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Regional Aquifer-System Analysis Program of the U.S. Geological Survey, 1978–1992

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By Ren Jen Sun *and* Richard H. Johnston

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FIGURES

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer
acre	4,047.	square meter
	Volume	
acre-foot (acre-ft)	1,233.	cubic meter
	Flow	
gallon per minute (gal/min)	0.063098	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
billion gallons per day (Bgal/d)	43.81	cubic meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch per year (in/yr)	25.4	millimeters per year
foot squared per day (ft^2/d)	0.0929	meter squared per day

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

Regional Aquifer-System Analysis Program of the U.S. Geological Survey, 1978–1992

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ABSTRACT

The major ground-water systems of the United States have been investigated by the U.S. Geological Survey (USGS) through its Regional Aquifer-System Analysis (RASA) Program. During the first 15 years of the program (1978–92), 25 regional aquifer systems, including the most heavily pumped aquifers in the Nation, were intensively studied. As of mid-1992, 18 of the regional aquifer studies are completed or nearly so; 7 of the regional aquifer studies are ongoing, and compilation of a national ground-water atlas is in progress.

This report summarizes the status of each RASA study and briefly describes the hydrology of the 25 regional aquifer systems. Important study results and examples of applications of study results are presented for some of the completed RASA investigations.

The major contributions of the RASA Program are (1) assembly of data from numerous local studies and long-time data collections into systematic regional data bases; (2) comprehensive descriptions of the geologic, hydrologic, and geochemical characteristics of the regional aquifer systems; and (3) an understanding of how the regional ground-water-flow systems function under natural (predevelopment) and current (developed) conditions. To provide the comprehensive system descriptions, many of the RASA studies present, for the first time, maps depicting the hydrogeologic frameworks, water chemistry, potentiometric surfaces, and other aspects of entire regional aquifer systems. To provide an understanding of how the flow systems function, several of the completed RASA studies provide, for the first time, hydrologic budgets for both predevelopment and developed conditions.

The results of the RASA Program are contained in nearly 900 reports published by the USGS, as well as various State and local agencies, and in articles published in scientific journals. A series of U.S. Geological Survey Professional Papers are being published to summarize and synthesize the results of each RASA study.

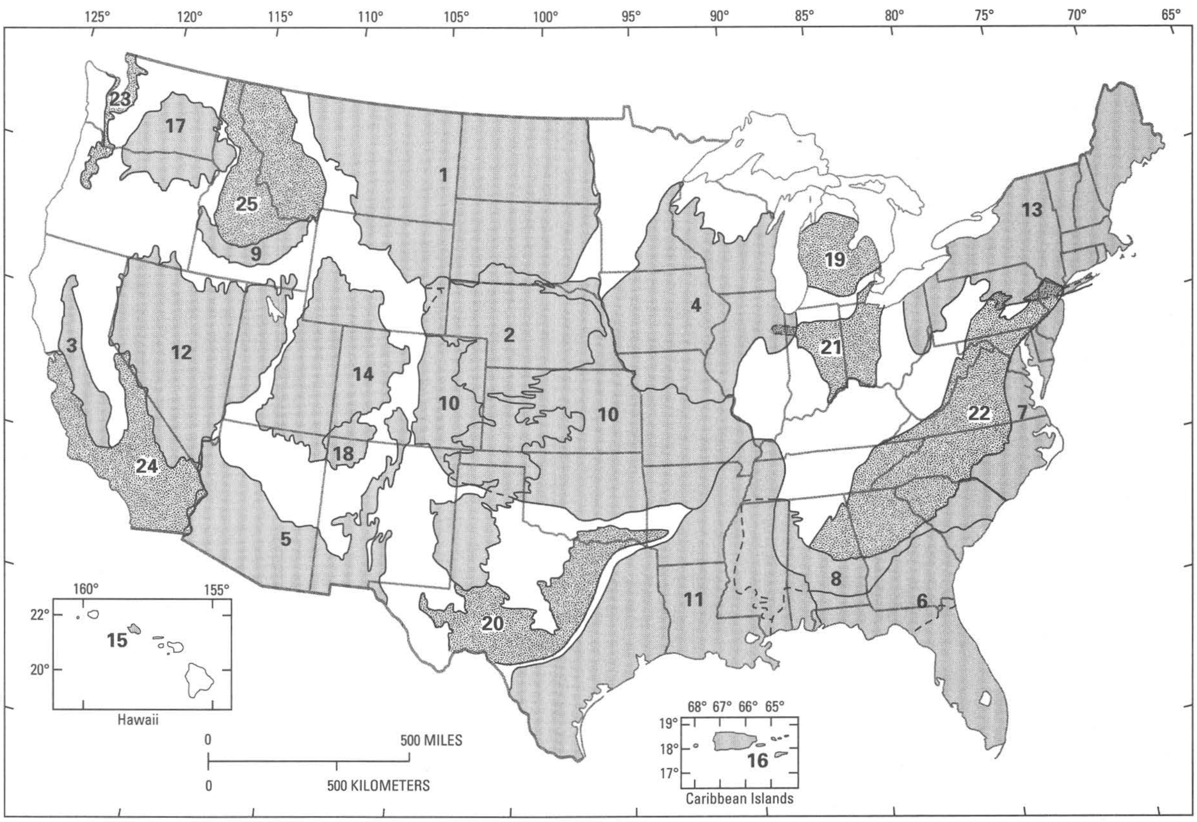
INTRODUCTION

Ground water is one of the Nation's most important natural resources. According to water-use information compiled by the U.S. Geological Survey (USGS), ground water supplied about 74 billion gallons per day in 1985, which was about 20 percent of the Nation's total freshwater withdrawals. Ground water is the source of about 40 percent of the Nation's public water supply and 30 to 40 percent of water used for irrigation. Ground water provides drinking water for more than 97 percent of the rural population who do not have access to public water-supply systems (Solley and others, 1983, 1988).

Many problems of ground-water quantity and quality that are related to development of the ground-water resources have been documented. To resolve such development-associated problems, information on characteristics of aquifers and the functioning of ground-water systems is needed. In the past, most ground-water studies were conducted within county or State boundaries. In evaluating the effects of development and assessing the potential water quality and quantity available for development, a question frequently asked is, what will happen beyond the extent of the study area? Often, ground-water hydrologists begin a local ground-water study only to find limited information on regional geology, hydrology, or water chemistry. These facts underscore the need for a broad regional study of the Nation's major aquifers.

In response to recommendations made by the U.S. National Water Commission and U.S. Comptroller General and the effects and persistence of the 1977 drought (Sun, 1986), the Committee on Appropriations of the U.S. House of Representatives of the 95th Congress, in a report of the appropriations for the Department of the Interior and related agencies for fiscal year 1978, stated that "The Committee is providing funds to initiate a program to identify the water resources of the major aquifer systems within the United States. This program will establish the aquifer boundaries, the quantity and the quality of the water within the aquifer, and the recharge characteristics of the aquifer. Although this initiative comes too late to help the present drought (1977), the action taken will develop an inventory of the major ground-water systems of the United States so that in the event of another drought we may be able to draw upon the ground-water reservoir system without doing irreparable damage to the system. The Committee expects the Survey to press this program vigorously." (U.S. House of Representatives, 1977, p. 36–37).

As a result of these specifications in the appropriations bill, and in response to needed information for better managing, planning, and developing of the Nation's ground-water resources, the USGS started the Regional Aquifer-System Analysis (RASA) Program in 1978; 28 major regional aquifer systems were identified for study under the RASA Program (fig. 1). As of mid-1992, 25 of 28 studies either have been completed or are in progress, as shown in figure 1. Three aquifer systems (the alluvial basins in California, Nevada and Oregon; the Illinois Basin; and the Pecos River Basin in Texas and New Mexico) have yet to be studied. Investigation activities of 18 aquifer systems have been completed, and 7 aquifer systems are currently under study.



EXPLANATION

Completed studies

Northern Great Plains (1)
High Plains (2)
Central Valley, California (3)
Northern Midwest (4)
Southwest alluvial basins (5)
Floridan (6)
Northern Atlantic Coastal Plain (7)
Southeastern Coastal Plain (8)
Snake River Plain (9)
Central Midwest (10)
Gulf Coastal Plain (11)
Great Basin (12)
Northeast glacial aquifers (13)
Upper Colorado River basin (14)
Oahu, Hawaii (15)
Caribbean Islands (16)
Columbia Plateau (17)
San Juan Basin (18)

Active studies

Michigan Basin (19)
Edwards–Trinity (20)
Midwestern basins and arches (21)
Appalachian valleys and Piedmont (22)
Puget–Willamette Lowland (23)
Southern California alluvial basins (24)
Northern Rocky Mountain intermontane basins (25)

Figure 1. Locations of regional aquifer-system studies.

In addition to the major regional aquifer studies, three ancillary activities were undertaken to provide support for the regional studies and to make the information developed during the studies available to potential users with a broad range of interests. These activities are the Ground Water Atlas of the United States, studies to solve specific hydrologic problems, and basic hydrologic research.

In 1988 the RASA Program used part of its resources to begin compilation of a Ground Water Atlas of the United States. The atlas presents a comprehensive summary of the Nation's ground-water conditions and serves as a basic reference for the location, geography, geology, and hydrology of the Nation's major aquifers. Information presented in the atlas primarily comes from the RASA studies. However, information and data resulting from many decades of ground-water studies by cooperative projects between States and the USGS, as well as local and other Federal agencies, also are included in the atlas. The atlas has a graphical format and is composed of 14 chapters. One of the chapters presents an overview of the Nation's ground-water conditions and development effects, and contains maps showing the locations of the Nation's major aquifers. The remaining 13 chapters (segments) collectively cover the 50 States and Puerto Rico and describe geologic and hydrologic conditions of and development effects on major aquifers in each segment area. Locations of the 13 segments are shown in figure 2. The atlas is published as the USGS Hydrologic Investigations Atlas HA-730 series, with a letter A–N assigned to each chapter, as shown in figure 2. The atlas project is scheduled for completion by 1994.

During the RASA studies, problems with no readily available solutions were encountered. For example, determination of the flow from individual aquifers tapped by wells open to several aquifers, analyzing flow in aquifers containing water with variable density, and estimating the permeability of rocks. The RASA staff spent considerable time and effort to develop new techniques and methods for resolving such problems. For example, a multiaquifer well simulation technique was developed by Bennett and others (1982), an improved method of simulating movement of ground water with variable density was developed by several hydrologists (Weiss, 1982; Kuiper, 1983, 1985; Kontis and Mandle, 1988), mass-transfer and reaction models were formulated by Plummer and others (1990), basin geochemical models were constructed by Robertson (1991), and methods of estimating rock permeability and porosity from geophysical logs were developed by Jorgensen (1988).

The RASA Program has benefited from findings of the long-term research efforts of the National Research Program (NRP) of the Water Resources Division of the USGS. Examples of products from NRP that were available at the beginning of the RASA Program are computer-based models for simulating ground-water flow in three dimensions (Trescott, 1975; Trescott and Larson, 1976), geochemical models and concepts that have regional applications (Back, 1966; Plummer, 1977), and results from investigations of anomalous fluid pressures in sediments of the Gulf Coastal Plain (Bredehoeft and Hanshaw, 1968; Wallace and others, 1979). Results from the NRP since the beginning of the RASA Program that were particularly helpful include development of methods to address data uncertainty in ground-water-flow modeling (Cooley and others, 1986) and development of a computer model for simulating ground-water flow with heat or solute transport (Voss, 1984). To support the research projects of the NRP, the RASA Program contributes about 15 to 20 percent of its annual allocations. This contribution is a long-term investment that benefits the RASA Program as well as future programs.

The RASA Program has produced a vast amount of important information on the Nation's major aquifer systems. As of mid-1992, nearly 900 reports were published. Additional reports are currently in preparation or in review. These reports range from articles in specialized scientific journals and contributions to national and international meetings and symposia, to map, data, and interpretive reports published by the U.S. Geological Survey and cooperating State and local agencies.

This circular (1) states the objectives and approaches of the RASA Program, (2) describes the aquifer systems investigated by the RASA Program, and (3) summarizes significant findings and describes the status of the program as of mid-1992.

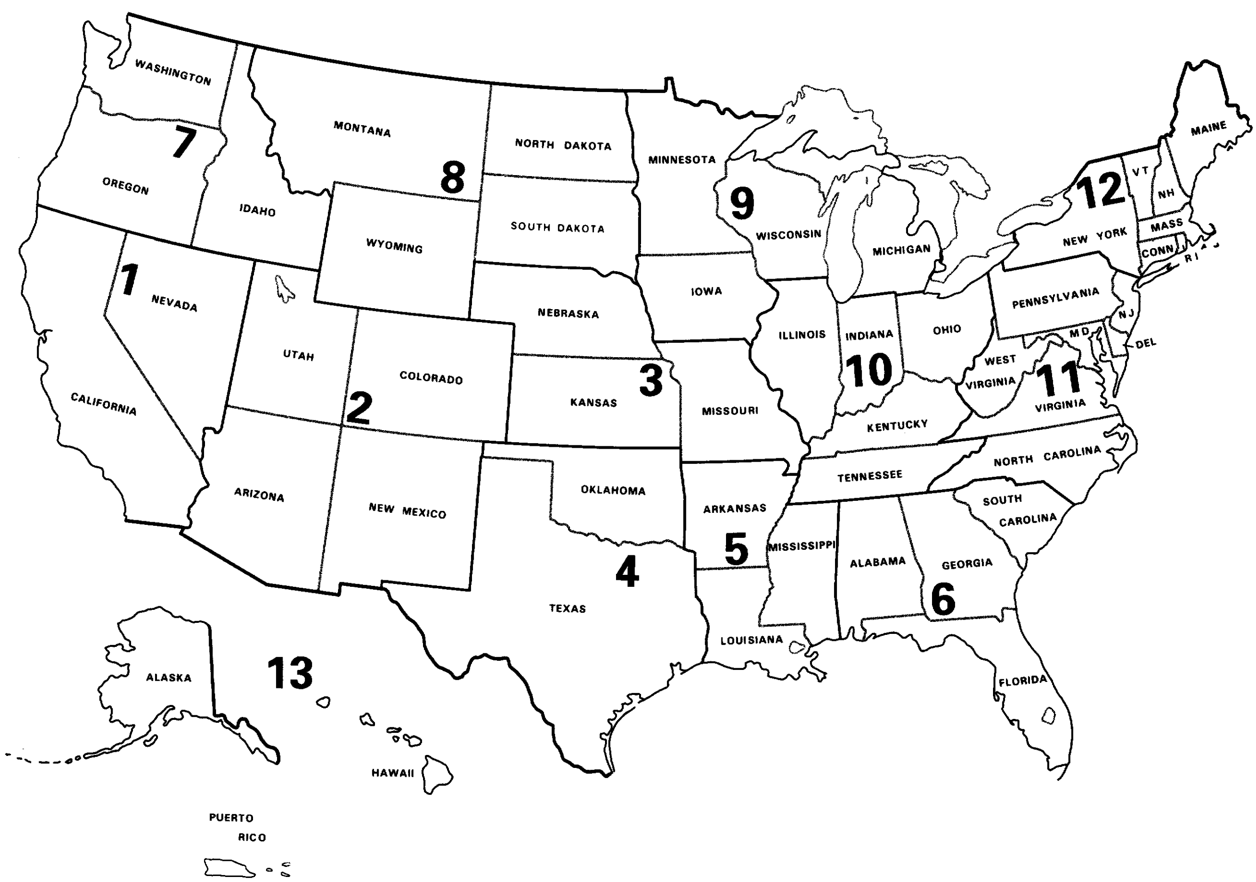
REGIONAL AQUIFER SYSTEMS

The concept of regional ground-water flow was formulated in the 1800's when artesian ground-water flow was discovered in the central and western parts of the United States.

T.C. Chamberlin (1885) outlined seven prerequisites for artesian ground-water flow and described the hydrogeologic properties of water-yielding beds and confining units. The seven prerequisites described by Chamberlin are (1) a pervious stratum to permit the entrance and the escape of the water; (2) a water-tight bed below to prevent passage of the water downward; (3) a like impervious bed above to prevent escape upward, for the water, being under pressure from the fountain-head, would otherwise find relief in that direction; (4) an inclination of these beds, so that the edge at which the waters enter will be higher than the surface at the well; (5) a suitable exposure of the edge of the porous stratum, so that it may take in a sufficient supply of water; (6) an adequate rain-fall to furnish this supply; and (7) an absence of any escape for the water at a lower level than the surface at the well. Importantly, Chamberlin recognized that there are no totally impermeable confining beds: "*** no rock is absolutely impenetrable to water" (Chamberlin, 1885, p. 137).

One of the earliest descriptions of a regional aquifer system is given by N.H. Darton (1896) of "The great artesian basin of the eastern portion of South Dakota and North Dakota." Darton (1896, p. 612–613) described the "water horizons" as follows:

> The principal water-bearing bed in the Dakotas appears to be the eastward extension of the Dakota sandstones, but water is also found in smaller amounts in the Niobrara Chalk beds above, in the basal beds of the drift formations, and in local beds of sand in the great series of clays lying above the Dakota formation. The Dakota formation consists of sand and sandstones which are particularly favorable in their character for the storage and transmission of water. The formation is not entirely sand and sandstone, but contains beds of clay irregularly dispersed, and often streaks of iron pyrites and iron stone. The texture of its sands and sandstones being variable, the capacity for holding water is



EXPLANATION

Segment	Content	Atlas chapter
–	Introductory material	730—A
1	California, Nevada	730—B
2	Arizona, Colorado, New Mexico, Utah	730—C
3	Kansas, Missouri, Nebraska	730—D
4	Oklahoma, Texas	730—E
5	Arkansas, Louisiana, Mississippi	730—F
6	Alabama, Florida, Georgia, South Carolina	730—G
7	Idaho, Oregon, Washington	730—H
8	Montana, North Dakota, South Dakota, Wyoming	730—I
9	Iowa, Michigan, Minnesota, Wisconsin	730—J
10	Illinois, Indiana, Kentucky, Ohio, Tennessee	730—K
11	Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia	730—L
12	Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont	730—M
13	Alaska, Hawaii, Puerto Rico	730—N

Figure 2. States contained in each segment of the Ground Water Atlas of the United States.

> by no means constant. In every well of which I have heard that has penetrated the Dakota formation, some water has been found in one bed, if not in others, and often several horizons of water-bearing sands have been penetrated. In many of the wells two or three, and in some as many as seven flows have been found, separated either by clays, beds of pyrites, or more compact sands or sand rock.

Later, Darton (1905) presented a potentiometric surface map of the Dakota Sandstone and associated sandstones based on well reports and altitudes of sandstone outcrops in several States. This map indicated a west-to-east potentiometric gradient and led Darton to conclude that recharge occurred on the west on the flanks of the Black Hills and Front Range of the Rockies and discharge occurred several hundred miles to the east along the Missouri River.

The pioneer concepts of Chamberlin and Darton about regional aquifers, confining units, and regional flow are still valid today. A mapped regional aquifer may contain many locally discontinuous, low-permeability confining beds. On the other hand, a mapped regional confining unit may contain locally discontinuous, permeable beds that yield significant amounts of water to wells. Aquifers and confining units are mapped on the basis of their hydraulic properties, specifically the degree of contrast in hydraulic conductivity (a parameter used for measuring the ease of transmitting water through rocks), rather than on geologic age of the rocks. Thus, a regional aquifer or a regional confining unit may contain many different geologic formations or time-stratigraphic units or parts of such units (for examples, see fig. 4 in Laney and Davidson, 1986). A regional aquifer system is defined as a body of rock containing two or more regional aquifers separated at least locally by confining units. Examples include aquifer systems underlying the Great Plains, Gulf Coastal Plain, and Atlantic Coastal Plain.

In many parts of the country, individual aquifers are present within a single basin or valley and regional aquifers do not exist. Although, each basin or valley aquifer is hydrologically independent, many of the basin and valley aquifers share common characteristics. Investigations of a few of these aquifers can establish common principles and hydrogeologic factors controlling the occurrence, movement, and quality of water. Examples of such aquifers are found in the alluvial basins of Arizona and New Mexico and in the glacial outwash valleys in the Northeastern United States.

Thus, aquifer systems studied in the RASA Program are of two general types: (1) an aquifer system comprised of an extensive set of aquifers and confining units that may be discontinuous locally, but which act hydrologically as a single system on a regional scale; and (2) a system consisting of a set of independent aquifers that share many common characteristics hydrologically. Twenty-eight such aquifer systems were selected for study under the RASA Program (fig. 1).

OBJECTIVES AND APPROACH

The objectives of the RASA Program are to define the regional aspects of geology, hydrology, and geochemistry of each studied aquifer system. The two basic approaches used to meet RASA Program objectives are the compilation of data and the construction of computer-based models to simulate ground-water flow. Study results are intended to be used for regional assessment of the ground-water resources and for support of local and detailed studies. Each study is designed to fit particular regional needs. However, every study uses computer-based simulation models to characterize the flow system and to evaluate the effects on the system by ground-water development and various types of land uses.

One of the important aspects of the RASA Program is the synthesis of a large volume of data (collected during specific studies or obtained from individual wells) into a new data set that broadly describes an aquifer system covering an area of tens of thousands of square miles on a regional scale. Many detailed aspects that are important for local studies therefore are eliminated during the data-synthesizing process. A regional study has a different scope and purpose than a local study. This can be illustrated by drawing an analogy between the ground-water information required for local- and regional-scale studies and the highways and streets shown on maps with different scales. Information needed for a regional study is analogous to a map showing interstate highways and major State roads. Information needed for a local ground-water study is analogous to a city street map. This concept of scaling should be kept in mind when using the RASA results.

Each RASA study relies primarily on existing data that are assembled, analyzed, examined, synthesized, and interpreted from available sources. These sources include publications, and office files as needed to form a complete new data set. This new data set is then analyzed and incorporated into simulation models. If critical data gaps are discovered, new data-collection activities such as exploratory drilling and synoptic water-level measurements are undertaken. New data collection is kept to a minimum to conserve the limited financial and human resources. Examples of new data collection have included drilling test wells during studies of regional aquifer systems in the Midwest and along the Atlantic Coastal areas (Davis and others, 1983; Trapp and others, 1984; Reid and others, 1986; Sun, 1986, fig. 37) and collection of water samples for isotope analyses to support the interpretation of anomalous geochemical data observed in a regional aquifer system in the northern Midwest (Siegel, 1989, 1991).

The RASA Program took advantage of available opportunities to broaden data bases. For example, during the study of the Floridan aquifer system in 1979, four "wildcat" oil-test wells were drilled on the Atlantic continental shelf offshore from southeast Georgia and northeast Florida. One of the test wells, about 55 mi east of Fernandina Beach, Florida, was estimated to be located near the seaward limit of freshwater discharge from the Floridan aquifer system. The USGS obtained permission from the well owner to conduct hydrologic testing before the well was abandoned and plugged. With this new information it was possible to estimate the offshore location of the freshwater-saltwater transition zone in the Floridan aquifer system (Johnston and others, 1982). At a fraction of the cost of several million dollars needed to drill an offshore test well, the RASA study gained valuable information on the Floridan aquifer system. Similar efforts are found throughout the RASA Program.

