Gulf of Mexico coastline except on the western side of the Mississippi embayment. The sediments in the study area generally dip toward the Gulf of Mexico and generally become thicker and less permeable downdip. The regional ground-water flow pattern in these sediments is interrupted downdip by faulting or by the geopressured zone.

On the basis of differences in regional ground-water flow patterns and sediment characteristics, three aquifer systems have been delineated in the Gulf Coast--the Mississippi Embayment aquifer system, the Texas Coastal Uplands aquifer system, and the Coastal Lowlands aquifer system. The three regional aquifer systems have been developed to varying degrees throughout the area. A variety of problems has resulted from development, such as movement of the saline-freshwater interface into parts of aquifers that were previously fresh, lowering of the potentiometric surface with resulting increases in pumping lift, and land-surface subsidence due to the compaction of clays within the aquifer. Demand for ground water is expected to increase in the future to meet the needs of urban growth, energy development, and irrigated agriculture.

The Gulf Coastal Plain regional aquifer-system study began in 1980. Its objectives are to: (1) Define the geohydrologic framework of the aquifers, (2) describe the chemistry of the ground water, (3) analyze the regional ground-water flow patterns, and (4) evaluate the potential for compaction of confining units resulting from changes in fluid pressures. Computer models are being used to simulate ground-water flow and test hypotheses about the aquifer system. As of December 1986, 23 reports, which are listed in the following bibliography, were completed.

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Great Basin

The Great Basin regional aquifer-system study included about 140,000 square miles in parts of Nevada, Utah, and adjacent States (fig. 1). The area is characterized by generally north-trending mountain ranges which have a width ranging from 5 to 15 miles. The mountain ranges rise 1,000 to 5,000 feet above adjoining valleys. The widths of the valleys are about the same as widths of the adjacent mountain ranges. The valleys are typically elongated, and many extend more than 50 miles in a north or northeast direction.

The area has a complex geologic history that includes major episodes of sedimentation, igneous activity, orogenic deformation, and continental rifting. A major tectonic change occurred about 17 million years ago with the onset of extensional faulting, which has formed the major basins and ranges that characterize the topography. The Great Basin contains a regional aquifer system in that most of its separate valley basins share common geologic and hydrologic characteristics. Currently, some 242 hydrographic areas are recognized within the study area; most include one or more structural basins and associated basin-fill aquifers. A special situation exists in eastern Nevada and western Utah, where permeable carbonate rocks underlying the basin-fill deposits form a complex ground-water flow system with the characteristics of both basin-fill and carbonate aquifers.

In recent years, much of the study area has been considered for use by the MX missile system; also, large coal-fired powerplants are being constructed at several locations, and the potential for disposal of solidified high-level radioactive waste at Yucca Mountain, Nev., is being studied. These activities will greatly affect the ground-water resources in much of the study area within the next several decades.

The Great Basin regional aquifer-system study was started in 1980 and completed in 1986. The objectives of this study were to describe the aquifer systems in the Great Basin and, to the extent possible, to develop techniques that can be used for quantitative evaluation of the aquifer systems. This regional aquifer-system study provided a basis for evaluating the local and regional effects of future development. The approach was strongly influenced by the diverse nature of the ground-water flow systems and the large number of basins. A detailed appraisal of 242 individual areas was not feasible. Consequently, the approach taken was to study selected typical areas, identify key hydrologic processes, and then attempt to tranfer the knowledge developed to areas of similar hydrology. The study resulted in 21 reports which are listed in the following bibliography.

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Northeast Glacial

The Northeast Glacial regional aquifer-system study includes most of the glaciated parts of the northeastern United States and extends as far west as Ohio (fig. 1). Long Island, New York, and Cape Cod, Massachusetts, are excluded from the study because the ground-water hydrology of these areas has been extensively studied. The study area includes (1) mountainous areas of New Hampshire, Maine, Vermont, and New York; and (2) low-lying areas along the Great Lakes, major rivers, and the Atlantic Coast.

The study area has been subdivided into three major geohydrologic terrains to group and describe aquifer systems that have similar characteristics. These subdivisions are based largely on the geology of glacial deposits and physiography. Much of the study area and most of the productive glacial aquifers are in type A terrains, where aquifers were formed largely in valleys that generally drained away from glacial ice. Glacial aquifers in type B terrains were formed by large glacial lakes or marine waters. In type C terrains, glacial aquifers were formed in valleys that drained toward glacial ice.