During the early 1980's, formalized computer-based geographic information systems (GIS) were not widely available. Therefore, it was necessary for personnel of early RASA studies to develop their own systems to handle the vast quantities of data. Some of the studies that began later used GIS to handle the data. Most of the early RASA data were stored on magnetic tapes (Kontis and Mandle, 1980's; Downey, 1982; Luckey and Ferrigno, 1982).

A major objective of the RASA Program was to provide a complete description of the hydrogeologic framework, hydraulic properties, regional flow system, and geochemistry of regional aquifer systems. To meet this objective, it was necessary to prepare a series of regional maps that generally did not exist prior to the RASA studies. Some of the most important are regional potentiometric surface maps of the principal aquifers. Such maps are essential for analyzing regional ground-water flow systems. The effect of development can be evaluated using maps of estimated predevelopment potentiometric surfaces together with a series of potentiometric maps constructed for various times since development began.

Other important regional maps show the altitude and configuration of tops of aquifers, the thicknesses of aquifers and confining units, and hydraulic properties such as transmissivity and specific yield. Most RASA Projects also prepare regional maps describing the ground-water chemistry; these maps show concentrations of major dissolved constituents, chemical water types, and other chemical parameters. These maps can be used to interpret the evolution of water chemistry from recharge areas to discharge areas. Examples of regional geohydrologic and geochemical maps prepared during the RASA Program are presented in the following sections.

The other major approach of the RASA Program is the use of computer-based models to simulate ground-water flow systems using estimated hydrogeologic and hydrologic characteristics as model inputs. The input values to the model are then adjusted until the model-simulated water levels or flows closely match the observed or estimated water levels or flows of the aquifer system. Simulations of both natural (predevelopment) conditions and present-day conditions are generally done. Results of these simulations are used to define changes in recharge and discharge conditions brought about by development. In addition, geochemical models are used in some RASA projects to examine changes in ground-water chemistry along flow paths from recharge areas to discharge areas.

The regional flow models are intended to provide an improved understanding of the major features of regional flow systems. However, owing to the large area covered by the regional models and the coarse mesh used in them, they generally do not provide detailed information on aquifer systems useful to water planners and managers at a local level. To provide the greater resolution needed for a more detailed analysis of the effects of ground-water development, RASA regional flow models may be further divided into subregional models. Boundary conditions for subregional models are supplied by the regional flow model. For example, the Northern Atlantic Coastal Plain RASA study included a regional flow model that represented an aquifer system underlying an area from the Fall Line on the west to the offshore boundary in the Atlantic Ocean on the east and from Long Island, New York, in the north to Cape Hatteras, North Carolina, in the south. The flow system was further simulated by subregional models for (1) New Jersey; (2) Delaware, Maryland, and District of Columbia; (3) Virginia; and (4) North Carolina.

AVAILABILITY OF STUDY RESULTS

Results of RASA studies are being released through scientific journals, proceedings of symposiums, and U.S. Geological Survey publications such as Open-File Reports, Water-Resources Investigations Reports, Hydrologic Investigations Atlases, Water-Supply Papers, Professional Papers, and Miscellaneous Maps. Upon completion of each RASA study, U.S. Geological Survey Professional Papers are being published to summarize the study results. A block of Professional Paper numbers between 1400 and 1428 is reserved for release of the RASA results. A Professional Paper number assigned to a particular RASA study is further divided into chapters that are designated by letters. Typically chapter A summarizes important aspects of the study, such as the hydrogeologic framework, hydrologic properties of aquifers, quality of water, and dynamics of the regional flow system. Succeeding chapters B, C, D, and so forth discuss a specific subject or area in more detail than given in chapter A. As of mid-1992, nearly 900 reports had been published under the RASA Program. A bibliography of the RASA publications as of May 1991 has been compiled by Sun and Weeks (1991).

Compilations of data used to prepare regional hydrogeologic maps and cross sections, water chemistry maps, and potentiometric surface maps were generally released as Open-File Reports—for example, Lane (1988) and Miller (1988).

ACKNOWLEDGMENTS

The summaries of ongoing RASA studies presented in this report are based on writeups prepared by the project chiefs: Edward Bugliosi, Peter Bush, David Clark, Norman Grannemann, Peter Martin, James Miller, Lindsay Swain, and John Vaccaro. Thanks are also due the many former RASA investigators for providing information used by the authors to prepare the summaries of completed RASA projects. Thanks also to Peter Bush for rewriting the authors' preliminary draft of the section entitled "Simulation of regional ground-water flow and the effect of scale."

SIMULATION OF REGIONAL GROUND-WATER FLOW AND THE EFFECT OF SCALE

Nearly all of the RASA studies discussed in this report used computer-based models—that is, computerized numerical methods to solve mathematical models of ground-water flow—to simulate ground-water flow. The primary goal of the modeling is to provide a quantitative understanding of regional flow in the aquifer systems. Most of the flow models are three-dimensional, finite-difference models with modules or groups of modules for simulating specific features of the hydrologic system; for example, pumping from wells screened in more than one aquifer, land subsidence, or stream-aquifer relations. The models require definition of conditions at aquifer-system boundaries, and input data that typically include transmissivity, storage coefficient, recharge and discharge, measured or estimated heads, and other properties pertaining to specific hydrologic features. Once developed, models are calibrated by adjusting the input data within physically realistic ranges in a series of simulations until computed heads and flows approximate measured values. Most RASA model calibrations were achieved by trial-and-error processes, although some used computer methods to estimate selected input properties (parameter estimation techniques). The final step associated with model development involves simulation of historical hydrologic conditions different from (and independent of) those used for calibration. This process, sometimes referred to as verification, commonly requires additional adjustment or refinement of the input data until satisfactory simulation of both calibration conditions and verification conditions are obtained. Some hydrologists have objected to the use of the terms verification or validation to describe this process because of the inference that the resulting model is capable of accurately predicting future responses to pumping or other stresses. Konikow and Bredehoeft (1992) state that these terms are misleading and suggest using more meaningful descriptors of the process such as model testing, history matching, and sensitivity testing. For this reason, the terms "verification" and "validation" are not used in this report.

The regional RASA models are not intended to be used for management or planning purposes at a local scale. The large areal extent of aquifers modeled and a lack of data in large areas preclude the use of these models to address local or site-specific water-resource issues. RASA model studies have drawn attention to the fact that modeling results are scale related and have provided insight on the subject, but they have not explained all of the complexities, some of which are discussed below.

The computerized numerical methods for simulating ground-water flow are based on discretization; that is, dividing the aquifer system into a series of blocks or elemental volumes within which all of the hydrogeologic properties are assumed to be equal. In the finite-difference approach, a single head value, whether measured or calculated, is associated with a block. Flow enters or leaves a block through its faces. However, because the actual distributions of hydrologic properties are continuous rather than discrete, numerical methods of simulation are approximate. Even if the distributions of aquifer-system properties were known exactly (which they can never be), characterizing each as a series of discrete values associated with finite volumes in the subsurface for modeling purposes would render the simulations approximate. Logic indicates that the larger the blocks of equal properties (that is, the larger the scale of discretization), the more "approximate" the simulation likely becomes, and the less accurately the simulated system represents the actual system.

Because the regional RASA models were developed to simulate aquifer systems of tens of thousands of square miles—for example, those underlying the Atlantic and Gulf Coastal Plains, the High Plains, the Great Plains, the California Central Valley, and the Snake River Plain—the discretization of the systems is relatively coarse. The features of these "coarse-mesh" models are summarized in table 1. The area of the blocks in the models ranges from 16 to 256 mi^2. In most terranes where a model includes near-surface hydrogeologic units, as the blocks of the model become larger, the fraction of the total ground-water flow that the model simulates becomes smaller. Water moves under the influence of a gradient in head; in the approximated flow system of the model, gradients in head exist only between blocks. Thus, water that enters and leaves the aquifer system within the area represented by the faces of a single block cannot be simulated (except by superimposing sources or sinks, a mechanism that cannot be practically used to account for all inflows and outflows). In areas of hills and valleys with numerous small streams, large variations in head may exist within volumes in the subsurface represented by model blocks (and single head values). Much of the recharge in such areas travels only short distances before discharging to the streams. These local variations in head and the consequent local flow are not simulated by regional models, as indicated in figure 3. In contrast, in areas of little topographic relief

Table 1. Coarse-mesh computer models used for simulation of flow in very large regional aquifer systems.

Regional aquifer system	Problem	Characteristics of model used	Computer program references	RASA report references
1. California Central Valley aquifer system	Simulation of flow in sand-silt-clay aquifer system involving very large ground-water withdrawals, land subsidence, and recharge by imported surface water	3-D finite-difference model; 4 active layers and 6-mile grid spacing	Trescott (1975), Trescott and Larson (1976), Meyer and Carr (1979), Torak (1982)	Williamson and others (1989)
2. Floridan aquifer system	Simulation of flow in carbonate aquifers characterized by large areal variations of transmissivity, flow activity, and pumpage	3-D finite-difference model; 2 active layers and 8-mile grid spacing	Trescott (1975), Trescott and Larson (1976)	Bush and Johnston (1988)
3. Great Basin aquifer systems	Simulation of shallow flow in basin-fill deposits superimposed over deeper flow through fractured carbonate rocks	3-D finite-difference model; 2 active layers and 5- by 7.5-mile grid blocks	McDonald and Harbaugh (1988)	Prudic and others (in press)
4. Great Plains aquifer system (of the Central Midwest RASA)	Simulation of flow in Dakota Sandstone and associated strata involving withdrawal of ground water and petroleum	3-D finite-difference model; 4 active layers and 14-mile grid spacing	McDonald and Harbaugh (1988)	Helgesen and others (1993)
5. Gulf Coastal Plain aquifer systems	Simulation of variable density flow in very thick sand-silt-clay aquifer systems with faulting, salt domes, geopressured zones at depth, and large ground-water withdrawals	3-D finite-difference model; 10 active layers and 10-mile grid spacing	Kuiper (1983, 1985)	Williamson and others (1990)
6. High Plains aquifer	Simulation of flow in unconfined aquifer with largest ground-water withdrawals in the U.S. and large reductions of saturated thickness locally	2-D finite-difference model; single layer and 10-mile grid spacing	Trescott and Larson (1976), Larson (1978)	Luckey and others (1986)
7. Northern Atlantic Coastal Plain aquifer system	Simulation of flow in heterogeneous clastic aquifers with localized pumping centers	3-D finite-difference model; 10 active layers and 7-mile grid spacing	Trescott (1975), Leahy (1982)	Leahy and Martin (1993)
8. Northern Great Plains aquifer system	Simulation of regional flow system in Paleozoic and Mesozoic bedrock aquifers prior to development of ground water and petroleum, and involving water of variable density	3-D finite-difference model; 5 active layers and variable grid spacing	Trescott (1975), Weiss (1982)	Downey (1986)

9. Northern Midwest regional aquifer system	Simulation of flow in Cambrian-Ordovician sandstone-carbonate aquifers involving pumping from multiaquifer wells and water of variable density	3-D finite-difference model; 5 active layers and 16-mile grid spacing	Trescott (1975), Kontis and Mandle (1988)	Mandle and Kontis (1992)
10. Snake River Plain aquifer system	Simulation of flow in basalt aquifers of Eastern plain involving large withdrawals and recharge by imported surface water	Combined 2-D parameter estimation model and 3-D finite-difference model; 4 active layers and 4-mile grid spacing	Garabedian (1986) including code by R.L. Cooley; McDonald and Harbaugh (1988)	Garabedian (1993)
11. Southeastern Coastal Plain aquifer system	Simulation of deep flow in clastic coastal plain aquifers with locally heavy pumping	3-D finite-difference model; 3 active layers and 8-mile grid spacing	McDonald and Harbaugh (1988)	Barker and Pernik (in press)

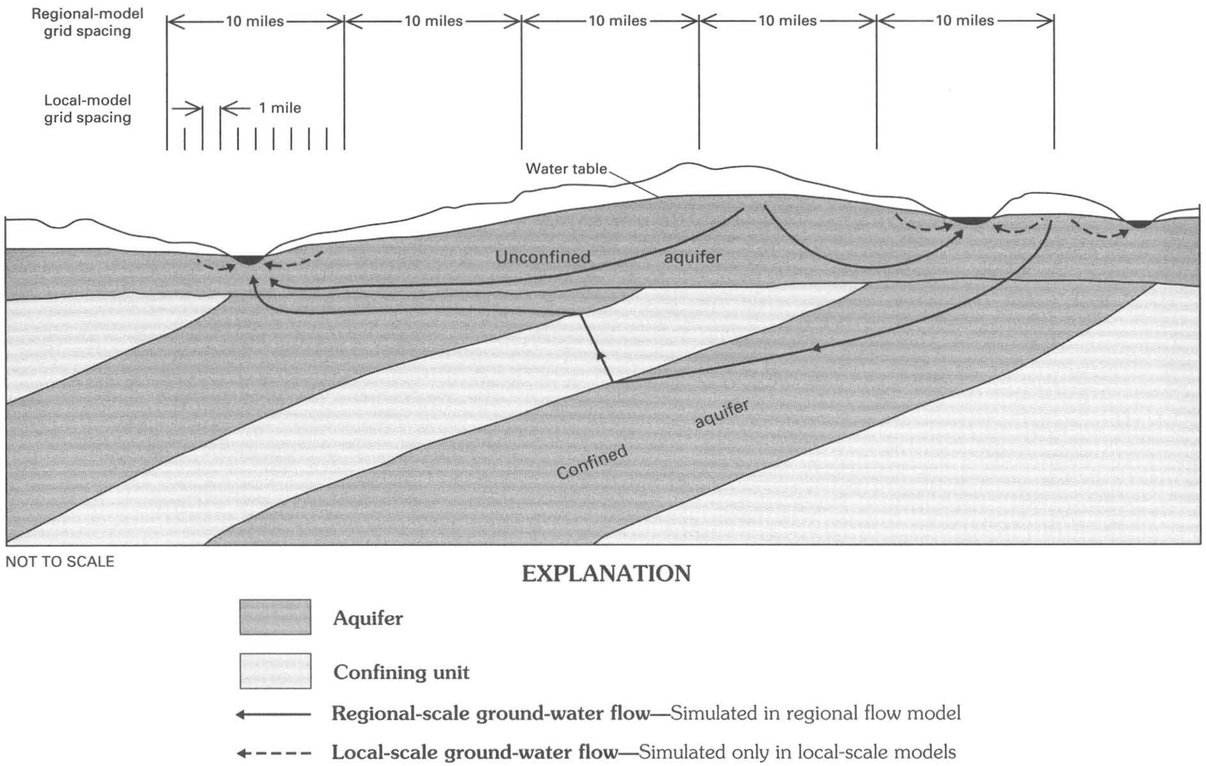


Figure 3. Relation of local- and regional scale ground-water flow to discretization in computer flow models.

and few streams, variations in head are relatively small, a much smaller fraction of the recharge discharges locally, and proportionately more of the total ground-water flow is simulated by a regional model.

Although other factors are involved, the most important factors controlling the fraction of total ground-water flow simulated by a regional model that includes near-surface units are topography and surface drainage. These characteristics are typically variable across large regional aquifer systems; these variations, in turn, cause the fraction of total ground-water flow simulated by a coarse-mesh RASA model to vary spatially, thus making the flow difficult to quantify for the model as a whole. Most RASA modelers have confronted this problem by describing its effect on their simulations, but rigorous quantitative analysis of the effect is lacking.

For most of the larger RASA studies in which regional models were made, subregional models of parts of the aquifer systems were also constructed. The areas of the blocks in the subregional models were correspondingly smaller. Thus, more of the local flow, and a larger fraction of the total ground-water flow, was simulated by these subregional models, although even the model block area (typically 4 to 16 mi^2) is too large for these models to be used to address site-specific management issues. For investigating site-specific ground-water problems, local models (fig. 3) with a smaller block size (1 mi^2 or less) are generally required.

In essence, the difference between the amount of recharge and discharge in a real-world aquifer system and the amount of recharge and discharge in the corresponding simulated system is greatest where the variation in head is greatest in the real system. As block size in a model increases, the head variability within a volume of the subsurface represented by a model block likely increases. Where there is little head variation in the real system, there is less opportunity for discrepancy between the generalized aquifer head representing an entire model block and the actual heads in the real aquifer system. Accordingly, block size causes less of a difference between actual and simulated flow components in such areas.

PART I. SELECTED DESCRIPTIONS AND FINDINGS ABOUT REGIONAL AQUIFER SYSTEMS

The difficulty in trying to summarize the multiplicity of findings from the RASA Program resulted in a two-pronged approach for this report. First, examples of selected findings are given (this section of the report). These examples serve to highlight the type of regional synthesis that has resulted from the RASA Program. They include example descriptions of hydrogeologic frameworks, different approaches used to define hydraulic properties, and comparisons of regional ground-water budgets. Finally, a summary evaluation of ground-water development effects is presented and possible and actual uses of results from the RASA Program are discussed. The examples are neither the most important nor exhaustive; rather, they are those from reports that are in print or those that are most illustrative. Abbreviated summaries of each regional aquifer system for which studies had begun by mid-1992 constitute the second major part of this report.

REGIONAL DESCRIPTIONS OF HYDROGEOLOGIC FRAMEWORKS, FLOW-SYSTEM CHARACTERISTICS, AND GROUND-WATER CHEMISTRY

A description of the hydrogeologic framework, hydraulic properties of regional aquifers and confining units, ground-water chemistry, and flow-system characteristics of the Nation's major aquifer systems has been an important part of the RASA Program. This aquifer system definition generally has been presented as regional maps from compilations of existing data such as drillers' logs, geophysical logs, geologic maps, and other ancillary information. However, the availability of existing data tends to be unevenly distributed for many of the major ground-water systems because most previous hydrologic investigations have been conducted in areas of heavy pumping with water quantity or quality problems. Elsewhere, data are often sparse. Therefore, an important task of RASA projects has been to fill data voids to provide more complete descriptions of a regional aquifer system. This effort to fill data voids has involved some exploratory drilling, conducting synoptic measurements of ground-water levels to map regional potentiometric surfaces, and collecting and analyzing water samples where water chemistry is unknown.

The regional system descriptions derived from existing and newly acquired data have been described in several hundred reports. A number of these publications present, for the first time, maps depicting the hydrogeologic framework, water chemistry, and potentiometric surfaces of entire regional aquifer systems. A few examples of such maps are presented in this section.

HYDROGEOLOGIC FRAMEWORKS

RASA investigations are concerned with understanding ground-water flow systems on a regional scale, and therefore the focus of hydrogeologic framework studies is the delineation of regional aquifers and confining units. However, most previous hydrogeologic studies of the Nation's major ground-water systems have focused on local problems. As a result, the extent, thickness, and hydraulic properties of local aquifers and confining beds tend to be well known near pumping centers but may be poorly defined elsewhere. As noted by Sun (1986), the delineation and continuity of aquifers and confining units are dependent on the scale of the problem under study. Thus, a major effort of RASA projects has involved the combination of many "local" aquifers and confining beds into a small number of regional aquifers and confining units.

The subdivision of a complex sedimentary or volcanic rock sequence into a few regionally extensive aquifers and confining units creates some problems. The use of different aquifer or rock-stratigraphic nomenclature in adjacent States for virtually continuous rock units must be considered in defining the "new" set of regional hydrogeologic units. In addition, the tops and bases of the newly delineated regional units may not coincide with those of either time-stratigraphic or rock-stratigraphic units or even previously defined aquifers and confining units.

After a decision has been reached about a tentative framework of regional aquifers and confining units, the hydrogeologist must define the lateral and vertical extent of these "new" units. Such definition generally requires preparation of maps and sections showing the top, base, and thickness of these new regional hydrogeologic units. In addition, the relation of all previously defined aquifers and confining units and geologic units to the proposed regional hydrogeologic units need to be explained.

An example of a terrain where many problems were encountered in defining a set of regional hydrogeologic units is the thick sequence of clastic and carbonate sediments underlying the Coastal Plain of the southeastern United States. The clastic rocks were studied under the Southeastern Coastal Plain RASA and the carbonate rocks under the Floridan RASA (fig. 1). The relations among the regional hydrogeologic units defined for the Southeastern Coastal Plain RASA and previously defined rock-stratigraphic units is shown in figure 4. Note that the regional aquifers generally consist of several formations. On the other hand, a formation may be partly in one aquifer and partly in another (for example the Eutaw Formation). Renken (1984) noted that it is difficult to impossible to apply existing formation or local-aquifer nomenclature to the regional aquifers and confining units in this RASA area. For each regional hydrogeologic unit, it was necessary to propose a new name.

Difficulties can also arise in defining relations at the interface of major Coastal Plain aquifer systems. In southeastern Georgia and parts of Florida, the clastic rocks of the Southeastern Coastal Plain aquifer interfinger with the carbonate rocks of the Floridan aquifer system and facies changes are complex and occur over short distances (Miller, 1986). The updip limit of the Floridan was arbitrarily placed where its thickness is less than 100 ft and where the clastic rocks interbedded with the limestone make up more than 50 percent of the rock column (Miller, 1986, p. 48).

For both the Southeastern Coastal Plain and Floridan aquifer systems, it was necessary to prepare maps showing the configuration of the top and thickness of the aquifer systems and their component aquifers and confining units. For the Floridan, it was not necessary to propose a new set of hydrogeologic names. However, as defined by Miller (1986, p. 44), the Floridan aquifer system encompasses more of the geologic section and extends over a wider geographic area than previous descriptions of the "Floridan" in the literature. It is noteworthy that, despite the large amount of hydrologic and geologic literature on the Floridan, the maps presented by Miller (1986) are the first detailed regional definition of the Floridan aquifer system and its component aquifers and confining units.

The problems involved in defining the framework of a regional unconfined aquifer would appear to be less than those of the complex Coastal Plain aquifer system just described. The upper surface of an unconfined aquifer is simply the water table; the lower surface is the top of the underlying low-permeability rocks. However, mapping of these two surfaces must be done accurately because it is the basis for determining the volume of ground water in storage.

The most extensive and heavily pumped unconfined aquifer in the United States is the High Plains aquifer, which underlies parts of eight western States between Texas and South Dakota (fig. 1). As described by Gutentag and others (1984), the High Plains aquifer is a water-table aquifer composed principally of near-surface sand and gravel deposits. The aquifer is made up of several geologic units of late Tertiary and Quaternary age. According to Gutentag and others (1984), "Hydraulic interconnection between geologic units that comprise the High Plains aquifer is sufficient to permit contouring a continuous water table throughout most of the region." A regional water-table map of the High Plains aquifer was prepared based on water-level measurements made during the winter and spring of 1980. Because the High Plains aquifer is very heavily pumped, this period was selected to minimize the effects of seasonal irrigation pumping.

The High Plains aquifer is underlain by sedimentary rocks that range in age from Permian to Tertiary. The configuration of the base of the aquifer has been greatly affected by local faulting and also by dissolution in underlying Permian evaporite beds. As with most regional aquifers, data required to define the configuration of the High Plains aquifer are adequate in some areas; however, in other areas, few data exist and mapped contours must be generalized (Gutentag and others, 1984). Based on the vertical distance between the 1980 water table and the base of the aquifer, the saturated thickness of the High Plains aquifer in 1980 was mapped as shown in figure 5. This map, together with data on the distribution of specific yield, was used to estimate the volume of "drainable water" in storage in the High Plains aquifer as of 1980.

AREAL DISTRIBUTION OF HYDRAULIC PROPERTIES

The principal hydraulic properties that control flow in unconfined aquifers are hydraulic conductivity and specific yield, and in confined aquifers are transmissivity, storage coefficient, and leakage coefficient (of confining units). Information on the areal distribution of these properties is required for the computer-based models used by nearly all RASA projects to study regional ground-water flow systems. Prior to the RASA Program, maps showing the distribution of transmissivity, specific yield, and other hydraulic properties did not exist for many of the regional aquifer systems. Publication of these maps are an important product of the RASA Program.

Different approaches have been used in RASA projects to define the distribution of hydraulic properties depending on data availability and the local geology. Two maps presented here are based on different approaches to defining the areal distribution of transmissivity for (1) a

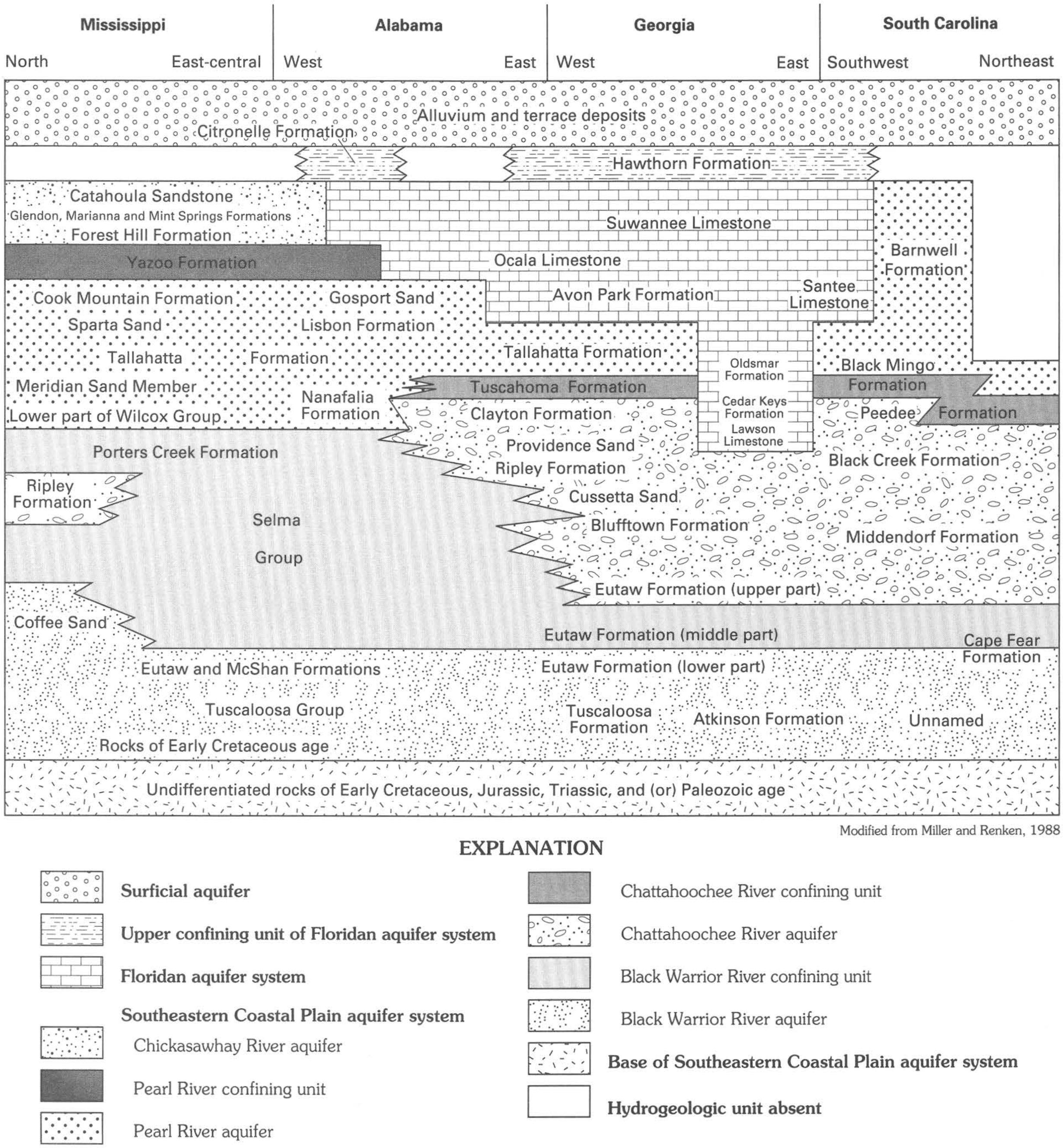


Figure 4. Rock-stratigraphic and regional hydrogeologic names applied to clastic and carbonate rocks of the Southeastern Coastal Plain.

fractured Paleozoic carbonate aquifer in the arid west, characterized by deep burial and slight ground-water development; and (2) a semiconsolidated Tertiary carbonate aquifer in the humid southeast, occurring at shallow to moderate depth and having large ground-water withdrawals locally. The first map was compiled from drill-stem tests and core measurements, and the second from aquifer test data, geologic information, and simulation results.

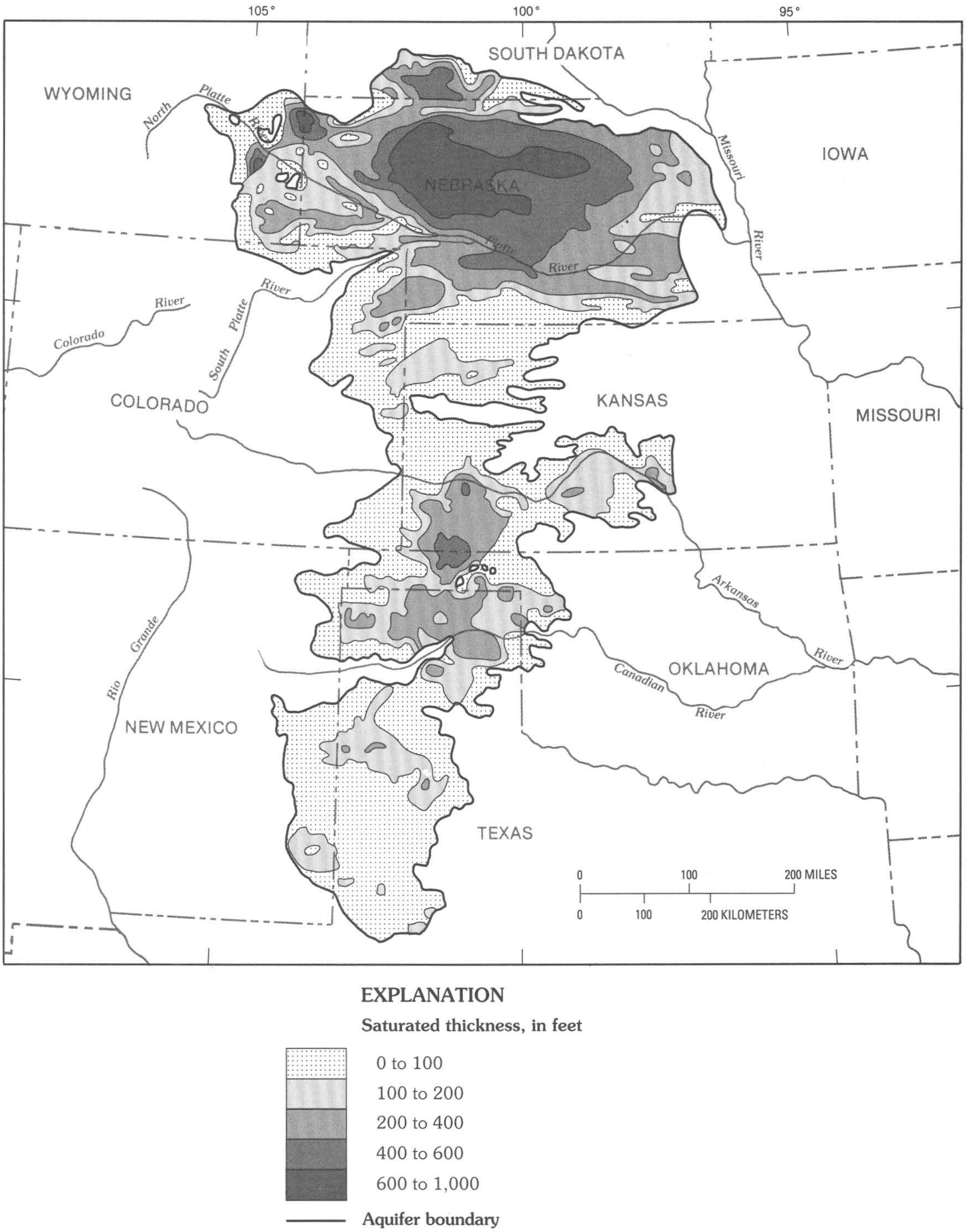


Figure 5. Saturated thickness of the High Plains aquifer, 1980 (from Gutentag and others, 1984).

The distribution of transmissivity for a regional aquifer composed of Devonian and Mississippian carbonate rocks in the Upper Colorado River Basin of the Western United States is shown in figure 6. The aquifer consists of limestone and dolomite that crop out on the flanks of mountain ranges but, for the most part, are deeply buried beneath younger Paleozoic and Mesozoic sedimentary rocks. Permeability of the carbonate rocks is derived from intergranular porosity and interconnected fractures and vugs. The permeability increases from structural basins to uplifted areas as the rocks become increasingly fractured and less cemented (Geldon, 1988). Estimates of transmissivity are based largely on drill-stem tests and laboratory (permeameter) measurements on cores. The estimated transmissivity ranges from less than 0.1 ft^2/d in the deeper parts of the basins to more than 10,000 ft^2/d in the uplifted areas.

The transmissivity of the Upper Floridan aquifer in the southeastern United States is shown in figure 7. The aquifer consists of semiconsolidated limestone and dolomite of Tertiary age in which the water-bearing openings range in size from small intergranular openings in coquinas (fossil hash) to large solution cavities. Transmissivity values were obtained from more than 100 multiwell aquifer tests, located mostly in areas of large ground-water development. Elsewhere, transmissivity was estimated either on the basis of lithology and thickness of the aquifer or on simulation results. Estimates of transmissivity based on lithology assume that micrites (lime muds) have permeabilities similar to clay and silt and thus low transmissivity. In contrast, pelletal limestones (made up largely of loosely cemented fossil fragments and locally containing large solution openings) were considered to have permeabilities similar to sand and gravel and thus high transmissivity. Specific capacity was determined to be a poor basis for estimating the transmissivity of the Upper Floridan aquifer (Bush and Johnston, 1988).

The highest transmissivities (greater than 1 million ft^2/d) are in areas where the Upper Floridan is thick, either unconfined or thinly confined, and characterized by extensive karst development. Aquifer tests (involving pumping and observation wells) are virtually impossible to conduct in the karst areas because of logistical problems (removing large volumes of water to prevent recycling) and because non-Darcian flow can preclude the use of standard methods of aquifer-test analysis. However, simulation suggests that transmissivity is in the range of 1 to 10 million ft^2/d. The areas of low transmissivity (less than 10,000 ft^2/d) occur either where the aquifer contains large amounts of micritic limestone or in updip areas where the aquifer is thin.

FLOW-SYSTEM CHARACTERISTICS

The areal distribution of hydraulic heads and the historical changes in water levels in the major aquifer systems were reasonably well documented prior to the RASA Program. However, the available water-level data and potentiometric surface maps tend to be concentrated in areas of large ground-water withdrawals. Many water-level contour maps have been prepared for States, counties, or other political subdivisions; however, maps rarely are prepared that provide complete areal coverage of a regional aquifer. A major contribution of the RASA Program has been preparation of some of the first aquifer-wide potentiometric surface maps. For example, although synoptic potentiometric surface maps had been prepared individually for the Florida and Georgia parts of the Upper Floridan aquifer, no such maps had been compiled for the four-State area that is underlain by the Floridan. Under the RASA Program, an aquifer-wide synoptic potentiometric surface map of the Upper Floridan was prepared on the basis of more than 2,700 water-level and pressure-head measurements made in May 1980.

A major objective of the RASA Program is to define the effect of development on ground-water-flow systems. This task normally involves comparison of predevelopment and recent potentiometric surface maps to define the areal extent and magnitude of long-term regional head declines caused by pumping. Examples of such maps (figs. 8 and 9) show the estimated predevelopment and 1985 potentiometric surfaces for the composite Cambrian-Ordovician aquifer system in parts of Illinois, Indiana, and Wisconsin.

Comparison of the two maps indicates that groundwater withdrawals have created major cones of depression around the cities of Chicago and Milwaukee. Maps such as these are essential for calibrating computer flow models for predevelopment and recent pumping conditions.

Maps showing head differences between aquifers are essential for quantifying vertical flow rates in complex aquifer systems. The head difference between the water table and the lower pumped zone (a confined aquifer) in the Central Valley aquifer system of California is shown in figure 10. Such head data can be used in computer flow models to simulate rates of flow between the unconfined and confined aquifers if field values of leakage coefficient of the intervening confining units are available or can be estimated. Alternatively, if the rates of vertical flow can be estimated independently (from water budgets), the head difference can be used to compute the values of leakage coefficient for the confining unit to deliver the estimated flow rates.

GROUND-WATER CHEMISTRY

RASA projects are concerned with describing the water chemistry and identifying the geochemical processes taking place in regional aquifer systems. For the descriptions of ground-water chemistry, RASA investigators rely primarily on analyses of water samples from wells and springs in computer files of the U.S. Geological Survey.

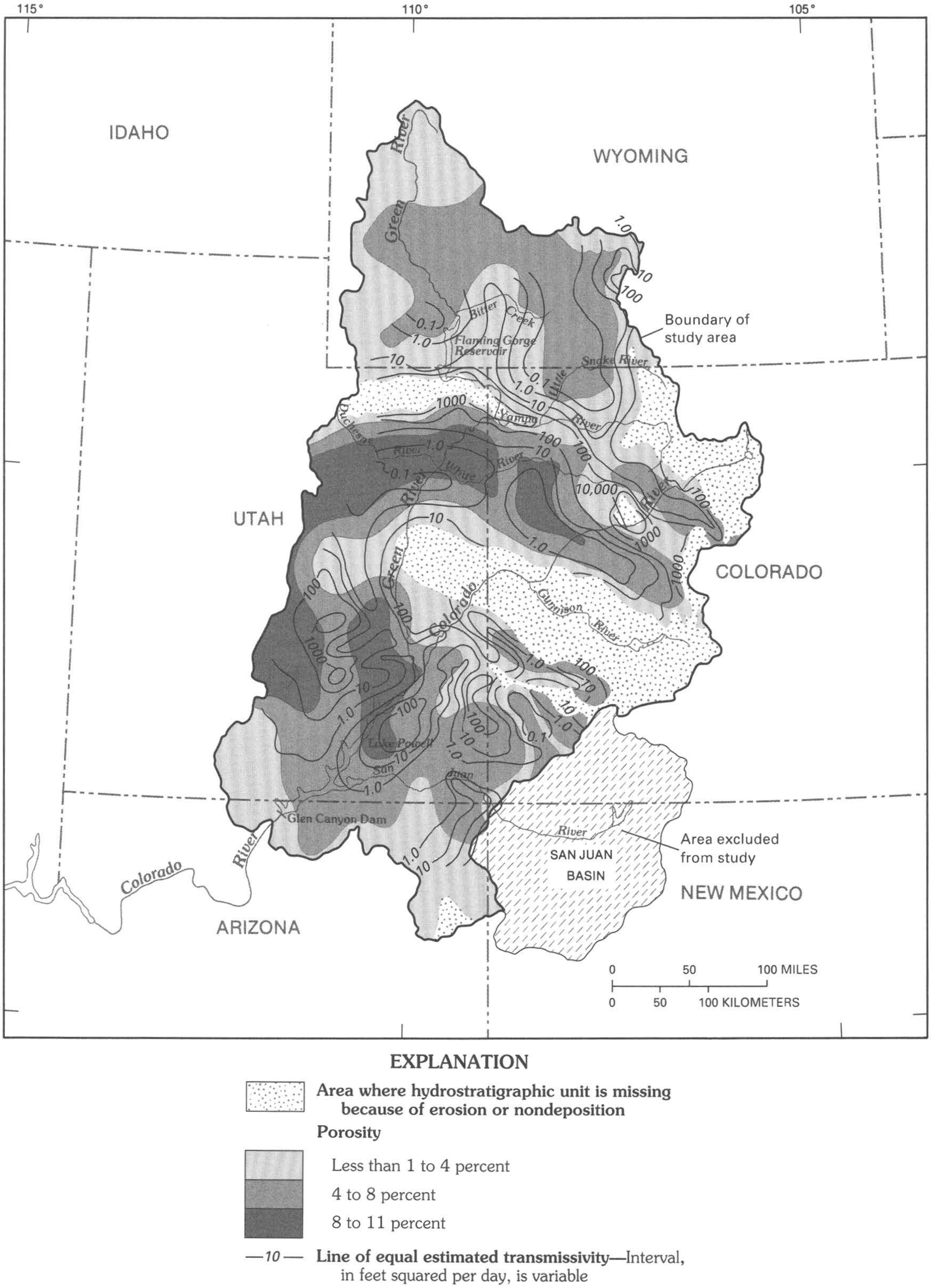


Figure 6. Porosity and transmissivity of the Devonian and Mississippian carbonate rocks hydrostratigraphic unit in the Upper Colorado River Basin, Arizona, Colorado, New Mexico, Utah, and Wyoming (from Geldon, 1988).

These data are used to prepare maps and diagrams showing concentrations of major constituents (such as calcium and sulfate), total dissolved-solids concentrations, and hydrochemical facies. Although this approach is similar to that traditionally used in county or small-basin studies, description of ground-water chemistry on a regional scale generally requires more explanation of the spatial variations. Some of the factors that must be considered in regional-scale studies are the continuity of minor aquifers and pumped zones and their relation to regionally extensive aquifers, mixing of ground water among permeable zones in open-hole wells, and the geochemical processes that have affected the ground-water chemistry through geologic time.

An example of one type of map used to characterize the water chemistry in regional aquifers is shown in figure 11. This map shows the hydrochemical facies of ground water in two aquifers of the Cambrian-Ordovician aquifer system in the Northern Midwest United States. The map was used by Siegel (1989) to relate ground-water chemistry to aquifer lithology and the major geochemical and hydrologic processes that are occurring in the aquifer system.

REGIONAL GROUND-WATER BUDGETS

One of the major contributions of the RASA Program was the calculation of hydrologic budgets for major

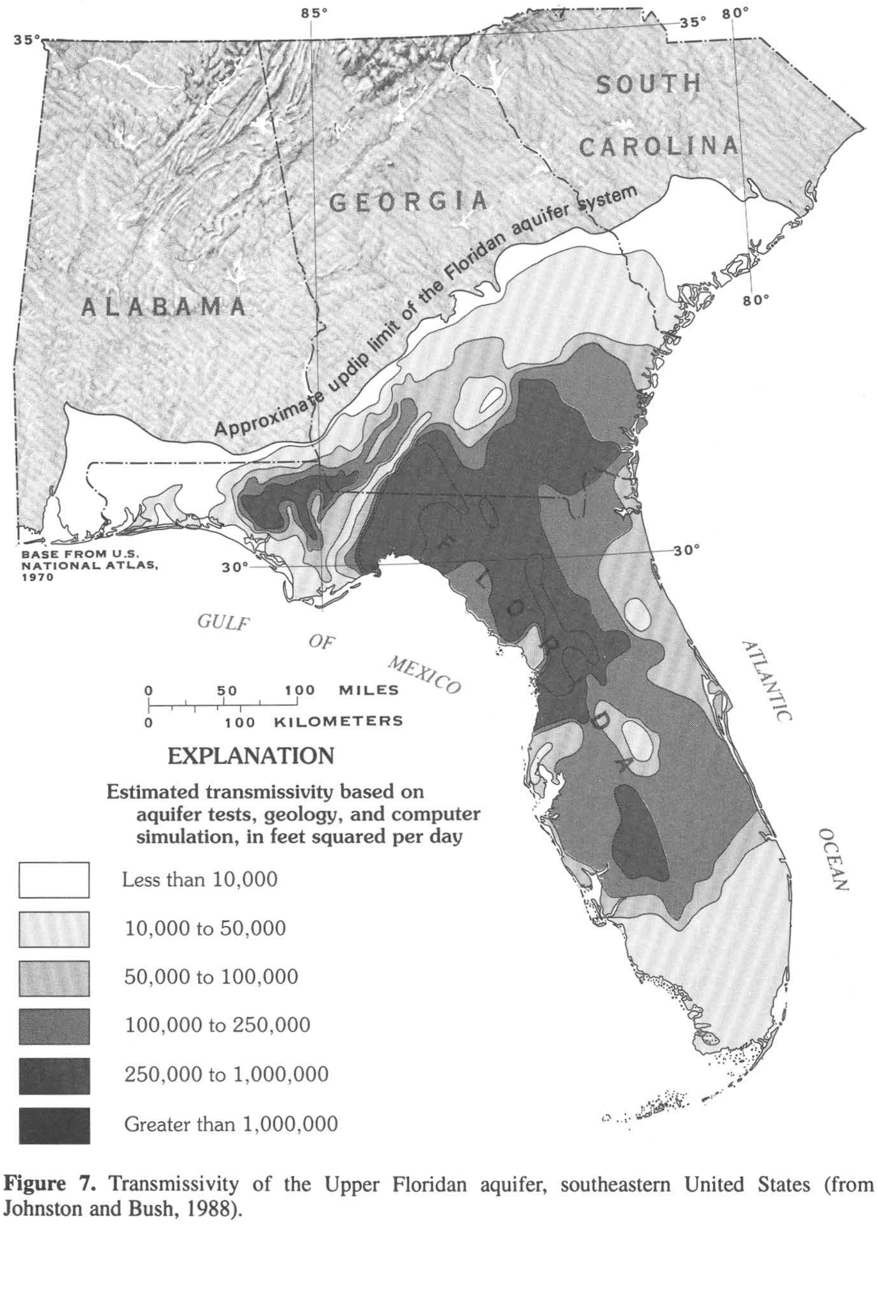


Figure 7. Transmissivity of the Upper Floridan aquifer, southeastern United States (from Johnston and Bush, 1988).