The Northeast Glacial regional aquifer-system study was started in 1981. The purpose of the study is to investigate the sand and gravel aquifers that were formed during advances and retreats of the continental glaciers in the northeastern United States. Glacial sand and gravel aquifers, though consisting of many geographically separated independent systems, share many geologic, hydrologic, and geochemical characteristics because of their common depositional origins and physiographic settings. This study will document the variations in magnitude and areal distribution of key components of the aquifers through evaluation of the response of the aquifers to pumping and to climatic stresses. As of December 1986, ten reports, which are listed in the following bibliography, were completed.

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Upper Colorado River Basin

The Upper Colorado River Basin has a drainage area of about 113,500 square miles in western Colorado, eastern Utah, southwestern Wyoming, northeastern Arizona, and northwestern New Mexico. The area contains a variety of landforms including rugged mountains, broad plains, deeply dissected canyons, relatively flat flood plains, and many erosional features. The area has been subjected to repeated tectonism. The predominant tectonic features are numerous basins and uplifts. The resulting structural relief is nearly 30,000 feet above the basin floors in places.

Consolidated sedimentary formations of Paleozoic, Mesozoic, and Cenozoic age attain a maximum thickness of tens of thousands of feet. These formations include aquifers within beds of fractured limestone, dolomite, sandstone, and shale. Low-permeability limestone, dolomite, shale, and evaporite deposits act as confining units. Igneous rocks, especially volcanic rocks, are also present, but they are not regional aquifers.

Annual precipitation ranges from about 6 inches on the plains of Utah to about 40 inches in mountainous areas. Precipitation, in the form of snowmelt and rainfall, is the only source of recharge to the aquifers. Several aquifers that are deeply buried in basins are exposed on the margins of uplifts, where precipitation partly recharges the aquifers. Aquifers within stratigraphically younger formations tend to be exposed and recharged over extensive areas.

Ground-water flow systems in the Upper Colorado River Basin have been classified into three major groups. In descending order, they are:

(1) Cenozoic-rock aquifers, (2) Mesozoic-rock aquifers, and (3) Paleozoic-rock aquifers. Within each flow system, rocks are grouped into aquifers and confining units on the basis of lithology, depositional environment, and hydrologic characteristics. A total of 25 hydrostratigraphic units has been identified for the Upper Colorado River Basin regional aquifer system.

The Colorado River Compact of 1922 divided the Colorado River Basin into an upper and a lower basin in order to allocate water supplies. Water shortage is common in the Colorado River Basin, and increasing water demand is expected. The Upper Colorado River Basin regional aquifer-system study was started in 1981. The purpose of the study is to obtain regional information on hydrology, geology, and water chemistry so that the water resources of the Upper Colorado River Basin aquifer system can be assessed and the potential for development evaluated. The upper part of the San Juan River Basin, which is being investigated in a separate study, was excluded from this study. The remaining study area includes about 100,000 square miles (fig. 1). As of December 1986, ten reports, which are listed in the following bibliography, were completed.

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Oahu Island, Hawaii

The Island of Oahu (fig. 1) has a land area of 604 square miles and was formed through the building and subsequent coalescence of two shield volcanoes, the Waianae and Koolau Volcanoes. The Waianae Volcano forms the western part of Oahu, and the Koolau Volcano forms the eastern part. A long period of quiescence followed the initial mountain building. During the quiescence, both volcanoes were deeply eroded. The Waianae Volcano became dormant first, and the westward dipping flows of the Koolau Volcano overlapped the eroded surface of the Waianae Volcano in the central part of the island. Subsidence of Oahu submerged permeable lava flows and placed them in hydraulic contact with the surrounding ocean water. Shifts in sea level and erosion allowed deposits of marine and terrestrial sediments to accumulate behind barrier reefs, forming coastal plains in some areas.

Due to the complexity of the volcanic rocks, the Oahu regional aquifer system has been divided into several aquifers. Most of the basaltic lava flows of the Koolau Volcano are thin-bedded and highly permeable. The surficial lavas of the Waianae Range are somewhat less permeable than those of the Koolau Volcano.