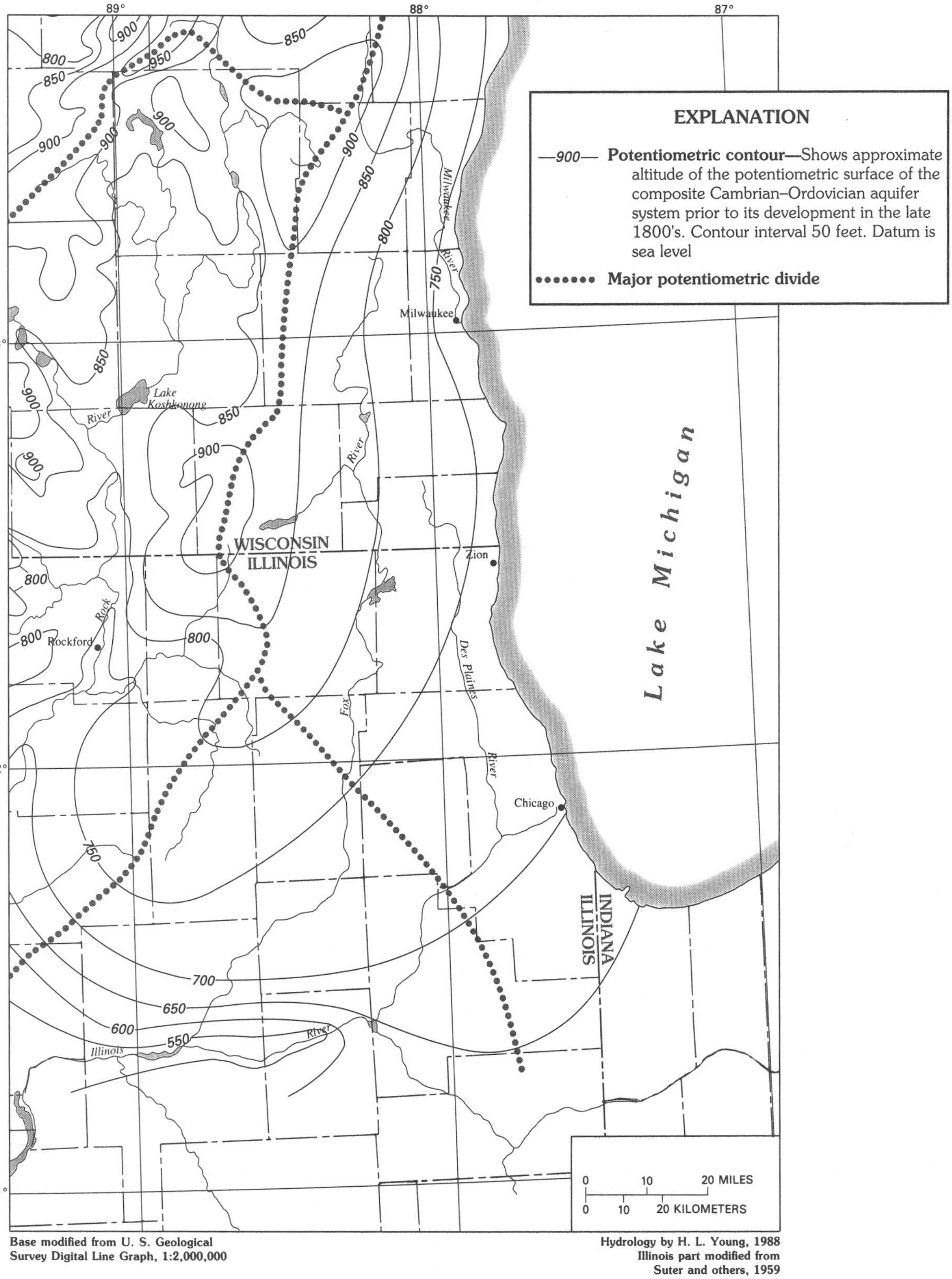
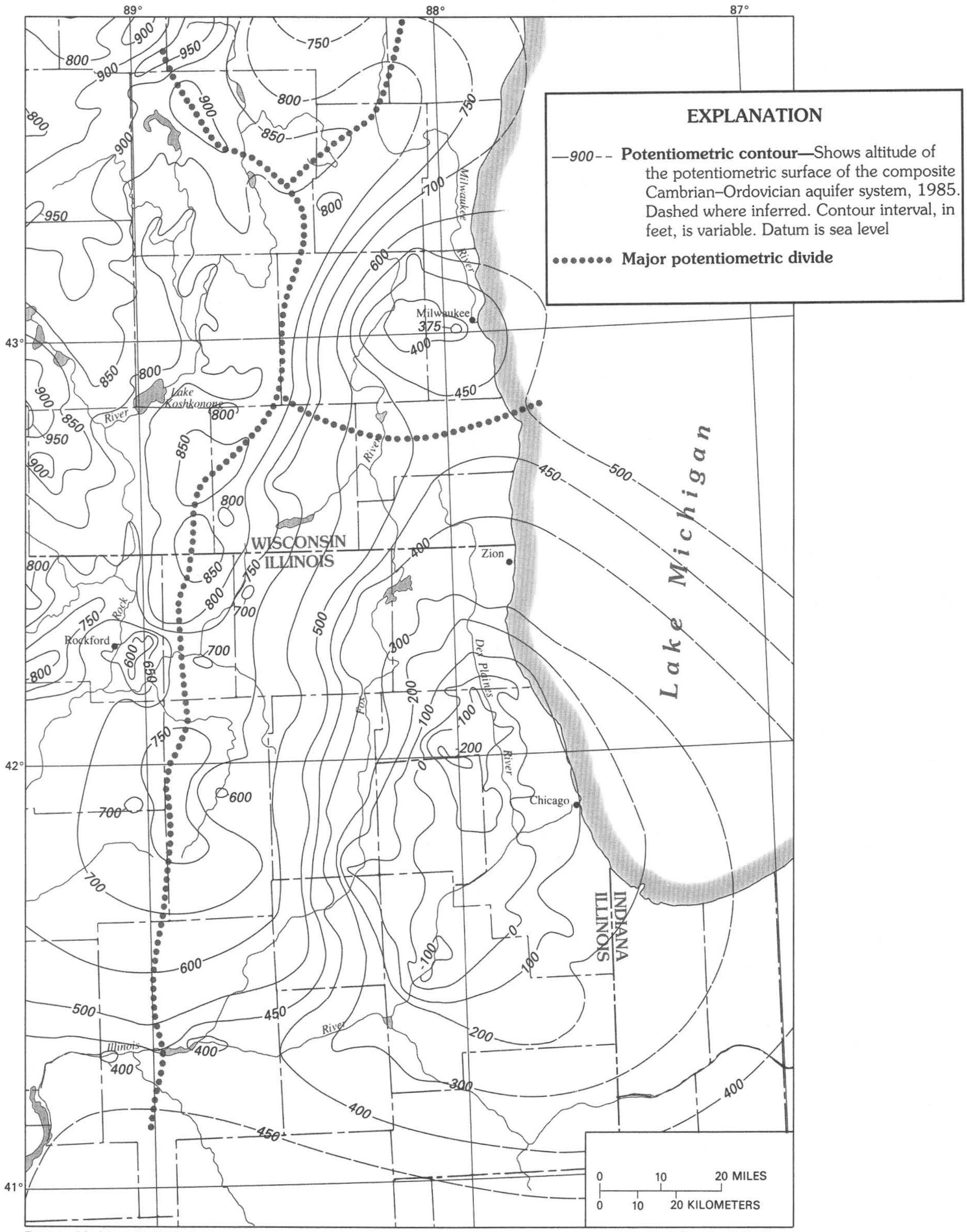


Figure 8. Approximate predevelopment potentiometric surface for the composite Cambrian-Ordovician aquifer system in the Chicago-Milwaukee area (from Young and others, 1989a).



Base modified from U. S. Geological Survey Digital Line Graph, 1:2,000,000

Hydrology by H. L. Young
Illinois part modified from Sasman and others, 1986

Figure 9. Potentiometric surface for the composite Cambrian-Ordovician aquifer system in the Chicago-Milwaukee area, 1985 (from Young and others, 1989a).

ground-water systems in the United States. Several of the completed RASA projects provide for the first time hydrologic budgets for both predevelopment and developed conditions. These budgets are based on computer simulations of predevelopment and development conditions and utilize the regional hydrologic data bases, information on

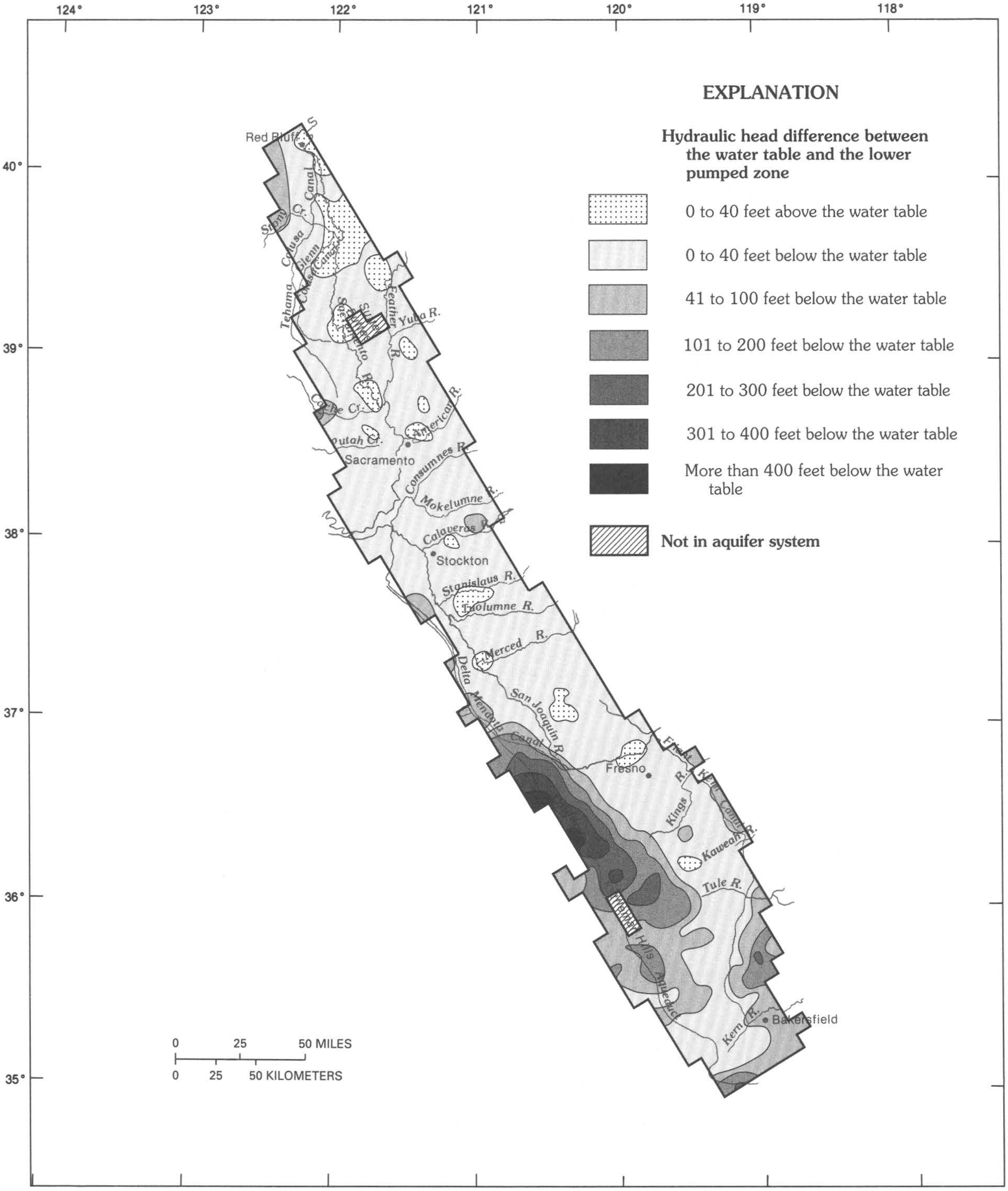
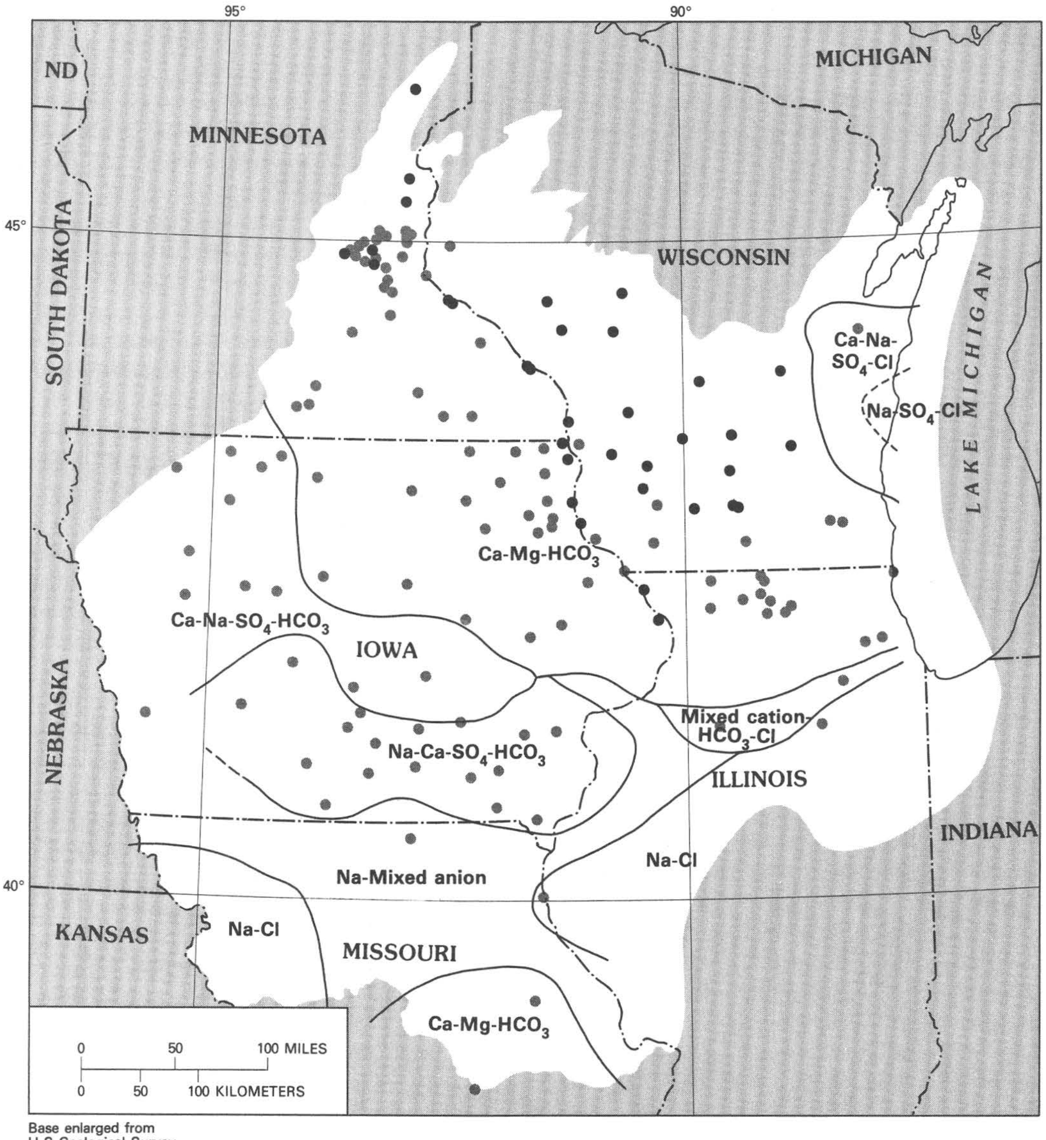


Figure 10. Hydraulic head difference between the water table and the lower pumped zone, Central Valley aquifer system, California, spring 1961 (from Williamson and others, 1989).

boundary conditions, and pumpage data, compiled during the RASA studies.

Some of the ground-water budgets are derived from coarse-mesh computer models designed to simulate "regional flow." Such budgets do not include local flow that enters and exits regional aquifers after traveling only a few miles, or flow in overlying surficial aquifers (fig. 3). The percent of the total ground-water flow system represented by "regional flow" is dependent on the mesh size of the model as discussed in the earlier section on simulation of regional



Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

EXPLANATION

——-- **Hydrochemical facies zone boundary**—Dashed where approximate

Well sampled for chemical analysis during this study

● Open to Mount Simon aquifer

● Open to St. Peter–Prairie du Chien–Jordan aquifer

Figure 11. Hydrochemical facies of ground water in the Mount Simon and St. Peter–Prairie du Chien–Jordan aquifers, Cambrian-Ordovician aquifer system in the Northern Midwest (from Siegel, 1989).

flow. Under natural conditions, the amount of local flow is commonly much greater than regional flow, especially in humid areas. A common characteristic of both humid and semiarid areas is that rates of regional flow are almost always increased by development (Johnston, 1989). In the humid East, especially, much "local" flow is diverted into the regional flow system as withdrawals from confined aquifers increase. Therefore, the regional ground-water budget is characterized by increased recharge and increased ground-water circulation overall. However, the total recharge to the ground-water system may not have increased; only that part of the total recharge that percolates to the regional flow system increases.

In this section, regional water budgets for eight of the most heavily pumped aquifer systems in the United States (fig. 1) are discussed. In the humid East and South, regional water budgets for the Northern Atlantic Coastal Plain, Gulf Coastal Plain, and Floridan aquifer systems are described. In the climatically diverse Central United States, budgets for the Cambrian-Ordovician aquifer system of the Northern Midwest, the Great Plains aquifer system (Dakota Sandstone and associated beds), and the High Plains aquifer (southern part) are examined. In the semiarid Western United States, budgets for the Central Valley aquifer system in California and the Snake River Plain aquifer system in Idaho are described. The brief summaries presented for each of the major systems emphasize changes in the rates of recharge and discharge caused by development.

AQUIFER SYSTEMS OF THE ATLANTIC AND GULF COASTAL PLAINS

The three major aquifer systems for which ground-water budgets are presented underlie the Eastern, Southeastern, and south-central United States, a region of humid, temperate to subtropical climate. The ground-water budgets were derived from simulation and vary somewhat in the percent of the total ground-water flow system that is represented as follows:

(1) Northern Atlantic Coastal Plain—budget includes all flow (local and regional) in the ground-water system.

(2) Floridan aquifer system—budget includes only flow that enters the Floridan and moves several miles prior to discharging from it. The percent of the total ground-water system included in the budget varies areally. In karst areas of central and northwest Florida, almost all recharge enters the Floridan and moves at least 10 mi prior to discharging to springs—thus, the budget for the aquifer system in that area represents nearly all flow in the ground-water system. In narrow outcrop belts or confined areas, local flow in surficial aquifers or within Floridan outcrops is generally not simulated—thus, the budget for the aquifer system in those areas represents only a small percent of the total ground-water flow system.

(3) Gulf Coastal Plain aquifer systems—budget includes only regional ground-water flow because of the coarse mesh used in the flow model (10-mi grid spacing). Because ground-water withdrawals have diverted water from local flow systems into the regional flow system, the water budget for development conditions includes a much greater percentage of the total ground-water flow than does the predevelopment budget.

NORTHERN ATLANTIC COASTAL PLAIN AQUIFER SYSTEM

The Northern Atlantic Coastal Plain aquifer system extends from Long Island, New York, to the North Carolina–South Carolina State boundary and includes approximately 55,000 mi^2 (fig. 1). The aquifer system consists of consolidated and unconsolidated sand, silt, and clay of Jurassic to Holocene age (Trapp, 1993). These sediments form an eastward-thickening wedge and contain aquifers that are the major source of fresh ground water in the area.

Ground-water withdrawals, primarily from the confined aquifers, were about 1.2 Bgal/d in 1980. Simulation of pumping conditions in the coarse-mesh regional model used a top boundary condition termed "modified specified-flux boundary condition" to simulate withdrawals in the unconfined aquifers (Leahy and Martin, 1993). This boundary condition "which included stream-stage elevations, deep percolation, and discharge to streams allowed heads in the unconfined system to change with time in response to changing withdrawals" (Leahy and Martin, 1993). As a result, the model simulated local flow in the unconfined part of the aquifer system in addition to deep (regional) flow in the confined aquifers.

Ground-water budgets for the Northern Atlantic Coastal Plain aquifer system for predevelopment and 1980 conditions are shown in figure 12. These budgets represent the total ground-water flow system, not simply deep regional flow. For this reason, the areal recharge rate is the same for both predevelopment and 1980 conditions—about 40 Bgal/d. Note that pumpage in 1980 represents only about 3 percent of the total recharge entering the flow system. Pumpage, which is primarily from the confined aquifers, is supplied mostly by an increase in downward percolation to the confined aquifers and a decrease in upward leakage from them. Less than 2 percent of the pumpage is supplied by water released from aquifer storage. However, Leahy and Martin (1993) emphasize that, because withdrawals are not evenly distributed over the system, the local effects of water released from storage can be significant. As in predevelopment time, shallow ground-water flow accounts for most of the flow through the aquifer system. However, by 1980, pumpage caused the rate of deep percolation into confined aquifers to more than double and the upward leakage from confined aquifers to occur at less than one-half the predevelopment rate. Based on simulation, Leahy and Martin (1993) conclude that the system rapidly adjusts (less than 3 yr) to changes in withdrawal rates.

FLORIDAN AQUIFER SYSTEM

The highly productive Floridan aquifer system underlies all of Florida, southern Georgia, and small parts of adjoining Alabama and South Carolina, for a total area of about 100,000 mi^2 (fig. 1). The aquifer system is a sequence of hydraulically connected carbonate rocks (limestone and dolomite) that generally range in age from late Paleocene to early Miocene (Miller, 1986). Average rainfall of about 53 in/yr and generally flat topography combine to provide abundant recharge to the Floridan. The unconfined and semiconfined parts of the Floridan are characterized by high recharge (averaging 10–20 in/yr) and a vigorous shallow flow system with most discharge occurring at large springs. In contrast, ground-water flow is sluggish in parts of the aquifer system that are deeply buried and tightly confined.

Increasing pumpage that reached 3 Bgal/d by 1980 has resulted in regional water-level declines in three broad areas where the Floridan is thickly confined. This withdrawal has not greatly affected the ground-water budget of the Floridan, as can be seen in figure 12. Pumpage from the Floridan is supplied primarily by reduction of natural discharge and by increased recharge rather than by depletion of aquifer storage (Bush and Johnston, 1988). About 20 percent is from reduced discharge to springs, streams, and lakes; about 20 percent is from reduced upward leakage, and about 60 percent is from increased recharge (downward percolation from surficial aquifers overlying the Floridan). As a result of induced recharge into the Floridan, the rate of flow through the aquifer system has increased from about 13.9 Bgal/d (predevelopment conditions) to about 15.7 Bgal/d in 1980.

The transient response to changes in withdrawal rates dissipates fairly rapidly (days or weeks) in most

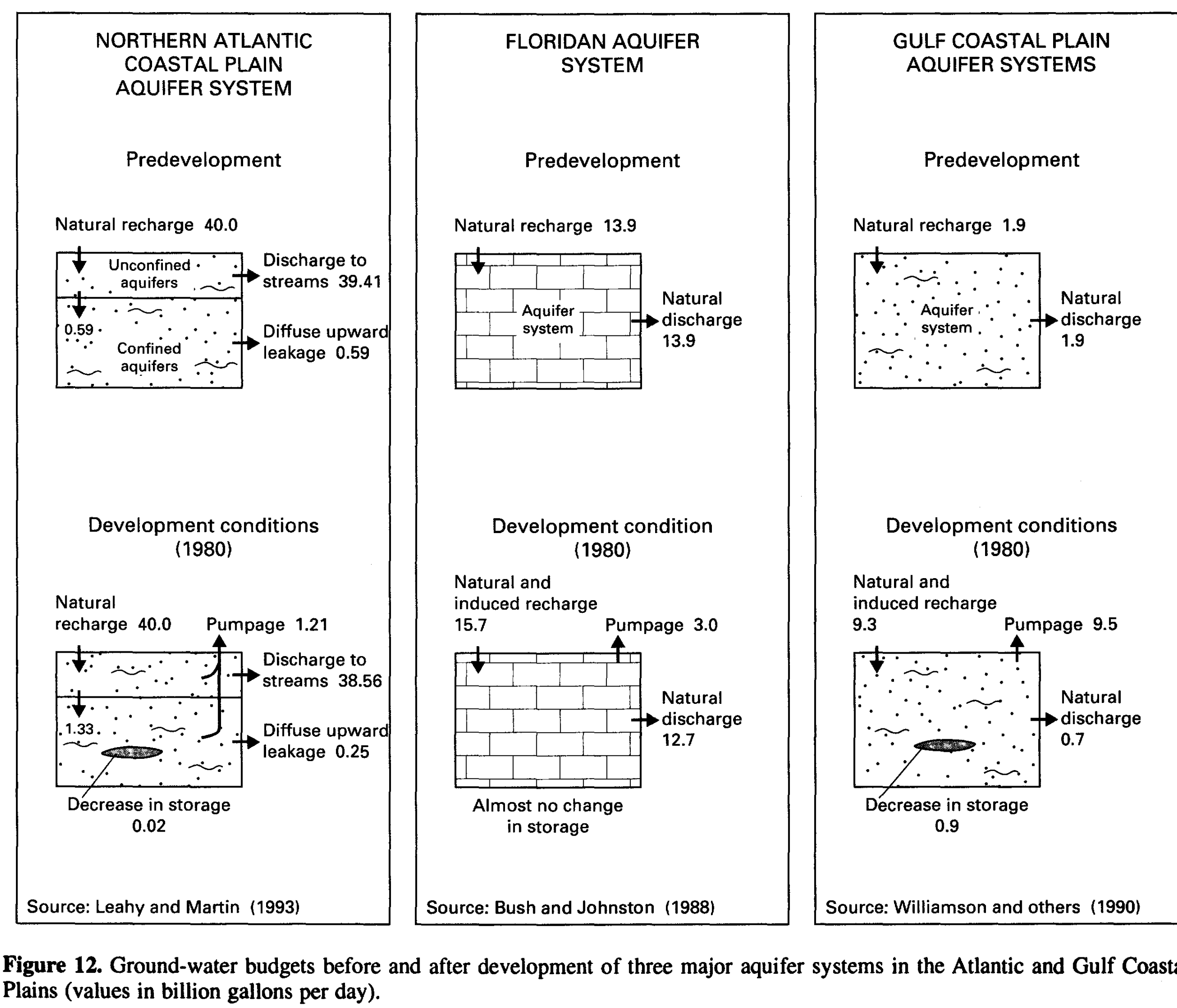


Figure 12. Ground-water budgets before and after development of three major aquifer systems in the Atlantic and Gulf Coastal Plains (values in billion gallons per day).

areas (Bush and Johnston, 1988). Thus (excluding seasonal changes), the Floridan aquifer system is considered to be approximately at equilibrium, except during periods following sustained increases in pumpage.

GULF COASTAL PLAIN AQUIFER SYSTEMS

The Gulf Coastal Plain aquifer systems consist mostly of Cenozoic age sediments that underlie approximately 290,000 mi^2 extending from Texas to Florida and including the Mississippi embayment, Gulf Coastal Plain of Texas, and offshore areas beneath the Gulf of Mexico (fig. 1). These sediments are an interbedded sequence of sand, silt, and clay with some gravel, lignite, and limestone (Hosman, 1991). The thickness of the sediments increases toward the Gulf of Mexico in a generally wedge shape.

Ground-water pumpage has steadily increased in recent years to nearly 10 Bgal/d and is used mostly for irrigation. The effect of ground-water withdrawals has been widespread water-level declines with land subsidence and saltwater intrusion locally.

Williamson and others (1990) state that the amount of recharge to the regional ground-water flow system is not related to average rainfall but is more likely limited by the capacity of the aquifer systems to transmit ground water away from recharge areas. Because of the very large study area, Williamson and others (1990) used a very coarse-mesh model to simulate regional ground-water flow. However, they state that even with their 10-mi horizontal grid spacing, "the regional features affecting flow in the aquifer systems are generally preserved."

Water budgets for the Gulf Coastal Plain aquifer systems for predevelopment and 1980 conditions (based on Williamson and others, 1990, p. 107–110) show that the rates of regional recharge and discharge have been substantially changed by ground-water pumpage, which by 1980 was about 9.5 Bgal/d (fig. 12). Note that the 1980 pumpage is about five times the predevelopment recharge rate. About 80 percent of the 1980 pumpage was supplied by an increase in percolation to the regional flow system. The remaining 20 percent was supplied by a decrease in natural discharge and to a lesser extent by loss of aquifer storage. Williamson and others (1990) noted that some aquifers are "self-supporting," that is, most of their pumpage was supplied by increased recharge to, or decreased discharge from, the aquifer itself. On the other hand, one major aquifer with a very narrow outcrop and subcrop band had 80 percent of its pumpage provided by downward leakage from an overlying aquifer.

AQUIFER SYSTEMS OF THE CENTRAL UNITED STATES

The major aquifer systems described in this section underlie a region with a temperate, humid to dry continental climate. The Cambrian-Ordovician and Great Plains aquifer systems contain sandstone and carbonate rock aquifers that receive much of their recharge by leakage across overlying less permeable rocks. Simulated ground-water budgets for these aquifer systems include only their internal flow and do not include flow in overlying surficial, glacial, or sedimentary rock aquifers. In contrast, the High Plains aquifer is a regional water-table aquifer with a regional flow system that forms a major part of the total ground-water budget of the region.

CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM IN THE NORTHERN MIDWEST

The Cambrian-Ordovician aquifer system consists of three major aquifers (sandstone and dolomite) and two internal regional confining units (primarily sandstone and shale) that underlie 161,000 mi^2 in Illinois, Indiana, Iowa, Wisconsin, Minnesota, and Missouri (fig. 1). Simulations of regional flow show that the aquifer system functions as a leaky confined system in which flow is controlled partly by internal confining units. Pumpage from the aquifer system began in 1860 and by 1976–80 averaged 781 Mgal/d. Largest withdrawals are in the Chicago/Milwaukee and Twin Cities (Minnesota) areas. The largest head declines (more than 900 ft; figs. 8 and 9) occur west of Chicago.

Most recharge and discharge in the Northern Midwest occurs in local flow systems within glacial drift (Young and others, 1989b). Most flow in these local systems either does not enter the bedrock aquifers or penetrates only to shallow depths in them. Some water enters the confined Cambrian-Ordovician aquifer system and moves along flow paths of intermediate length to discharge areas (river valleys and Lake Michigan). Some water moves along deep regional flow paths that are as much as 400 mi from recharge to discharge areas.

The predevelopment water budget (fig. 13) indicates that flow through this bedrock aquifer system was comparatively small (369 Mgal/d), considering the large areal extent of the system. The 1976–80 pumpage of 781 Mgal/d is more than double the predevelopment recharge rate. This pumpage was largely supplied by an increase in recharge (534 Mgal/d) and to a lesser extent by a decrease in natural discharge (103 Mgal/d) and release of water from aquifer storage (139 Mgal/d). A detailed simulation of flow in the Cambrian-Ordovician aquifer system in the Chicago-Milwaukee area indicates that recharge to the system occurs most readily where it subcrops beneath glacial drift (Young, 1992a).

GREAT PLAINS AQUIFER SYSTEM (DAKOTA SANDSTONE AND ASSOCIATED STRATA)

The Great Plains aquifer system consists of sandstone, siltstone, and shale of Early Cretaceous age, including the

Dakota Sandstone and equivalent beds. As discussed in the Introduction, this system was recognized early as a major artesian reservoir (Darton, 1896, 1905). The aquifer system underlies a 170,000 mi^2 area of Nebraska, Colorado, Kansas, and adjacent States. Withdrawals from the system have included both water and petroleum. The aquifer system transmits water very slowly, and in the deeper parts water is virtually stagnant (Helgesen and others, 1993). Much of the deep regional flow system contains saline water; however, along its eastern and southeastern margins, local shallow flow systems containing freshwater predominate.

Prior to development, natural recharge to, and discharge from, this very large aquifer system was only about 220 Mgal/d (fig. 13). Simulation indicates that 87 percent of the recharge was leakage from overlying units, and about 70 percent of the natural discharge was leakage to overlying units (Helgesen and others, 1993).

Oil and gas development has resulted in regional head declines of several hundred feet; in contrast, withdrawals of freshwater have resulted in head declines of several tens of feet. However, in parts of Nebraska and Kansas, much of the head decline is due to pumpage from the overlying High Plains aquifer. During the 1970's, withdrawals from the Great Plains aquifer system were about 517 Mgal/d, or more than twice the natural recharge rate. Helgesen and others (1993) noted that the rate of adjustment to pumping from the aquifer system is extremely slow in most areas, and storage depletion (based on head declines) may be substantial. As shown in figure 13, simulation indicates that about 30 percent of the withdrawals during the 1970's was supplied by a decrease in storage.

HIGH PLAINS AQUIFER

The High Plains aquifer is a regionally extensive water-table aquifer composed principally of near-surface sand and gravel deposits of late Tertiary and Quaternary age (Gutentag and others, 1984). The aquifer underlies 174,000 mi^2 in parts of eight States as shown in figure 1.

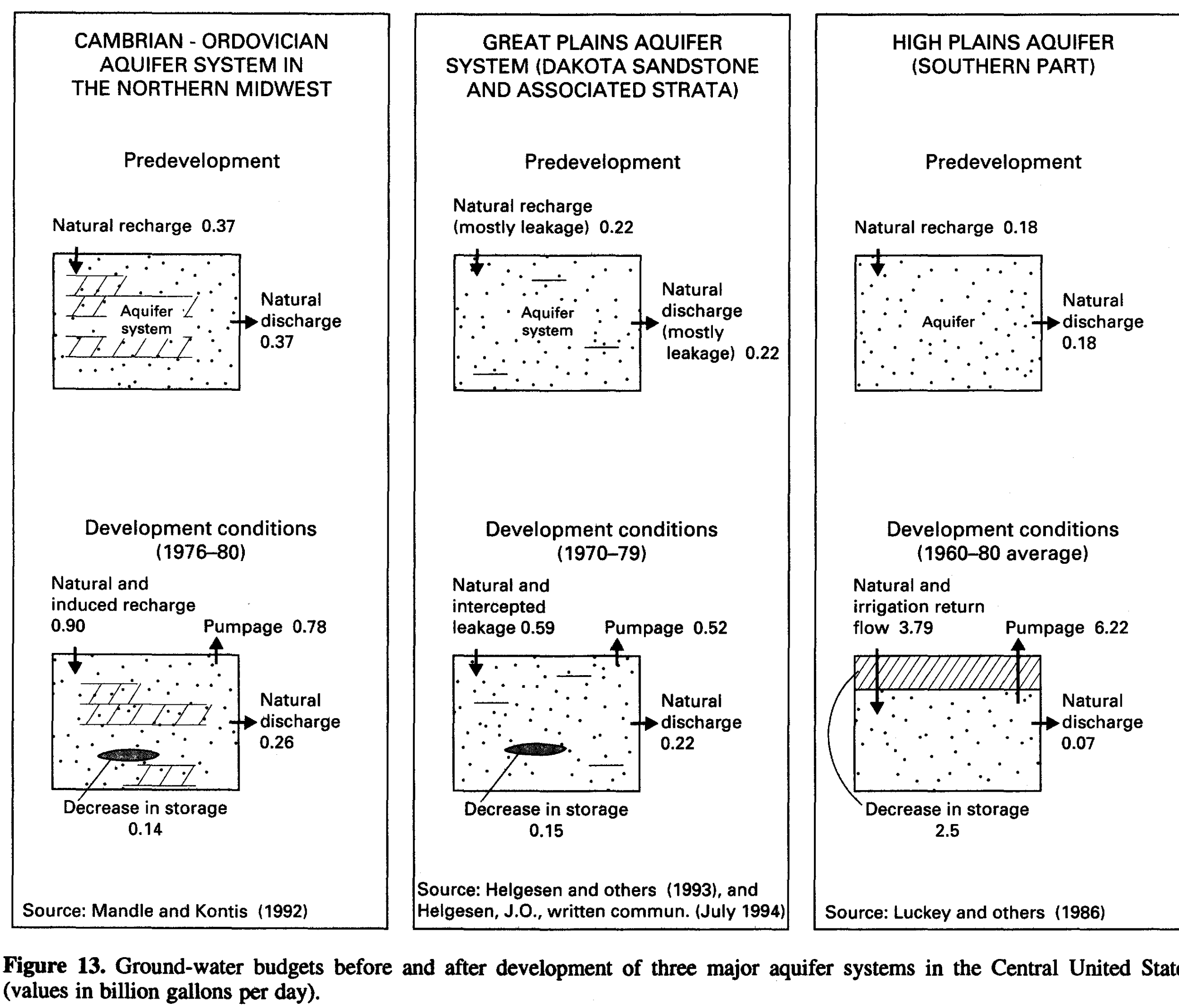


Figure 13. Ground-water budgets before and after development of three major aquifer systems in the Central United States (values in billion gallons per day).

Moderate precipitation combined with high evapotranspiration rates result in low recharge rates—generally less than 1 in/yr, except in areas with sandy soils. Water generally flows from west to east in the aquifer in response to the slope of the water table at a velocity of about 1 ft/d.

The High Plains aquifer is the most heavily pumped ground-water system in the United States. Pumpage is principally for irrigation, and during 1980 about 170,000 wells pumped almost 18 million acre-ft of water (equivalent to nearly 16 Bgal/d). This pumpage has resulted in regionally extensive water-level declines from predevelopment levels. The saturated thickness of the High Plains aquifer has decreased more than 25 percent over an area of 14,000 mi^2, mostly in the High Plains of Texas and in western Kansas. As a result, well yields have declined, and, in turn, the average number of acres irrigated per well has decreased (Weeks and others, 1988).

Water budgets for the aquifer in the southern High Plains of west Texas and eastern New Mexico for predevelopment and 1960–80 conditions show little resemblance (fig. 13). The 1960–80 pumpage exceeds natural recharge by more than 30 times, and depletion of aquifer storage occurs at a rate about 14 times greater than the rate of natural recharge. Most inflow to the aquifer is now return flow from irrigation (Luckey and others, 1986).

AQUIFER SYSTEMS OF THE WESTERN UNITED STATES

The Central Valley of California and the Snake River Plain of Idaho and eastern Oregon have arid to semiarid climates and both are underlain by highly productive aquifer systems. Both are areas of intensive agricultural production and are irrigated with a combination of imported surface water and large withdrawals from the aquifer systems. The combination of return flow of excess irrigation water to the aquifer systems and ground-water pumpage has significantly altered the ground-water flow systems in both areas. As described in this section, the components of the ground-water budgets differ greatly from those that existed prior to development.

CENTRAL VALLEY AQUIFER SYSTEM OF CALIFORNIA

The Central Valley of California is a long structural trough (20,000 mi^2) containing continental deposits of Tertiary and Quaternary age that constitute a major aquifer system (fig. 1). These deposits contain lenses of gravel, sand, silt, and clay with the fine-grained sediments making up about 50 percent of the sequence (Page, 1986). The climate is arid to semiarid with precipitation from 14 to 20 in/yr in the northern part (Sacramento Valley) and 5 to 14 in/yr in the southern part (San Joaquin Valley).

The intensive agricultural development in the Central Valley is supported by ground-water pumpage and large imports of surface water. During the 1960's and 1970's, pumpage from wells averaged about 10 Bgal/d and provided nearly 50 percent of the irrigation supply. The large ground-water withdrawals have caused water levels to decline hundreds of feet in the southern and western parts of the San Joaquin Valley. Overall, there was a net loss of aquifer storage of 60 million acre-ft from the start of development to 1977 (Williamson and others, 1989). The loss of storage resulting from inelastic compaction of clay beds has produced the largest volume of land subsidence in the world (discussed elsewhere in this report). However, importing surface water and decreasing ground-water pumpage has controlled land subsidence in the seriously affected areas in recent years.

Prior to development, recharge was supplied principally by streams entering the Central Valley from highlands on the northern and eastern sides. Ground-water discharge occurred as evapotranspiration or seepage to streams in the central part of the valley. The ground-water flow system has been completely changed by development, and flow is now largely from areas recharged by surface water imported for irrigation to areas where ground water is withdrawn for irrigation. The marked changes in the water budget for the Central Valley aquifer system are shown in figure 14. Recharge to the aquifer system has increased nearly six times and is mostly supplied by irrigation return flow (Williamson and others, 1989). Most discharge is now from pumping wells; natural ground-water discharge has sharply decreased. Net depletion of aquifer storage during the 1960's and 1970's occurred at a rate nearly one-half the rate of natural recharge. However, decreased ground-water pumpage in recent years generally has halted further depletion of ground water in storage.

SNAKE RIVER PLAIN REGIONAL AQUIFER SYSTEM

The Snake River Plain is an arcuate physiographic feature of about 15,600 mi^2 in southern Idaho and a small part of eastern Oregon (fig. 1). It consists of an eastern plain (10,800 mi^2) that is a downwarp filled with Quaternary basalt and a western plain (4,800 mi^2) that is a graben filled predominantly with fine-grained Tertiary and Quaternary sediments (Lindholm, 1986). The Quaternary basalt is a highly productive aquifer; simulation suggests that the transmissivity of the full thickness of aquifer may be as high as 10 million ft^2/d (Garabedian, 1993).

Diversion of surface water for irrigation began in the 1880's and initially caused an increase in ground-water recharge due to percolation of excess applied water (Lindholm, in press). The period from 1912 to the early 1950's was characterized by accretion of storage; however, there was generally more depletion than accretion of storage from the 1950's to 1980 (Kjelstrom, in press). The loss of storage during the latter period has been attributed to several factors including (1) decreased use of surface water for irrigation, (2) increased use of ground water, (3) conversion from flood to sprinkler irrigation, and (4) the occurrence of dry years during which ground-water pumpage increased and recharge from surface water decreased.

The ground-water budget for the main part of the eastern Snake River Plain has changed markedly since predevelopment time owing to imports of surface water for irrigation and increased pumping from wells (fig. 14). Before irrigation, about 60 percent of the recharge was from tributary basins (streamflow and ground-water discharge) and all discharge was to the Snake River. By 1980, flow through the aquifer system had increased by 80 percent and over 60 percent of the recharge was percolation of excess surface water on irrigated lands. Ground-water pumpage in 1980 was about 0.7 Bgal/d, or more than 10 percent of the total ground-water discharge. The decrease in aquifer storage represents about 5 percent of the total 1980 budget. However, it should be noted that the decrease in storage is simply removal of water that had previously been added to storage during the period from 1912 to the early 1950's.

EVALUATION OF GROUND-WATER DEVELOPMENT EFFECTS

Under natural conditions, a ground-water system generally is in a state of dynamic equilibrium; that is, recharge to the system is approximately equal to discharge from the system. However, when an aquifer system is developed, this state of dynamic equilibrium is disturbed. Initially, water stored in the pore spaces or fractures in an aquifer near pumped wells is removed to sustain pumping rates. This creates a hydraulic gradient sufficiently large to allow enough water to flow to the wells. The hydraulic gradient around a well resembles an inverted cone with the apex centered at the pumped well. Hence, it is called a cone of depression. The cone of depression expands outward from a pumped well as pumping continues. More water will be

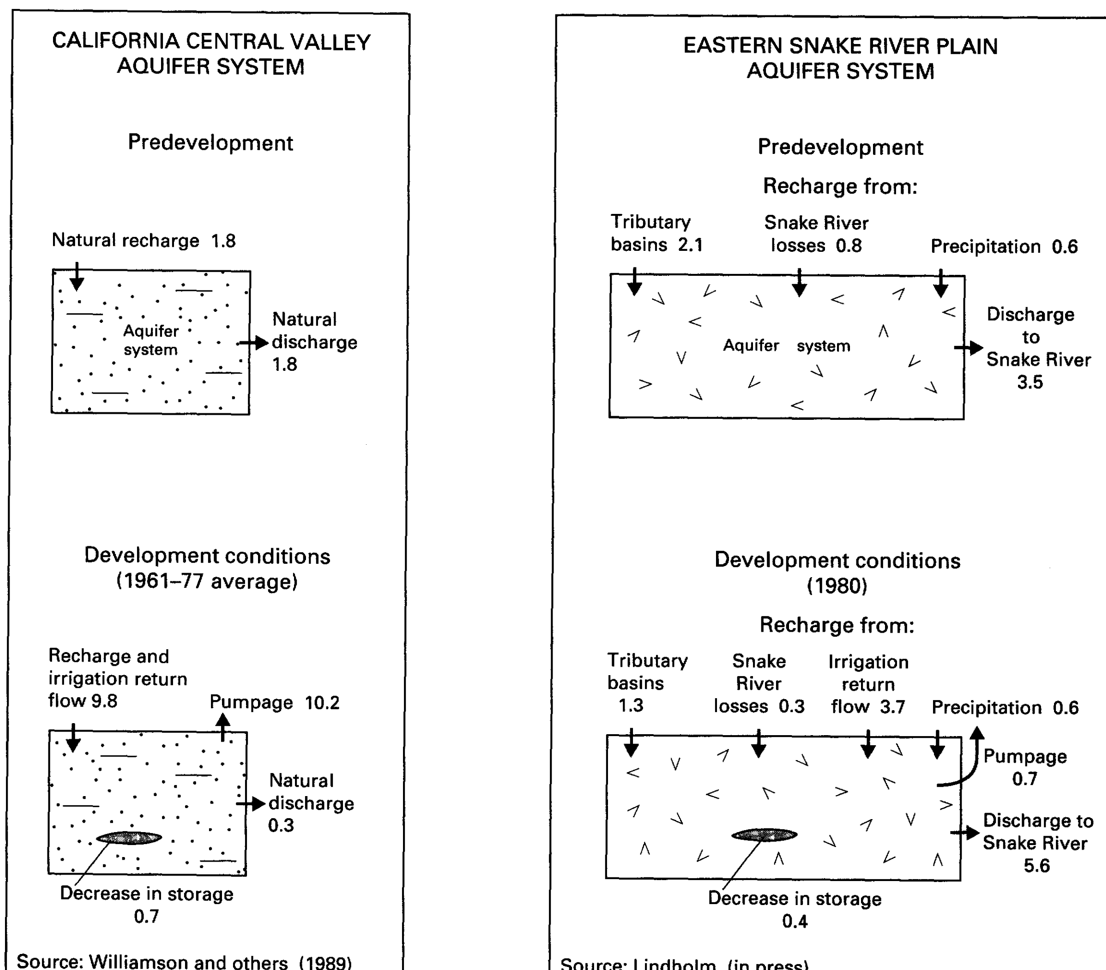


Figure 14. Ground-water budgets before and after development of two major aquifer systems in the Western United States (values in billion gallons per day).

removed from storage until equilibrium is reached or the cone of depression reaches a recharge or discharge boundary. An increase in recharge or a decrease in discharge (or a combination of both) then occurs until sufficient water is obtained to sustain the pumping rate. Thereafter, the growth of the cone of depression ceases. If a cone of depression does not reach either a recharge or discharge boundary, more and more water is removed from aquifer storage and ground-water levels continue to lower until equilibrium is reached. Therefore, one of the major effects of development in arid and semiarid areas is water-level declines due to pumping. Development effects commonly associated with water-level decline in various types of geologic terrains are land subsidence, creation of surface earth fissures, induced collapse of sinkholes, and saline-water intrusion. The RASA Program evaluates these effects using computer-based model simulations. The following are the principal effects of ground-water development:

1. Changes in water levels—The degree of water-level change differs in unconfined (water-table) aquifers and confined (artesian) aquifers. In unconfined aquifers, the standing water level is a water table which is at atmospheric pressure. In confined aquifers, however, water in the aquifer is under pressure greater than atmospheric. In wells tapping a confined aquifer, the water level in a well is always higher than, or equal to, the top of the aquifer. In a water-table aquifer, the hydraulic gradient formed around a pumped well is due to the removal of water from aquifer storage; the hydraulic gradient is generally steeper than in a confined aquifer. Hydraulic gradients around a pumped well in a confined aquifer are due principally to release of water resulting from compression of the aquifer material and expansion of water as a result of the reduced pressure. The propagation of a pressure wave in a confined aquifer occurs very rapidly and extends far from the pumping well. Therefore, the volume of water released from the expansion of water and compaction of the aquifer in response to the reduction in pressure is sufficient to sustain the pumping rate because the cone of depression extends over a very large area. The result is creation of a gentle hydraulic gradient in contrast to the steep gradient caused by a well tapping a water-table aquifer with the same pumping rate. The cone of depression surrounding a pumped well in a confined aquifer is much larger than that around a well in a water-table aquifer. Conversely, the slope of a hydraulic gradient formed by a well in a confined aquifer is much gentler than that of a well tapping a water-table aquifer.