Several recent studies have concluded that the ground-water resource of the Island of Oahu will be near maximum development by the year 2000. Estimates of the long-term potential of ground-water development of the Oahu regional aquifer system range between 480 and 635 million gallons per day. In 1980, the ground-water withdrawal rate was about 400 million gallons per day, which is 85 percent of the island's total water use. Development of this magnitude unquestionably imposes substantial stresses on the aquifer system.

The Oahu Island regional aquifer-system study was started in 1982 to evaluate the impact of the potential development of the aquifer system. Computer models are being used to simulate ground-water flow. The models will be used to evaluate the effects of ground-water development on water levels in the aquifer system as well as on the movement of the freshwater-saltwater interface. As of December 1986, six reports, which are listed in the following bibliography, were completed.

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Caribbean Islands

The Caribbean Islands regional aquifer system (fig. 1) includes Puerto Rico, its adjacent islands (Vieques, Culebra, and Mona), and the U.S. Virgin Islands (St. Croix, St. Thomas, and St. John). The most important ground-water areas in Puerto Rico are the limestone aquifers of the north coast and the alluvial aquifers of the south coast. In the U.S. Virgin Islands, the Kingshill aquifer of St. Croix is the only significant aquifer. The geohydrologic investigations of the Caribbean Islands regional aquifer-system study will concentrate in these three areas.

The Island of Puerto Rico has an area of about 3,300 square miles. It consists of a series of east-to-west mountain ranges, with a maximum altitude of about 4,400 feet, flanked on the north and south by foothills. Extensive coastal plains, as much as 8 miles wide, occur along the north and south coasts. Rainfall ranges from 200 inches in the rain forests of the northeast to 35 inches in the lowlands of the southwest. The annual average rainfall on the island is about 75 inches.

The geology of Puerto Rico is complex and varied. The central core of the island consists largely of volcanic and intrusive rocks of Late Cretaceous and early Tertiary age. Clastic sediments and limestones of Oligocene and Miocene age were deposited to the north and south of the central mountain core. The older clastic sediments are poorly sorted mixtures of gravel, sand, and fine-grained materials. These sediments grade upward into thick beds of relatively pure limestone. Ground water moving through joints and fractures in the limestone has formed solution cavities. In outcrop areas along the north coast, a mature karst topography has developed.

The Island of St. Croix, with an area of 82 square miles, is underlain by volcanic and sedimentary rocks of Late Cretaceous and early Tertiary age. The east and west parts of the island are separated by a graben filled with volcanic ash overlain by marl and limestone known as the Kingshill Marl. The Kingshill aquifer in St. Croix is the most important ground-water system in the U.S. Virgin Islands. It covers about 30 square miles in central St. Croix. Locally, it varies from marl to sandstone of Miocene to Oligocene age lying unconformably on bedrock. Alluvial deposits blanket the area to a thickness less than 20 feet except in stream courses where the thickness may be 200 feet.

The Caribbean Islands regional aquifer-system study will evaluate geohydrologic data and develop computer models to understand the ground-water flow systems, the potential for seawater encroachment near the coast, and the effects of changes in ground-water irrigation. The study began in 1984. As of December 1986, three reports were completed. The reports are listed in the following bibliography.

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Columbia Plateau Basalt

The Columbia Plateau is located in central and eastern Washington, northern Oregon, and a small part of northwestern Idaho (fig. 1). The plateau covers about 63,200 square miles entirely within the drainage of the Columbia River. The Columbia Plateau regional aquifer system consists of unconsolidated sediments, basaltic rocks, and intercalated sediments. Where saturated, unconsolidated sediments that overlie the basalts form a water-table aquifer called the overburden aquifer. This aquifer is the uppermost unit in the regional aquifer system. Rocks of the Miocene Columbia River Basalt Group make up most of the regional aquifer underlying the Columbia Plateau. The many layers of lava beds and sedimentary interbeds form a multilayered aquifer system which, for study purposes, has been divided into three units. The units correspond to three basalt formations in the Columbia River Basalt Group--the Saddle Mountains, Wanapum, and Grande Ronde Basalts--and include intercalated sediments. The three basalt units are connected hydraulically either directly or through confining sedimentary interbeds. The sedimentary interbeds between the units generally are fine grained and laterally extensive; the thickness of the interbeds is small compared to the thickness of the basalt units.

These four major geohyrologic units form the aquifer system that provides water for most municipal, industrial, and domestic needs and for most of the irrigated lands outside the Columbia Basin Irrigation Project and the Yakima River basin. Agriculture is the predominant economic activity in the study area. Because of the importance of ground water to the economy of this area, a better understanding of the aquifer system is needed.

The Columbia Plateau Basalt regional aquifer-system study began in 1982. The study was designed to address some of the hydrologic problems currently being encountered on the plateau. These problems include declining water levels of as much as 20 feet per year, the occurrence of sodium-enriched water, the need for additional ground water for expanding irrigated land, and the potential use of low-permeability zones in the deep basalts as a National repository site for solidified high-level nuclear wastes near Richland, Wash. As of December 1986, eight reports were completed. The reports are listed in the following bibliography.

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Edwards-Trinity, Texas, Oklahoma, and Arkansas

The Edwards-Trinity regional aquifer system underlies central Texas and small adjacent parts of southeastern Oklahoma and southwestern Arkansas (fig. 1). The system consists of three major aquifers and at least three minor aquifers in predominantly Cretaceous rocks, which together have an areal extent of about 80,000 square miles. The major aquifers, as identified by the Texas Department of Water Resources, are the Edwards-Trinity (Plateau) in west-central Texas, the Edwards (Balcones fault zone) in south-central Texas, and the Trinity in north-central Texas, southeastern Oklahoma, and southwestern Arkansas.

The Edwards-Trinity aquifer underlies about 35,000 square miles of the Trans-Pecos and Edwards Plateau physiographic regions of Texas. The aquifer generally is composed of limestone in its upper part and sandstone in its lower part. The aquifer dips to the southeast, and its thickness varies from a few tens of feet to more than 1,000 feet. Water in the aquifer exists under both unconfined and confined conditions. Regional flow is to the south and southeast. Numerous springs and seeps discharge from the limestone to streams in the southeastern part of the aquifer.

The Edwards aquifer underlies an area of about 3,500 square miles, generally coincident with the Balcones fault zone. The aquifer consists of limestone and dolomite ranging in thickness from about 350 to 600 feet. Unconfined conditions occur where the Edwards aquifer is close to the land surface or crops out along its northern and western extent. Confined conditions occur in downdip parts of the aquifer to the south and east of the outcrop. Regional flow is controlled by a complex pattern of faults. An appreciable part of the regional flow is generally northeast along the strike of the rocks parallel to the faults toward three relatively large springs.

The Trinity aquifer underlies about 36,000 square miles of central Texas, southeastern Oklahoma, and southwestern Arkansas. The aquifer consists of interbedded sand, shale, and limestone, which crop out to the west and north. The aquifer dips and thickens to the east and southeast and has a maximum thickness of more than 2,000 feet at its downdip limit of freshwater. Water in the aquifer is under unconfined conditions in the outcrop and confined conditions downdip. Ground-water flow is more vigorous in the outcrop than in downdip parts of the aquifer.

The Edwards-Trinity regional aquifer system supplies more than 0.78 million acre-feet of water per year (700 million gallons per day). The Edwards aquifer is by far the most productive aquifer in the study area. Municipal and industrial pumpage from the Edwards aquifer in the San Antonio area accounts for at least 30 percent of the total pumpage from the regional aquifer system. The Trinity aquifer in the Dallas-Fort Worth area, although much less productive than the Edwards aquifer in the San Antonio area, is extensively developed for municipal and industrial use. In the San Antonio area, increased withdrawals from the Edwards aquifer have the potential to cause decreases in (or elimination of) some spring discharges and encroachment of saline water from downdip. In the Dallas-Fort Worth area, pumping has lowered heads in the Trinity aquifer several hundred feet. Large head declines caused by pumping also have occurred in some other metropolitan areas supplied by the Trinity aquifer.