The lateral growth of a cone of depression stops when it reaches a recharge or discharge boundary. For example, in areas with unconfined aquifers and perennial streams, when the cone of depression reaches a stream, water will be supplied to a well by a reduction in ground-water discharge to the stream, by induced infiltration into the aquifer from the stream, or by a combination of these processes. In time, a new equilibrium will be reached and growth of the cone of depression stops. Under seasonal pumping conditions, such as irrigation, all or some of the water removed from aquifer storage during the pumping season is replenished by precipitation during a wet season. If the amount of precipitation is greater than the evapotranspiration, the water level generally recovers after cessation of pumping to the prepumping level. However, in arid or semiarid areas, the amount of precipitation generally is less than potential evapotranspiration and water levels that decline during the pumping season generally do not recover to prepumping levels. Therefore, depending upon the degree of stress, water levels in aquifers in arid and semiarid areas become lower from one pumping season to another. Continued water-level decline due to pumping eventually reduces the saturated thickness of the aquifer and ultimately decreases the yield of wells. Uncontrolled development of ground water in such areas can lead to many dry wells and ultimately could result in the aquifer being unusable. For example, in Floyd County, Texas, pumping for irrigation has resulted in a significant water-level decline and reduction of the saturated thickness in the High Plains aquifer (fig. 15). The consequence of this reduction of saturated thickness has been a large reduction in the number of acres that can be irrigated by a well (fig. 16).

Irrigation not only causes water levels to decline near pumping wells, but occasionally it causes water levels to rise. Most of the water-level rises result from excessive irrigation by imported surface water. For example, in the eastern Snake River Plain, millions of acre-feet of surface water have been diverted annually for irrigation since irrigation started in the 1880's. In one area south of the

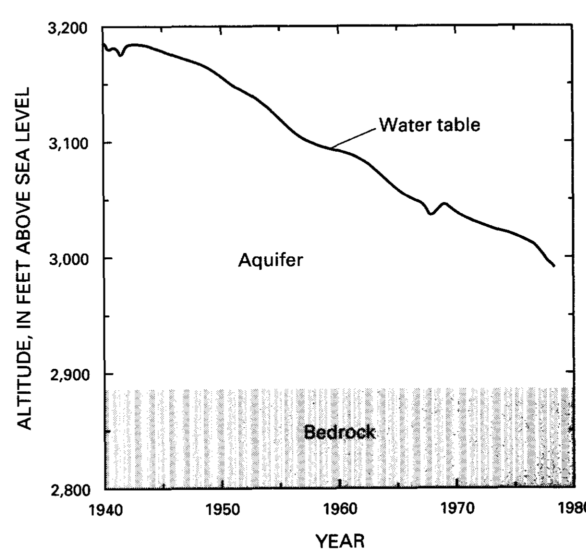


Figure 15. Water-level decline in the High Plains aquifer in Floyd County, Texas, due to irrigation pumping (from Luckey and others, 1981).

Snake River near Twin Falls, Idaho, ground-water levels rose as much as 200 ft in 5 yr after the start of irrigation (Lindholm, 1986). As water levels rose, ground-water discharge as springflow to the Snake River increased. A long-term trend of increase in ground-water discharge to the Snake River from the early 1900's to 1950 occurred in the reach from Milner to King Hill, whereas discharge to the upstream reach from Blackfoot to Neely remained relatively constant (fig. 17). In the early 1950's, ground-water discharge to the Milner to King Hill reach stabilized, indicating the creation of a balance between recharge and discharge. A period of general decrease in ground-water discharge followed and continued to 1980. This decrease probably was due to a combination of increased withdrawals of ground-water for irrigation, decreased surface-water diversions for irrigation, and increased irrigation efficiency. Climatological changes may also be one of the causes of the decrease, but this effect probably is negligible.

Rises of ground-water levels also can be caused by increases in recharge following the removal of vegetation or less permeable materials covering the land surface. In parts of Dawson and Lynn Counties in Texas, rises of ground-water levels in the High Plains aquifer (fig. 18) were attributed to clearing sandy soils of native vegetation for cultivation. The increased rate of recharge from precipitation on dryland crop areas resulted in water-level rises (Luckey and others, 1981).

In summary, land use and ground-water development can cause ground-water levels either to decline or to rise

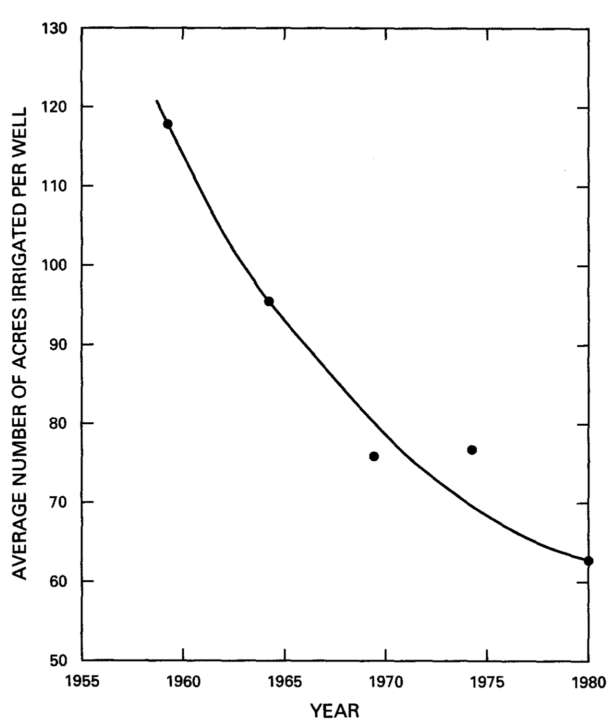


Figure 16. Decline of irrigated acreage per well due to reduction in saturated thickness of the High Plains aquifer in parts of Castro, Brosby, Floyd, Hale, Lubbock, Parmer, and Swisher Counties, Texas (from Luckey and others, 1981).

depending on whether development is accompanied by (1) an increase in ground-water withdrawals, (2) an increase in recharge by irrigation return flow using imported surface water, or (3) an increase in recharge by precipitation due to removing less permeable soil or vegetation.

2. Changes in recharge and discharge—As discussed above, land use and ground-water development affect water levels in aquifers, and such effects alter the characteristics of recharge and discharge from predevelopment conditions. In general, increases in ground-water withdrawals will result in increases in recharge rates and the size of recharge areas due to areally lowering water levels in aquifers. Conversely, withdrawals will decrease discharge rates and the size of discharge areas. For example, estimated predevelopment discharge from the Upper Floridan aquifer occurred mostly at springs and to surface-water bodies (about 80 to 90 percent of recharge); very little ground water was discharged as upward leakage through confining units and laterally to the sea (fig. 19). However, under 1980 conditions with pumpage of 4,170 ft^3/s (about 3 Bgal/d), simulation indicated that most of the pumpage was balanced by an increase in recharge (60 percent of the pumpage) and by a reduction in natural discharge (40 percent of pumpage) (see fig. 20). Simulation results also indicated that the total recharge area expanded from 67,000 mi^2 before development to 76,000 mi^2 in 1980, and that some former discharge areas under predevelopment conditions became recharge areas under 1980 pumping conditions. There has been almost no decrease in aquifer storage.

In semiarid areas where annual precipitation is less than annual potential evapotranspiration, recharge is insufficient to replenish the water removed from aquifer storage. Water-level declines due to pumping become permanent, resulting in a decrease in saturated thickness of aquifer materials. For example, in the High Plains aquifer, a comparison of predevelopment conditions with 1980 pumping conditions indicates that saturated thickness has been reduced by more than 10 percent over an area of about 44,000 mi^2, which is about 25 percent of the areal extent of the aquifer. More than 25 percent reduction in saturated thickness has occurred over an area of 14,000 mi^2 (Weeks and others, 1988). Today, the High Plains area is still experiencing water-level declines locally. From 1980 through 1989, water levels declined more than 15 ft in areas of intensive irrigation in Kansas, New Mexico, Oklahoma, Colorado, and Texas. A large area in northeastern Colorado and southwestern Nebraska is characterized by 7 to 15 ft of water-level decline. In the remaining area of the High Plains aquifer, water levels have either remained stable or risen slightly (Dugan and others, 1990). Except in intensive irrigation areas, the High Plains aquifer is not being extensively dewatered at present.

In summary, in humid areas there generally is sufficient precipitation to replenish the water removed from aquifer storage, and sufficient natural ground-water discharge

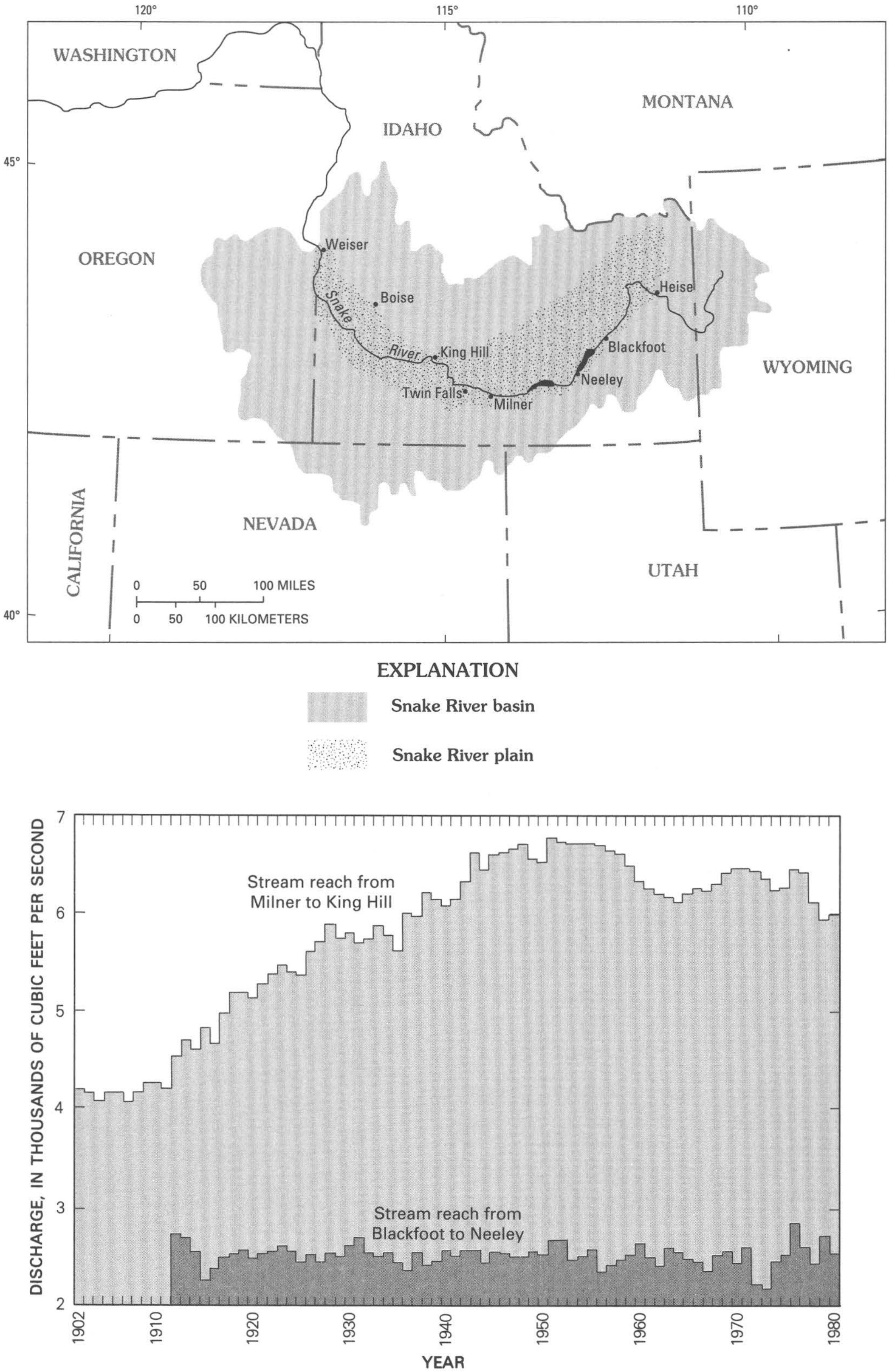


Figure 17. Changes in ground-water discharge to the Snake River due primarily to changes in irrigation with surface water in eastern Snake River Plain, Idaho (from Lindholm, 1986).

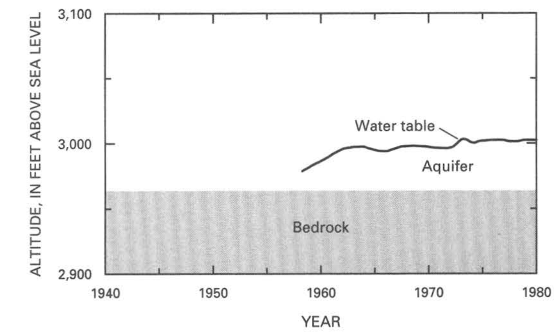


Figure 18. Rises of the water table in parts of Dawson and Lynn Counties, Texas, due to clearing sandy soils of native vegetation for cultivation (from Luckey and others, 1981)

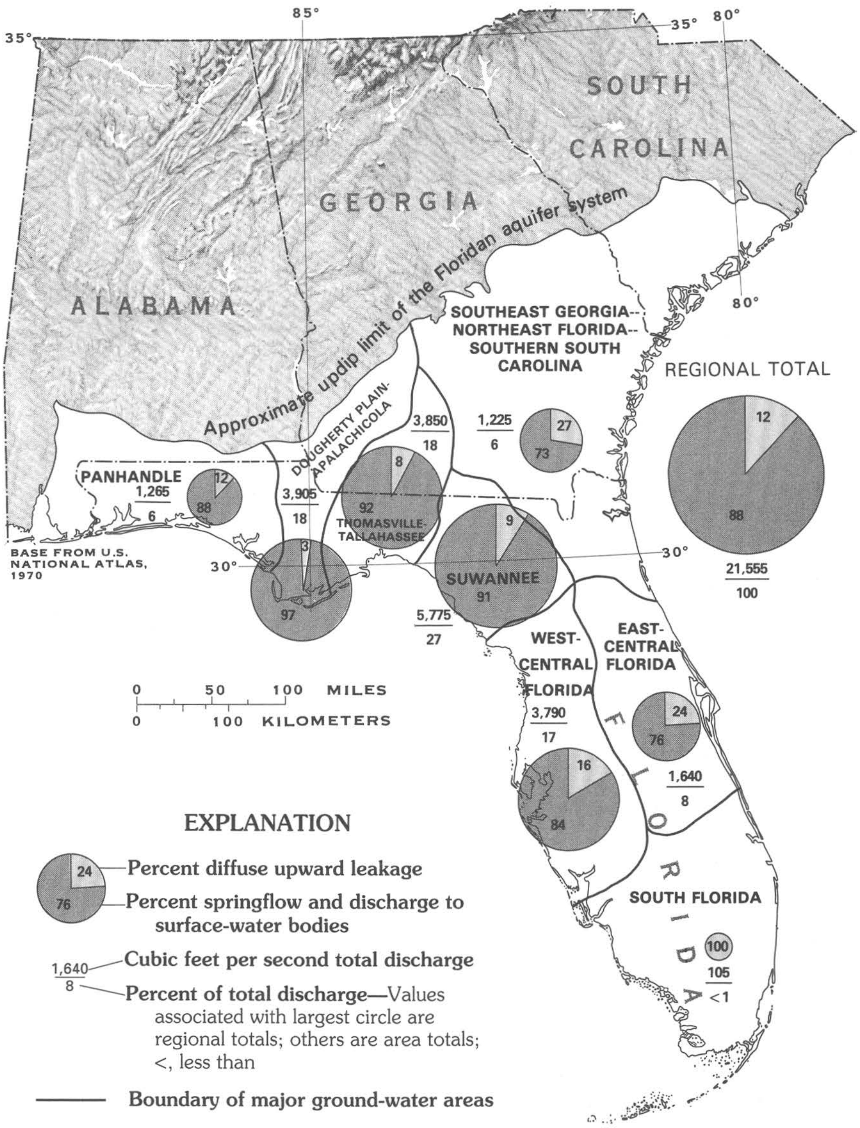


Figure 19. Estimated predevelopment discharge from the Upper Floridan aquifer (from Johnston and Bush, 1988).

can be diverted to sustain ground-water withdrawals. Therefore, the effects of development on aquifer systems are generally an increase in the size of recharge areas that results in an increase of total recharge, a decrease in natural ground-water discharge, or a combination of both. However, in arid and semiarid areas, an adverse effect of development can be reduction in saturated thickness of aquifers. Under severe conditions of dewatering, this can destroy the usage of parts of the aquifers.

3. Land subsidence—Another effect of ground-water development is subsidence of the land surface due to lowering of ground-water levels. Land subsidence has occurred in several areas, most notably in the Central Valley of California and in Houston, Texas. The principal cause of land subsidence is compaction of fine-grained aquifer materials (clay and silt). Compaction results from an increase of overburden pressure when the hydraulic head (or water level) in an aquifer is lowered by pumping. The mechanics of land subsidence due to compaction of aquifer materials is complex and difficult to explain. There are two ranges of compressibility. One is elastic compressibility, similar to that of a rubber ball. If the ball is squeezed, the ball will deform; however, the ball will return to its original shape if pressure is released. In contrast, inelastic

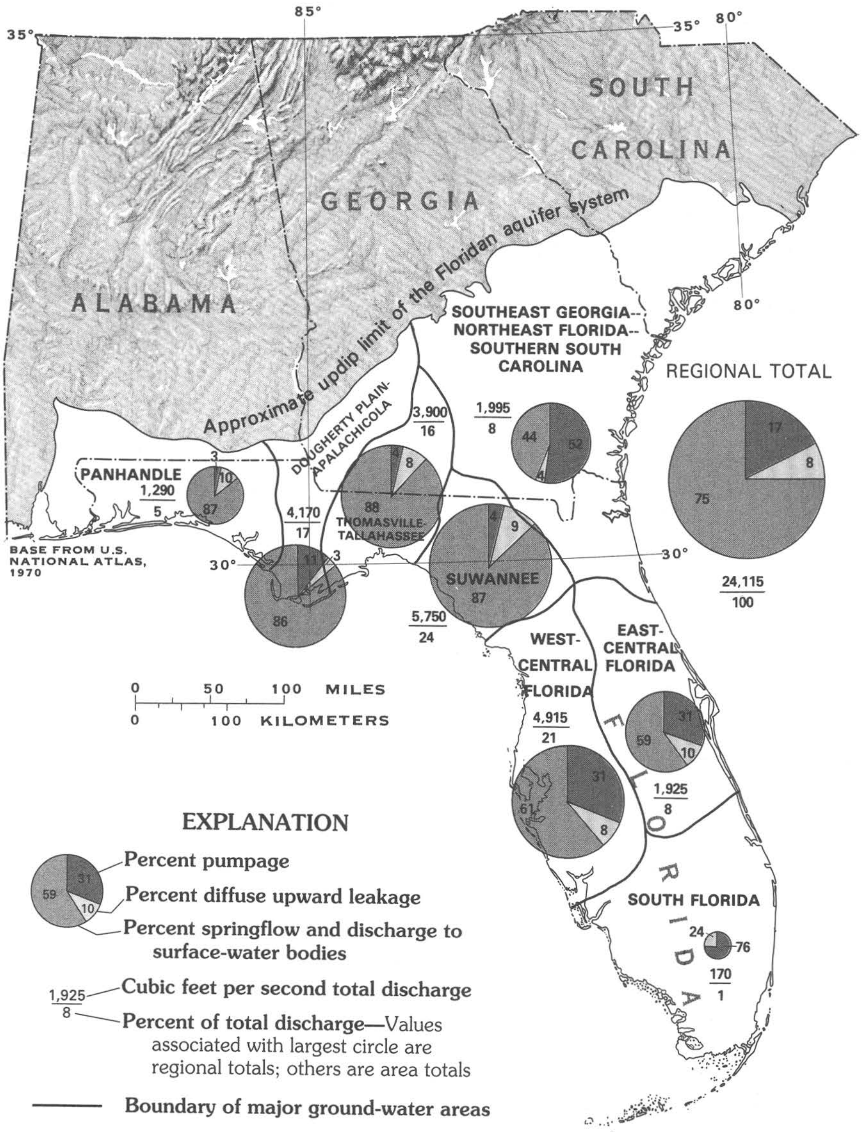


Figure 20. Estimated 1980 discharge from the Upper Floridan aquifer (from Johnston and Bush, 1988).

compression is similar to that of a clay ball, which, if squeezed, may rebound to some degree after pressure is released; however, the clay ball will never return to its original form. Compaction of fine-grained materials having high compressibility in an aquifer progresses slowly. On the basis of many years of field investigation on land subsidence, it was concluded that the ratio of land subsidence to water-level decline in an aquifer system is small until the water-level declines below a critical value (termed a preconsolidation level). Then the ratio of land subsidence to water-level decline will increase to a large constant value. When the water level decline is less than a critical value (preconsolidation level), the compaction is elastic and the small amount of land subsidence will rebound after the water level in the aquifer rises. However, when the water level declines below the preconsolidation level, the compression is inelastic, the amount of land subsidence is proportional to the water-level decline, and subsidence is permanent and nonrecoverable. The amount of water released from aquifer storage under the elastic condition is derived from the expansion of water and elastic compression of aquifer materials, which is much smaller than the amount of water released from inelastic compression of the aquifer materials. Under inelastic compaction, water is released from pores that are decreased in size by compaction.