The Edwards-Trinity regional aquifer-system study, which began in 1985, will define the hydrogeologic framework, describe the geochemistry and ground-water flow in the aquifer system, and provide a better understanding of the system's long-term water-yielding potential. A multidisciplinary approach is being used in which computer simulation of ground-water flow is the principal method of hydrogeologic investigation. As of December 1986, one report was completed. The report is listed in the following bibliography.

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Southern California Alluvial Basins

Southern California alluvial basins include an area of 75,000 square miles. The area includes 88 alluvial basins that can be grouped according to common characteristics and relationships into coastal and desert basins. In general, there are three distinct aquifers in the coastal basins: (1) A shallow perched aquifer that is virtually unconfined in the upper part of alluvial deposits of Holocene age; (2) a principal freshwater aquifer that is generally confined comprising the lower part of the Holocene alluvium and nearly all sediments of Pleistocene to middle Pliocene age; and (3) a deep saline-water aquifer that occurs in the consolidated rocks of Tertiary age and that underlies the principal freshwater aquifer. The desert basins also contain at least three distinct aquifers: (1) Unconsolidated alluvial deposits of Pliocene to Holocene age that comprise the principal aquifer, (2) loosely consolidated sedimentary deposits of Tertiary age, and (3) consolidated rocks of pre-Tertiary age.

The Southern California Alluvial Basins regional aquifer-system study began in 1984 (fig. 1). Mathematical models will be used to identify the hydrologic parameters that have the greatest control over: (1) Saltwater intrusion in coastal basins, (2) flow between aquifer layers, and (3) the quantity and distribution of recharge in coastal and desert basins. The models also will be used to determine the acceptable range in values of these parameters.

The activity of the Southern California Alluvial Basin regional aquifer-system study was temporarily suspended in 1985. All resources related to this study were transferred to the Central Valley, California, phase II study. As of December 1986, two reports, which are listed in the following bibliography, were completed.

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Michigan Basin

The Michigan Basin regional aquifer-system study includes about 29,000 square miles of the Lower Peninsula of Michigan (fig. 1). The study is limited to Mississippian and younger consolidated and unconsolidated sediments in the Michigan Basin, a large structural bedrock depression. This includes the Marshall Sandstone (Mississippian), Saginaw Formation (Pennsylvanian), and Pleistocene and Holocene deposits. These sandstone and unconsolidated sediments are the major aquifers in the Michigan Basin. The outermost boundary for this study has been defined as the contact between the Mississippian Coldwater Shale and the overlying Marshall Sandstone. The Saginaw Formation is stratigraphically above the Marshall Sandstone. The thickness of glacial deposits, which overlie nearly all of the study area, range from a few inches to about 1,000 feet.

Ground water has increasingly become an important source of water in Michigan. In 1978, use of ground water for public supply in the State totaled 215 Mgal/d (million gallons per day) for the study area. Of this total, about 82 Mgal/d was from the Saginaw Formation and Marshall Sandstone, and about 106 Mgal/d was pumped from the glacial deposits.

The Saginaw Formation and Marshall Sandstone contain sandstone aquifers that are the major source of ground water for about 70 communities with a composite population of about 500,000. The most significant problems related to ground-water supplies are the identification of potable sources of ground water in large quantities and the migration of saline ground water toward pumping centers. Saline water underlies the entire Lower Peninsula of Michigan in the deeper parts of the Saginaw Formation and Marshall Sandstone in the center of the Michigan Basin. In places, saline water is present in glacial deposits. In the Lansing-East Lansing area, where the Saginaw Formation is the principal ground-water source, a cone of depression extending over 100 square miles has developed; water levels near the center of the cone are as much as 160 feet below the prepumping level. In the Flint area, where both the Saginaw Formation and Marshall Sandstone were used for public supplies, heavy pumping caused migration of saline water to the pumping center; this was a major cause for the abandonment of the wells.

Increased demand for ground water in Michigan is anticipated because of population growth, irrigation, and industrial development. To manage and protect the fresh ground-water resources of Michigan, an understanding of the occurrence of saline water and the relation between saline and freshwater, as well as between saline water and past and present ground-water-flow patterns, is necessary.