In seasonal pumping areas, ground-water levels recover and compaction of the aquifer materials ceases when pumping stops. During the next pumping season, the decline of water levels due to pumping initially causes elastic compaction. Inelastic compaction will not occur until water levels are lowered below a critical value, as shown in figure 21. In reality, land subsidence is not as simple as illustrated in figure 21 because of a time lag during which lowering of water levels in fine-grained beds lags behind the lowering of water levels in permeable beds. However, the general concept of elastic and inelastic compaction in relation to hydraulic head declines is illustrated by figure 21.

Land subsidence is detected by comparison of the altitudes of a benchmark after several precise leveling surveys. Land subsidence in the San Joaquin Valley of California was discovered in the mid-1920's; subsidence continued until the late 1960's. Beginning in 1968, surface water was imported to the valley through canals and aqueducts to replace ground water as the major source of irrigation water, and subsidence stopped shortly thereafter. The areal extent of land subsidence in the Central Valley of California that exceeded 1 ft is shown in figure 22.

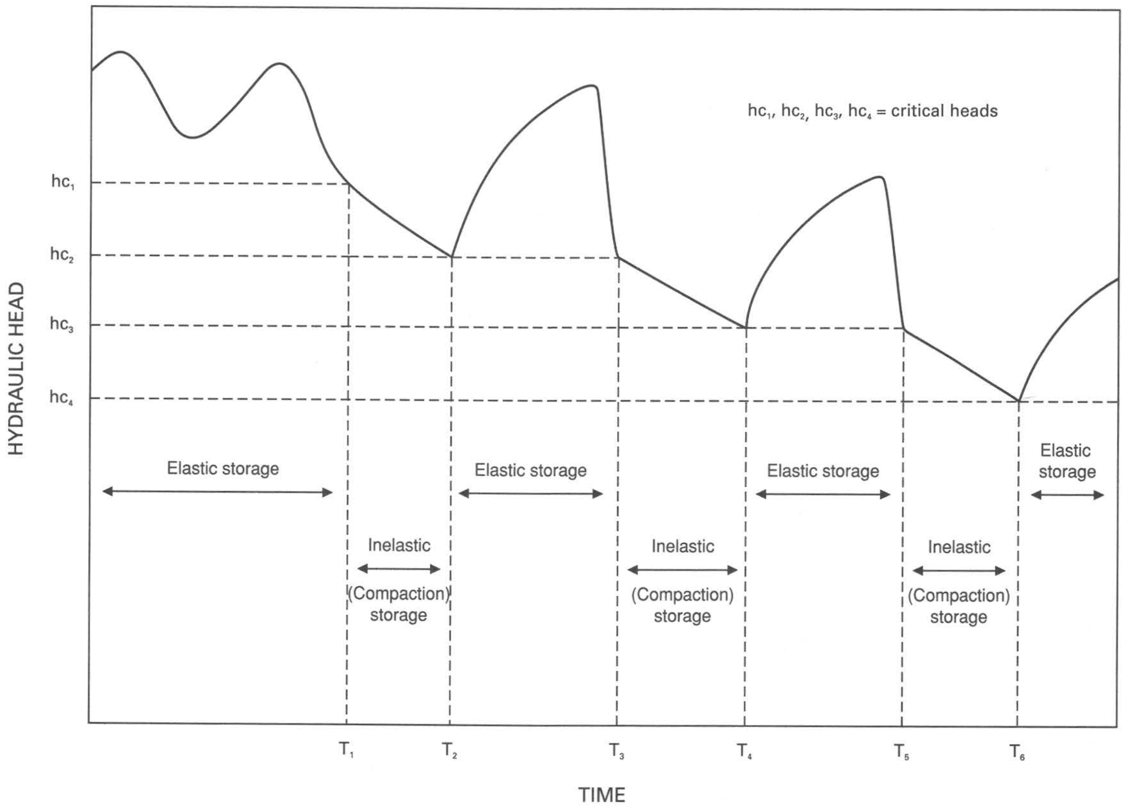
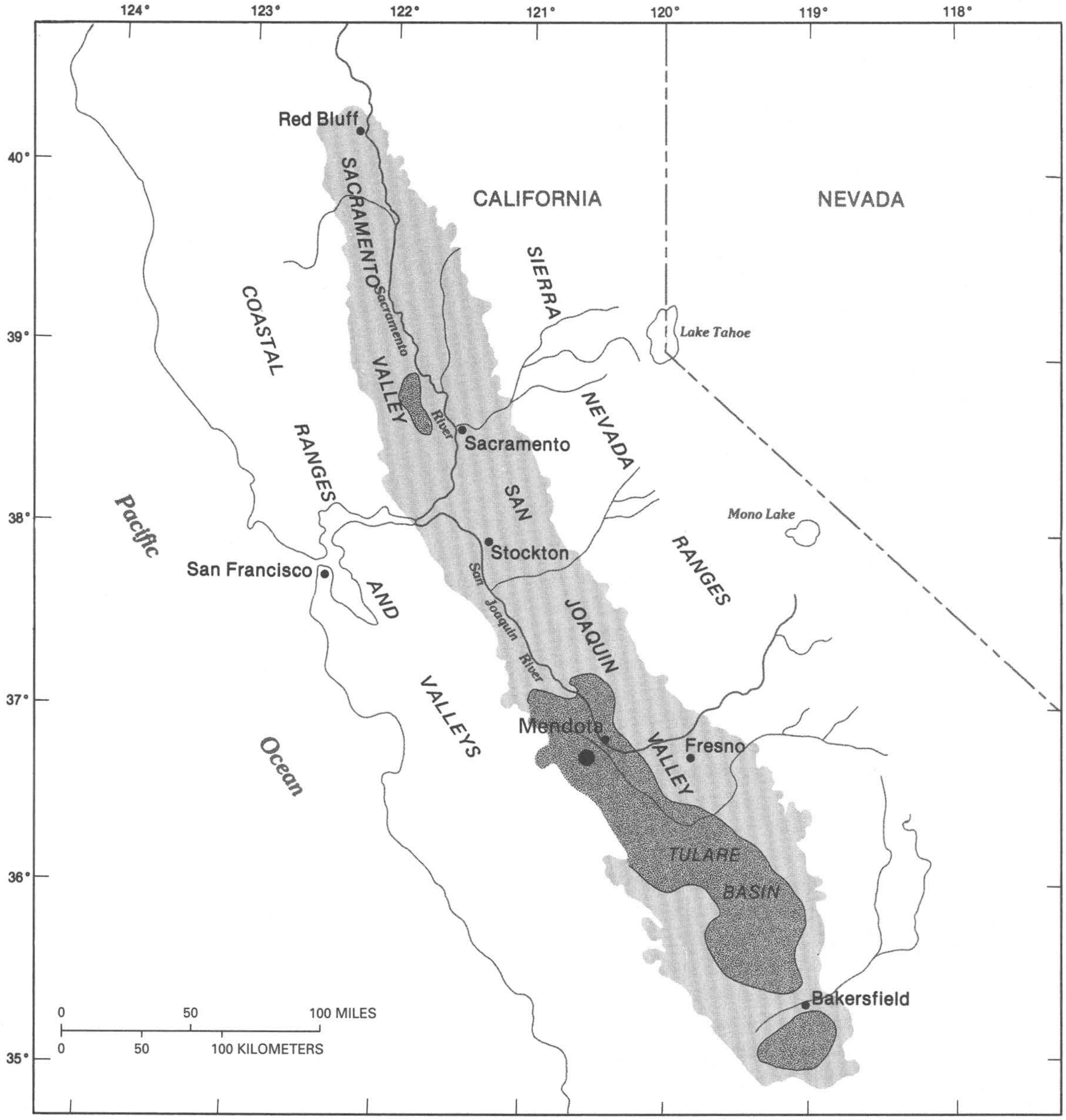


Figure 21. Relation of hydraulic heads and storage in a compacting aquifer system (modified from Williamson and others, 1989).

Maximum subsidence was nearly 30 ft in 1977 at a benchmark 10 mi southwest of Mendota in the Los Banos–Kettleman City area. The reconstructed land surface altitudes surveyed in 1925, 1955, and 1977 are shown in figure 23 (Ireland and others, 1984). This magnitude of land subsidence is not as spectacular in the field as in the picture because subsidence progressed over tens of years and spread over thousands of square miles. However, subsidence has created engineering and economic problems, including failure of well casings and cracking and loss of carrying



EXPLANATION

Study area

Area where land subsidence exceeded 1 foot caused primarily by ground-water pumpage

● Location of site southwest of Mendota shown in figure 23

Figure 22. Land subsidence in the Central Valley, California, 1926–70 (modified from Williamson and others, 1989).

capacity of irrigation and drainage canals. If land subsidence occurs in small basins surrounded by bedrock, earth fissures may be created. These earth fissures initially are tiny cracks that are enlarged by erosion and eventually become large crevasses (fig. 24). Such earth fissures have developed in Arizona and other places.

4. Sinkhole collapse—In carbonate rock terrains, the development of solution features ranging from widened fractures and joints to large caves and sinkholes is a natural erosional process. Exposed carbonate rocks or carbonate rocks covered with thin unconsolidated sediments can easily develop networks of solution channels. Ground water generally flows along paths of least resistance; therefore, solution channels are developed more readily along bedding planes, joints, and fractures. As solution channels along joints are enlarged and more and more carbonate rock is dissolved, large features such as caves, chimneys, and sinkholes are formed. Sinkholes have been defined as "closed depressions in the land surface that are formed by solution of near-surface limestone and similar rocks and by subsidence or collapse of overlying surficial material into underlying solution cavities" (Beck and Sinclair, 1986). In outcrop areas of carbonate rocks, sinkholes can be seen at the surface. However, where the carbonate rocks are covered by unconsolidated sediment, sinkholes are concealed by sediments that can collapse under certain conditions. After collapse of a sinkhole, either a large hole develops or a depression is formed at the surface. Collapse of sinkholes either can progress slowly for many years, or can occur suddenly. One trigger of sinkhole collapse is lowering or fluctuation of water levels due to pumping from wells. Before pumping from wells is initiated, unconsolidated sediments overlying enlarged solution channels are supported by the static pressure of water in the aquifer. After water levels decline due to pumping, the static pressure that supports the unconsolidated sediments is reduced. A close relation between initiation of pumping or increases in pumping from high-capacity wells tapping the Floridan aquifer system and collapse of nearby sinkholes has been described by Sinclair (1982).

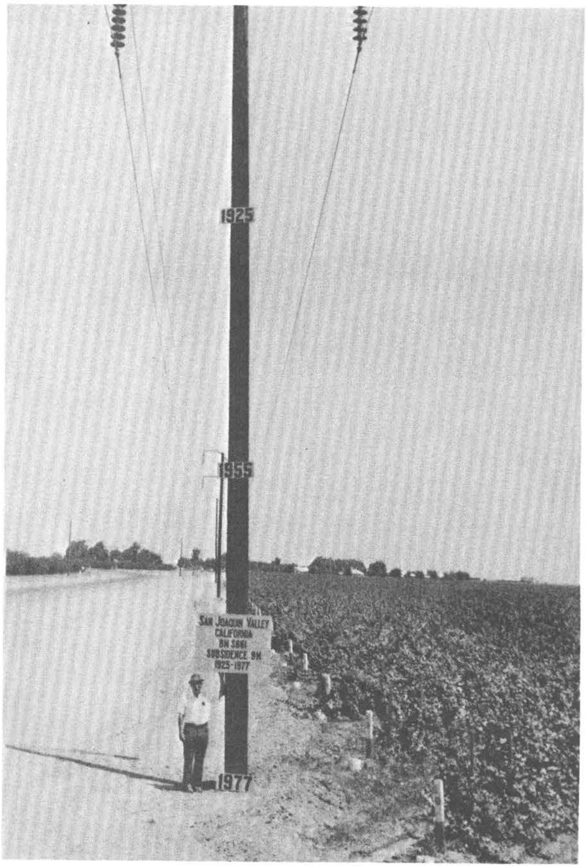


Figure 23. Observed land subsidence of approximately 29 ft at a surveying benchmark, 10 mi southwest of Mendota in the San Joaquin Valley, California (from Ireland and others, 1984).

Collapse of sinkholes can occur within days, even hours. A well-known and spectacular collapse of land surface to form a sinkhole occurred at Winter Park, Florida, in 1981 (fig. 25). In general, sinkholes were not a focus of RASA investigations because they are primarily local phenomena. However, results of RASA studies, particularly the data sets developed for ground-water flow models, can be useful in studying local sinkhole problems. For example, the St. Johns River Water Management District of Florida used such data sets to develop a flow model of the Floridan aquifer system in an area where sinkholes are common. One purpose of the model was to evaluate the effects of heavy pumping during overnight periods of freezing weather on the potential for sinkhole development.

5. Saltwater intrusion—Pumping of ground water in coastal areas or areas underlain by brackish or saltwater can create the potential for saltwater contamination. However, whether or not encroachment of saltwater actually occurs depends primarily on two factors: (1) the permeability of rocks separating the pumped wells and the saltwater body, and (2) the direction and magnitude of hydraulic gradients in these rocks. Generally, unconfined aquifers are more susceptible to saltwater contamination than are confined aquifers because: (1) unconfined aquifers lack the protective cover of a low-permeability confining bed, and (2) the low hydraulic heads common to coastal areas preclude the existence of a thick freshwater section and the presence of freshwater in the aquifer offshore.

Many studies of local instances of saltwater encroachment have been conducted in the Nation's coastal areas. However, because the RASA Program has focused on regional hydrology and regional water problems, investigations of saltwater contamination were limited to problems of regional importance. Two such investigations are as follows: (1) Simulation of saltwater intrusion on Hilton Head Island, South Carolina, due to the existence of a regional cone of depression in the Upper Floridan aquifer

Figure 24. Earth fissures enlarged by erosion, near Apache Junction, central Arizona (courtesy of Robert L. Laney, USGS).

Figure 25. Collapse of land surface due to formation of a sinkhole at Winter Park, Florida, in 1981. (Photograph courtesy of Jamal and Associates, Orlando, Florida.)

centered around Savannah, Georgia (Bush, 1988), and (2) Simulation of freshwater and saltwater movement in the most heavily pumped aquifer in Hawaii, which is termed the "Honolulu–Pearl Harbor basal water body" (Souza and Voss, 1986).

APPLICATION OF REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM INFORMATION

The results of the Regional Aquifer-System Analysis Program can be used or have been used in a variety of ways. A few examples are presented here to illustrate applications of the RASA study findings:

1. Ground Water Atlas of the United States—Prior to RASA, no detailed maps provided complete nationwide coverage of ground-water conditions at a regional scale. One previously published map that shows the major aquifers nationwide and withdrawals from wells at a scale of 1:7,500,000 was included in the National Atlas of the United States of America (U.S. Geological Survey, 1970, p. 122–123). Brief discussions of ground-water conditions in different regions have been presented by Heath (1984), and Back and others (1988). There was a need for a detailed ground-water atlas that could serve as a basic reference on the location, geology, hydrology, and water quality of the Nation's major aquifers. The vast amount of data resulting from the RASA studies, together with previously published information, provided the information needed to compile regional-scale maps showing ground-water conditions of the United States. These maps and explanatory text are currently being compiled into the National Ground Water Atlas by the U.S. Geological Survey as part of the RASA Program.

2. Planning and development of ground-water resources—An important task in the planning and development of ground-water supplies is to identify areas where development can proceed without causing adverse effects. Although some regional aquifers have large quantities of freshwater remaining for development, parts of the aquifers should be avoided because of poor water quality, large current withdrawals and accompanying regional water-level declines, or poor water-transmitting properties and thus low well yields. Such problem areas are identified and described in RASA reports. For ease and use by planners, some RASA reports provide regional aquifer maps showing possible future declines in water levels and well yields based on simulation of different water-management strategies. For example, such maps are presented for the High Plains aquifer by Luckey and others (1988). Some RASA reports include maps showing potentially favorable areas for development of large ground-water supplies. For example, a map showing highly favorable areas for development of the Upper Floridan aquifer based primarily on minimizing head decline and thereby reducing the likelihood of water-quality deterioration is presented by Bush and Johnston (1988, pl. 17). Maps showing potentially favorable areas for constructing wells that would yield more than 500 gal/min in the Madison Limestone and Red River Formation (Northern Great Plains) are presented by MacCary and others (1983).

Regional and subregional flow models constructed during the RASA studies can be used to estimate the impact of hypothetical pumpage rates on aquifer systems. For more detailed studies, local flow models can be constructed on the basis of the regional or subregional flow models and supplemented with additional information. The regional or subregional model can also be used to determine the appropriate boundary conditions to use for local flow models.

In the southern High Plains, pumpage exceeds the natural recharge rate by more than 30 times (fig. 13), and most pumpage is supplied by depletion of aquifer storage. Under such conditions, withdrawals need to be carefully managed to prevent pumping water levels in wells from declining to depths near the bottom of wells, making the wells unusable. In areas with low recharge and high pumpage, such as the High Plains of Texas, water managers need to consider pumping rates, pumping times, and areal distribution of wells, so that water-level declines due to pumping will not cause wells to go dry. Such planning can be aided by the use of model simulations. Calibrated models developed during the High Plains RASA study were used to project future water levels that would result from various water management strategies. Maps showing projected water-level declines, changes in saturated thickness, and probable well yields are presented by Luckey and others (1988).

As discussed in the previous section, a serious side effect of large declines in ground-water levels is subsidence of the land surface. Land subsidence can cause engineering problems, including cracking of irrigation and drainage systems and failure of well casings. In low-altitude coastal or estuarine areas, land subsidence can cause dry land to become swampy or submerged by seawater, as has happened in the Houston area, Texas. Land subsidence is caused by large declines in water level in aquifer systems confined by thick units made up of fine-grained sediments. However, not all such aquifer systems are subject to land subsidence; only those confining units consisting of fine-grained materials that have a high compression index (such as montmorillonite clay) are likely to cause land subsidence if ground water is extensively pumped. If highly compressive materials are present within thick confining units, water managers should consider using land-subsidence models developed by the RASA Program to evaluate whether land subsidence will be triggered by proposed pumping. Such models can indicate withdrawal rates and pumping durations that will not result in irreversible damage to an area.

3. Planning drought-resistant water-supply systems—Droughts are natural occurrences. It is impossible to prevent a drought; however, with proper planning, the problems caused by a drought can be minimized. Water managers can use RASA information to plan drought-resistant alternatives. For example, along the California aqueducts that supply the Central Valley with surface water, a series of wells could be drilled. During wet seasons, these wells could be used as recharge wells to raise water levels in the aquifers. During droughts, the wells could be pumped to supplement surface-water deliveries in the aqueducts. Results of model simulation described in many RASA reports should be useful in planning management alternatives during droughts.

4. RASA information has been used and disseminated by scientific institutions—Much of the information resulting from the RASA Program will not be published by the U.S. Geological Survey for many years. As an expedient method of providing timely release of information, the American Water Resources Association (AWRA) in 1985 initiated a series of conferences and symposiums in different parts of the country to discuss regional aquifer systems in the United States based on findings of the RASA Program. Almost all papers presented in the symposia were authored by RASA investigators. As of mid-1992, eight symposia have been held and the papers have been published in the AWRA monograph series. The published monographs are: (1) Southwest Alluvial Basins of Arizona (Anderson and Johnson, 1986); (2) Aquifers of the Atlantic and Gulf Coastal Plain (Vecchioli and Johnson, 1987); (3) The Northeast Glacial Aquifers (Randall and Johnson, 1988); (4) Aquifers of the Midwestern Area (Swain and Johnson, 1989); (5) Aquifers of the Caribbean Islands (Gomez-Gomez and others, 1991); (6) Aquifers of the Western Mountain Area (McLean and Johnson, 1988); (7) Aquifers of the Far West (Prince and Johnson, 1992); and (8) Aquifers of the Southern and Eastern United States (Hotchkiss and Johnson, 1992). In addition to the publication of RASA findings by AWRA, 20 RASA investigators were invited to prepare regional descriptions for the volume on hydrogeology that is part of the Decade of North American Geology series of the Geological Society of America (Back and others, 1988). Special facets of the RASA studies are also described in numerous articles appearing in the various hydrologic, geologic, and geochemical journals.

5. RASA information has been used directly in the management of ground-water resources—The following examples illustrate how RASA information was used for management of ground-water resources: (1) the New Jersey part of a regional flow model developed for the Atlantic Coastal Plain was used to manage a coastal-plain aquifer in New Jersey in designated critical development areas, (2) relations between waste-disposal sites and well locations were evaluated using the RASA information in South Carolina, (3) the Internal Revenue Service and the Federal Land Bank used the High Plains RASA results to evaluate tax depletion allowances and to appraise farmlands, (4) Idaho water agencies used the information resulting from the Snake River Plain RASA study in negotiations of water rights between irrigators and hydropower-generating companies, (5) Snake River Plain RASA results also were used to help develop Idaho's ground-water-quality management plan, and (6) The Water Management Districts of Florida have used data sets from RASA models of the Floridan aquifer system to develop local models for evaluating the effects of ground-water withdrawals on lake levels and on potential sinkhole development.

PART II. STATUS OF THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

A short summary of the individual RASA studies is given in this section of the report. The studies are grouped into three categories relative to the status of progress as of mid-1992. The three categories are fully completed, completed, and ongoing. The fully completed studies have all reports printed or approved for release to the public and preparation of the manuscripts for printing was in progress as of mid-1992. The completed studies have finished data compilation and investigative activities, have printed many reports, and final reports are either in review or in preparation. The ongoing studies have data compilation and investigative activities in progress and may have only a few reports printed as of mid-1992.

FULLY COMPLETED REGIONAL AQUIFER-SYSTEM ANALYSIS STUDIES

The six regional studies that were fully completed as of mid-1992 are summarized in this part of the report. The studies are: the Floridan aquifer system, the High Plains, the Northern Atlantic Coastal Plain, the Northern Great Plains, the Southeastern Coastal Plain, and the Southwest alluvial basins.

FLORIDAN AQUIFER SYSTEM

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, southern Georgia, and small parts of the adjacent States of Alabama and South Carolina, a total area of about 100,000 mi^2 (fig. 26). Pumpage from the Floridan has increased steadily in recent years, from about 0.63 Bgal/d in 1950 to about 3.5 Bgal/d in 1985. In many areas, the Floridan is the sole source of freshwater.

The Floridan is a thick sequence of carbonate rocks that are mostly of late Paleocene to early Miocene age and that are hydraulically connected in varying degrees (Miller, 1986). The rocks vary in thickness from a featheredge where they crop out to more than 3,500 ft where the aquifer is deeply buried in southwestern Florida. The aquifer system generally consists of an upper aquifer and a lower aquifer, separated by a regional confining unit of highly variable hydraulic properties. Low-permeability clastic rocks overlie much of the Floridan aquifer system, and these rocks have a controlling effect on the development of permeability and ground-water flow in the Floridan.