The Michigan Basin regional aquifer-system study began in 1985. The purpose of the study is to define the geohydrologic system in the sedimentary rocks and glacial deposits in the study area. The study will describe the stratigraphy and geochemistry of the Mississippian and younger sedimentary rocks, delineate the freshwater-saline-water interface, and quantitatively describe the past and present ground-water-flow systems. As of December 1986, three reports, which are listed in the following bibliography, were completed.

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San Juan Basin

The San Juan structural basin, in New Mexico, Colorado, Arizona, and Utah, has an area of about 21,600 square miles (fig 1). The regional aquifer system includes rocks of Triassic or younger age which underlie about 19,400 square miles of the structural basin. Annual precipitation in the mountainous areas along the northern and eastern margins of the basin ranges from 20 to 30 inches, whereas the lower-altitude central part of the basin receives 10 or fewer inches per year. Altitudes in the study area range from about 11,000 feet in the southeast to about 4,500 feet in the northwest.

The San Juan basin is a northwest-trending asymmetric structural depression of Laramide (Late Cretaceous--early Tertiary) age at the eastern edge of the Colorado Plateau. The basin is about 140 miles wide and about 200 miles long. The San Juan structural basin contains a thick sequence (more than 14,000 feet) of sedimentary rocks ranging in age from Cambrian through Tertiary. These sedimentary rocks dip from the basin margins toward the trough-like structural center of the basin. The older sedimentary rocks crop out around the basin margins and are successively overlain by younger rocks toward the structural center of the basin. Tertiary volcanic rocks and various Quaternary deposits also are present in the basin.

The aquifers to be studied represent deposits from the Triassic through Tertiary time. The aquifer system has been grouped into eight aquifers ranging from single geologic formations to the entire Tertiary section. The most significant aquifers are the Morrison Formation, Gallup Sandstone, and Dakota Sandstone. The aquifers and confining units are not necessarily restricted to one geologic unit but may include all or parts of several geologic units.

The economy of the region is supported by exploration and development of petroleum, coal, and uranium resources; urban enterprise; farming and ranching; tourism; and recreation. The population of the basin in 1980 was about 190,000. Ground water is an important resource in much of the San Juan basin because surface water is not available or fully appropriated. Historically, the main uses of ground water were for municipal, domestic, and stock purposes; however, industrial use increased significantly since the late 1970's because of increased uranium mining in the Morrison Formation. Ground-water levels have declined in several areas where dewatering of the Morrison Formation was necessary for mining operations. Competition has been great among electric-power companies, municipalities, Indian communities, and mining companies for rights to use the limited ground-water supplies in the basin.

The San Juan Basin regional aquifer-system study was started in 1984 to: (1) Define and evaluate the aquifer system in the San Juan basin, (2) assess the effects of past, present, and potential ground-water use on aquifers and streams, and (3) determine the availability and quality of ground water in the basin. One report, which is listed in the following bibliography, has been completed as of December 1986.

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One of the goals of the National Research Program of the U.S. Geological Survey is to develop a sufficient understanding of hydrologic and geologic systems to permit quantitative evaluation of the response of those systems to either natural or man-made stresses. For example, hydrologic research in the National Research Program develops methodologies that are used to solve or mitigate critical water problems and improves the understanding of the movement of water, sediment, and chemical constituents through hydrologic and geologic systems.

The approach in the National Research Program is both basic and problem oriented. Basic research explores the scientific principles controlling the quantity and quality of the Nation's water resources. Problem-oriented research supports other programs of the U.S. Geological Survey by developing operational and interpretative tools for water-resources investigations.

The RASA Program has benefited from both the basic and operational research conducted in the National Research Program. The RASA Program has been assisted by the National Research Program staff directly through consultation, training, and workshops. However, the most important contributions of the National Research Program to the RASA Program have been the development of analytical and data-collection methods in ground-water hydrology during the years and decades preceding the RASA Program. Research is, by nature, a long-term process, and the U.S. Geological Survey programs that have funded the National Research Program in the past are in large part responsible for the development and success of the RASA Program.

The RASA program has contributed funding to the National Research Program to support continued research in hydrology and geology. In this way, the RASA Program is contributing to the funding of the research needs of future operational programs. The National Research Program conducts research in all phases of the hydrologic cycle. However, the following bibliography of the National Research Program includes 168 reports related to ground water that were partially funded by the RASA Program from 1978 through 1986.

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