The Floridan derives its permeability from water-bearing openings that range from small openings in loosely cemented fossil hashes to large cavernous openings in karst areas. For the Upper Floridan aquifer, the transmissivity is highest (greater than 1 million ft^2/d) in the unconfined karst area of central and northern Florida. The lowest transmissivity (less than 50,000 ft^2/d) occurs in the Florida panhandle and southernmost Florida, where the Upper Floridan aquifer is confined by thick clay sections.

High rainfall (averaging 53 in/yr) combined with generally flat topography provides abundant recharge to the Floridan. The dominant feature of the Floridan flow system,

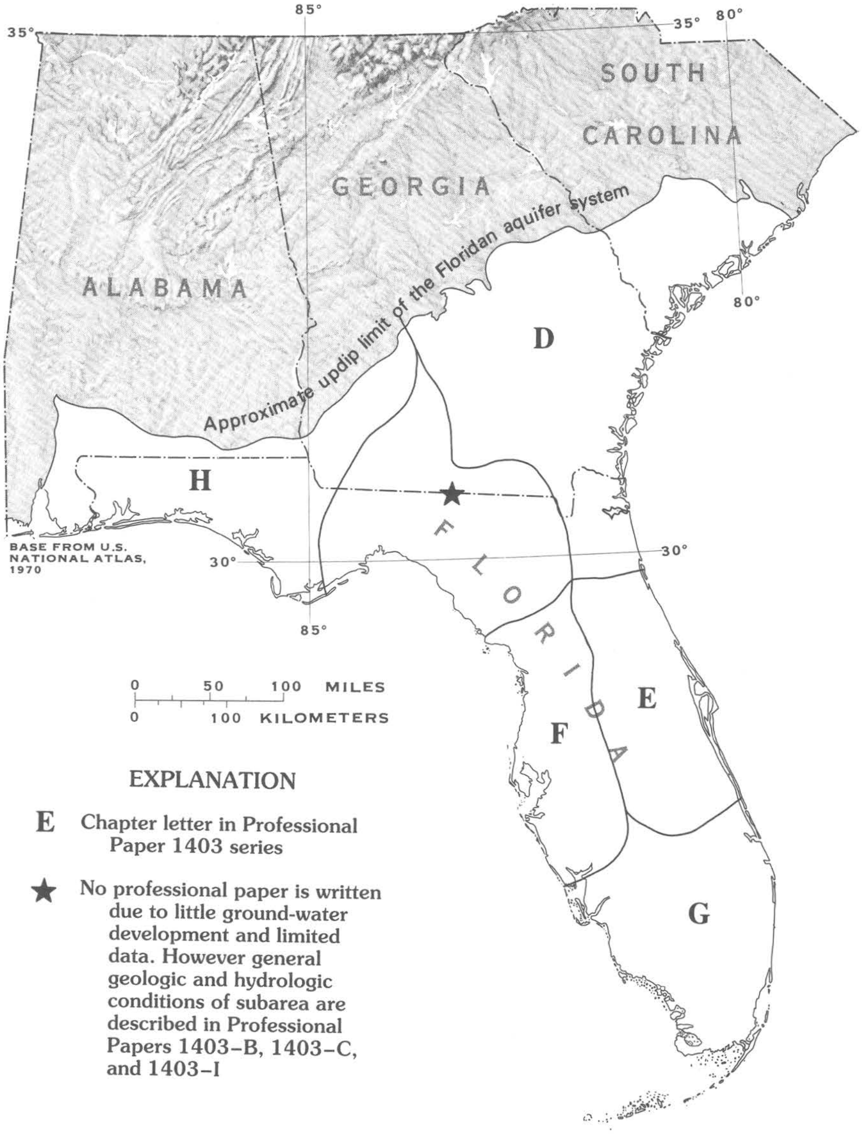


Figure 26. Extent of the Floridan aquifer system and subareas with descriptions of ground-water hydrology in U.S. Geological Survey Professional Papers 1403–D through 1403–H (from Johnston and Bush, 1988).

both before and after development, is spring discharge from the Upper Floridan aquifer. Most of the recharge necessary to sustain discharge to springs or streams and lakes occurs relatively close to the springs and surface-water bodies.

The 1980 pumpage (about 20 percent of the predevelopment recharge rate) is supplied primarily by induced recharge and diversion of natural discharge rather than loss of aquifer storage (Bush and Johnston, 1988). Withdrawal of 3 to 3.5 Bgal/d in recent years has not greatly affected the ground-water budget of the Floridan, as can be seen in figure 12 and discussed in the earlier section on regional ground-water budgets. However, pumpage has caused long-term head declines of more than 10 ft across three broad areas, and locally there are a few deep cones of depression where heads have declined more than 100 ft.

Water chemistry in the Upper Floridan aquifer is related to the flow system and proximity to the freshwater-saltwater interface. Generally, dissolved-solids concentrations are low (less than 250 mg/L) in the unconfined or semiconfined areas where flow is vigorous, and the concentrations are higher where the Floridan is thickly confined and flow is more sluggish, especially in coastal areas.

Large quantities of ground water are available from the Floridan aquifer system for future development. An appraisal of potentially favorable areas for large ground-water withdrawals is presented by Bush and Johnston (1988), which is based primarily on minimizing head decline and thereby reducing the chances of water-quality deterioration. The favorable areas are largely inland and characterized by high transmissivity and minimal development as of the early 1980's.

Several important contributions to understanding the Floridan aquifer system were provided by the Floridan RASA study including the following:

1. The first comprehensive geologic description of the Floridan aquifer system, including definition of its component aquifers and confining units and their relation to previously defined rock and chronostratigraphic units (Miller, 1986).

2. The first quantitative description of the regional flow system in the Floridan. This included the first synoptic potentiometric surface map covering the entire four-State area of the Upper Floridan aquifer and the first regional ground-water budgets for both predevelopment and development conditions (Bush and Johnston, 1988).

3. Definition of the offshore boundary of the freshwater flow system in the Floridan based on head and salinity data collected in an offshore, exploratory well 55 mi east of Fernandina Beach, Florida (Johnston and others, 1982).

4. Discovery of two large submerged springs based on a hydrologic analysis, including calibration of a ground-water flow model that indicated probable sites of ground-water discharge where the springs were subsequently found (Tibbals, 1990).

5. Support for a hypothesis (previously proposed by Kohout, 1965) of cyclic circulation in the Floridan in southern Florida was provided by new data on hydraulic heads, temperature, natural isotopes, and water chemistry obtained from a deep exploratory hole drilled as part of the RASA project. These data, together with isotope, temperature, and salinity anomalies in the Upper Floridan aquifer, suggest (1) inflow of cold seawater in the Lower Floridan from outcrops on the sea floor, (2) heating and upwelling of seawater from the Lower Floridan, and (3) mixing of the rising seawater with seaward-flowing freshwater in the Upper Floridan (Meyer, 1989).

The study of the Floridan aquifer system was started in 1978 and completed in 1986. Forty-five reports have been completed and published. The principal findings of the study are presented in nine comprehensive chapters published as U.S. Geological Survey Professional Paper 1403–A through I.

Professional Paper 1403–A (Johnston and Bush, 1988) summarizes important aspects of the hydrogeologic framework, hydraulic properties of the aquifers, regional flow system, effects of ground-water development, and geochemistry, which are described in detail in Professional Paper 1403–B through 1403–I.

Professional Paper 1403–B (Miller, 1986) presents a detailed regional description of the hydrogeologic framework of the Floridan aquifer system. The Floridan aquifer system was divided into regional aquifers and confining units that provide a generalized permeability distribution for analyzing the flow system by computer-based simulation and for relating the water chemistry to the flow system.

Professional Paper 1403–C (Bush and Johnston, 1988) discusses ground-water hydraulics, aquifer and confining-unit properties, and features of the regional flow system. On the basis of computer-based simulation, the regional flow system was described and the predevelopment flow conditions were contrasted with 1980 development conditions.

To address the ground-water hydrology in more detail, the Floridan aquifer system was divided into five subareas on the basis of predevelopment ground-water divides, which are shown in figure 26. Professional Paper 1403–D (Krause and Randolph, 1989) discusses the ground-water hydrology of the Floridan aquifer system in southeastern Georgia and adjacent parts of South Carolina and northeastern Florida. This part of the flow system is characterized by an extensive decline in artesian head due to withdrawals in a large coastal area. Differences between the relatively sluggish predevelopment flow system and the current heavily pumped system were emphasized. Various alternative development schemes for the future were evaluated by model simulation and are discussed.

Professional Paper 1403–E (Tibbals, 1990) summarizes the ground-water hydrology of the Floridan aquifer system in east-central Florida. By the late 1970's, pumpage accounted for about one-third of the aquifer discharge; however, declines in artesian head occur only in a few small areas. Computer simulation was used to evaluate predevelopment and late 1970's flow conditions and also to evaluate future increases in pumpage. The large springs and drainage wells in this area receive special attention in this chapter.

Professional Paper 1403–F (Ryder, 1985) describes the hydrology of the Floridan in west-central Florida. Ground-water pumpage in the area was 1 Bgal/d in 1976; however, the large springs in the northern part of the area are still the dominant feature of the ground-water flow system. Effects of future increases of ground-water pumpage were evaluated by computer simulation.

Professional Paper 1403–G (Meyer, 1989) discusses the ground-water hydrology in southern Florida, where the Floridan contains saline water and there has been little development for water supply. Due to the lack of deep wells, there is little subsurface geologic and hydrologic data. Therefore, the study consisted of deep test drilling, geochemical sampling, and offshore seismic surveys. The principal uses of the Floridan aquifer system in southern Floridan are subsurface storage of treated municipal waste water, oil-field brine, and industrial waste water and production of slightly saline water for desalinization plants.

Professional Paper 1403–H (Maslia and Hayes, 1988) discusses ground-water hydrology in southwestern Georgia, the Florida panhandle, and a small part of Alabama. The study concentrated on two areas: (1) the 15-county Dougherty Plain area of southwestern Georgia, where pumping for irrigation is heavy; and (2) the Fort Walton Beach area of the panhandle, where pumping produced a deep widespread cone of depression.

Professional Paper 1403–I (Sprinkle, 1989) describes the geochemistry of the Floridan aquifer system. Concentrations of total dissolved solids in water from the Upper Floridan aquifer generally range from less than 25 mg/L near outcrop areas to more than 25,000 mg/L along the coasts, where freshwater mixes with recent or residual seawater. Water in the Upper Floridan can be categorized into four hydrochemical facies, whose distribution is determined by confined or unconfined conditions of the aquifer and by chloride concentrations.

HIGH PLAINS

The High Plains regional aquifer-system analysis study covers an area of 174,000 mi^2 of flat to gently rolling terrain in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 27). The High Plains regional aquifer is unconfined and consists mainly of near-surface sand and gravel deposits. The Ogallala Formation of Tertiary age, which underlies about 80 percent of the High Plains, is the principal geologic unit of the aquifer. In the past it has commonly been referred to as the Ogallala aquifer. Saturated thickness of the High Plains aquifer averages about 200 ft; maximum thickness is about 1,000 ft in central Nebraska. Ground water generally flows from west to east and discharges to streams and springs and by evapotranspiration where the water table is near land surface. Infiltration of precipitation and seepage from streams are the principal sources of recharge to the aquifer.

Because the High Plains are mostly in a semiarid region, the amount of recharge to the aquifer is small. This small recharge coupled with large pumpage in parts of Texas, New Mexico, and Kansas has resulted in a large decline of water levels in these areas and reduction of saturated thickness of the aquifer (fig. 5). In turn, this has caused a reduction in well yields (fig. 16) and increased pumping costs. Locally wells have gone dry. However, these conditions do not occur throughout the entire High Plains. Regionally there is enough ground water for development at current rates of withdrawal for the next 40 years, although withdrawal rates are projected to decrease in some areas and increase in other areas.

The High Plains regional aquifer-system analysis was started in 1978 and completed in 1986. The study resulted

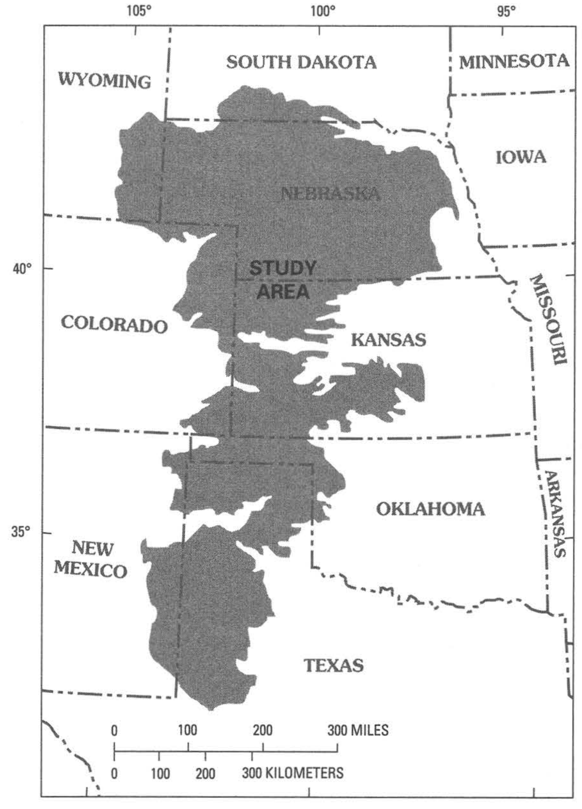


Figure 27. Study area of the High Plains regional aquifer-system analysis.

in 122 reports (Sun and Weeks, 1991), including 5 chapters in Professional Paper 1400. Professional Paper 1400–A (Weeks and others, 1988) summarizes the geohydrology of the aquifer system, effects of development, simulation of the regional flow system, and the use of flow models to evaluate the effects of future pumping strategies.

Professional Paper 1400–B (Gutentag and others, 1984) describes the geohydrology of the High Plains aquifer. The aquifer consists of sediments of late Tertiary or Quaternary age, underlain by lower Tertiary to Cretaceous sediments of low permeability for which the name Great Plains confining system was proposed by the Central Midwest RASA study (Signor and Imes, 1989, fig. 3). The sediments that make up the aquifer are mainly alluvial, dune-sand, and valley-fill deposits. Hydraulic conductivity of the aquifer ranges from less than 25 to 300 ft/d, averaging about 60 ft/d. Specific yield ranges from less than 10 to 30 percent and averages about 15 percent. Pumpage from the High Plains aquifer, principally for irrigation, was from about 170,000 wells in 1980. Most of the wells are in Kansas, New Mexico, Oklahoma, and Texas. Pumpage in 1978 was 2 to 100 times greater than annual recharge, resulting in large water-level declines in some areas. Water levels have declined more than 100 ft from the predevelopment level to the 1980 level in an area of 2,500 mi^2 in parts of Kansas, New Mexico, Oklahoma, and Texas. Professional Paper 1400–B also briefly discusses the quality of water in the aquifer, which is generally acceptable.

Professional Paper 1400–C (Thelin and Heimes, 1987) discusses the use of Landsat multispectral-scanner data to map irrigated cropland for determination of water-use from the High Plains aquifer. Information on irrigated acreage and water-use for irrigation is critical to evaluate the effects of agricultural development on the High Plains aquifer because water-use for irrigation accounts for about 95 percent of all water pumped from the High Plains aquifer. Several methods for determining irrigated acreage were evaluated. Digital analysis of Landsat data proved to be the most suitable approach. The reliability of irrigated-acreage estimates was tested in the field using a multistage random-sampling method. The information on irrigated acreage was combined with measurements of applied irrigation water at selected field sites to determine total irrigation pumpage. For the 1980 growing season, it was estimated that almost 18 million acre-ft was pumped from the High Plains aquifer to irrigate nearly 14 million acres. Statistical evaluation of the field data suggested that Landsat data and simple analysis techniques used during this RASA study can provide an efficient tool for mapping irrigated cropland on the High Plains. These techniques should also be applicable to similar areas of the Western United States.

Professional Paper 1400–D (Luckey and others, 1986) discusses the ground-water flow system on the basis of model simulation. The High Plains aquifer was divided into three parts for simulation. The southern High Plains includes the part of the Plains in Texas and New Mexico, south or west of Amarillo, Texas (fig. 28). The central High Plains is the area north and east of Amarillo and south of approximately 39 degrees latitude. The northern High Plains is the area north of approximately 39 degrees latitude. A narrow isthmus, approximately 12 mi wide, occurs along the boundary separating the southern and central High Plains models in the vicinity of Amarillo, Texas. The isthmus joining the central and northern High Plains is about 32 mi wide and follows a bedrock high where the aquifer is thin. Probably little exchange of water occurs between the three model areas (Luckey and others, 1986). The estimated predevelopment recharge for the southern, central, and northern High Plains models ranged from 0.086 to 1.03 in/yr, from 0.056 to 0.84 in/yr, and from 0.075 to 1.52 in/yr, respectively. Transient simulations of development conditions were made for 1940–60 and 1960–80. The simulations suggested that if net pumpage for irrigation (total pumpage minus irrigation return flow that infiltrates to the aquifer) is between 90 and 100 percent of the estimated irrigation requirements (defined as the product of irrigated acreage and composite crop water

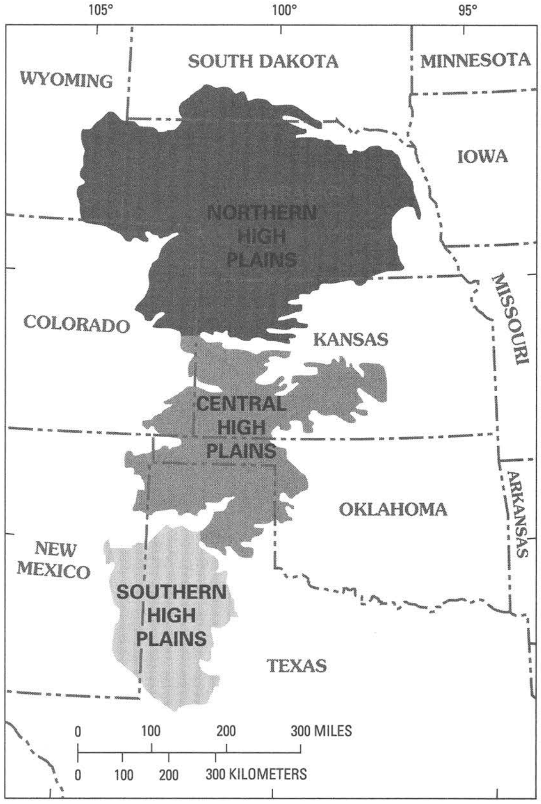


Figure 28. Subdivisions used in modeling the High Plains aquifer (from Weeks and others, 1988).

demands), then simulated water levels match observed water levels better.

Simulation provided water budgets for the heavily pumped southern High Plains. As discussed in the earlier section on ground-water budgets, simulation indicated that pumpage during 1960–80 exceeded natural recharge by more than 30 times.

Professional Paper 1400–E (Luckey and others, 1988) discusses the effects of pumpage on water levels in the High Plains aquifer under various scenarios of future water demand based on model simulation. Pumpage from the High Plains aquifer had been projected for 1977, 1985, 1990, 2000, and 2020 in a study conducted by the Economic Development Administration of the U.S. Department of Commerce; management strategies were proposed and recommended (High Plains Study Council, 1982; High Plains Associates, 1982). Three of the recommended management strategies were evaluated during the RASA study, and results are presented in Professional Paper 1400–E. In the southern High Plains, without significant control of pumpage, simulation indicated that saturated thickness in more than one-half of the area would be less than 25 ft due to water-level declines by the year 2000.

NORTHERN ATLANTIC COASTAL PLAIN

The Northern Atlantic Coastal Plain regional aquifer system underlies about 50,000 mi^2 of gently rolling to nearly flat topography. The system extends from Long Island, New York, to the North Carolina–South Carolina State boundary and from the Fall Line (inner Coastal Plain margin) eastward to the Atlantic Ocean (fig. 29). The aquifer system consists of a seaward-thickening wedge of predominantly unconsolidated sediments that thickens from a featheredge at the Fall Line in the west to more than 8,000 ft along the coast of Maryland and 10,000 ft at Cape Hatteras in North Carolina. The sediments are mostly gravel, sand, silt, and clay of Jurassic to Holocene age. Limestone occurs principally in North Carolina. During this RASA study, the sediments were grouped into 10 regional aquifers, consisting principally of sand, gravel, or limestone, separated by 9 confining units, consisting principally of clay and silt. A regional aquifer may coincide with a recognized local aquifer in one area and comprise several local aquifers in another, or it may constitute only a part of an aquifer. None of the regional aquifers extend over the entire study area. The delineation of aquifers and confining units was based on the predominant lithologies, depositional environment, and hydraulic relations between the sediments. Lateral facies shifts that were caused by marine transgressions and regressions determined the areal distribution of the aquifers and confining units (Trapp, 1993).

Recharge to the aquifer system is from precipitation and occurs chiefly in upland and interfluvial areas. The recharge rate ranges from 10 to 25 in/yr; most of the recharge flows through shallow parts of the aquifer system and discharges to streams that dissect the Coastal Plain sediments. A small amount of recharge, generally about 0.5 in/yr, replenishes the deeper confined parts of the aquifer system. Water in the deep aquifers discharges upward across confining units into shallow aquifers and ultimately into major rivers, coastal estuaries, sounds, bays, and the ocean. Pumpage from the confined part of the aquifer system, principally for municipal and industrial use, has increased from 100 Mgal/d in 1900 to about 1,200 Mgal/d in 1980, resulting in widespread potentiometric head declines that have significantly altered rates and conditions of ground-water recharge, discharge, and flow patterns. However, results of model simulation indicate that the aquifer system adjusts readily to changes in pumpage and reaches a new equilibrium after about 5 yr following changes in pumpage. Storage change resulting from pumping is minimal (Leahy and others, 1987; Leahy and Martin, 1993). A ground-water budget for predevelopment and 1980 conditions is presented in the earlier section on regional ground-water budgets (fig. 12).

Salty ground water underlies freshwater in the eastern part of the Northern Atlantic Coastal Plain. Chloride concentrations generally increase with depth within a transition zone between the deepest freshwater and the underlying saltwater. The zone contains concentrations of chloride ranging from 1,000 to 18,000 mg/L. (A 18,000 mg/L chloride concentration is approximately the chloride concentration of seawater.) The saltwater-freshwater transition zone generally deepens inland from the coast, except in New Jersey and locally in North Carolina, where it is deepest along the coast. The transition zone is shallowest in North Carolina, particularly in the vicinities of the Cape Fear River and Albemarle Sound, and deepens northward to Maryland and the coast of New Jersey. However, the transition zone is relatively shallow in the vicinity of Delaware Bay. Chloride concentration of less than 5,000 mg/L extends 55 mi off the New Jersey coast. The offshore extension of the transition zone decreases southward toward southern Virginia. Depth to the saltwater-freshwater transition zone is partly controlled by the natural flow pattern of fresh ground water. Areas where the transition zone is relatively shallow generally coincide with areas of ground-water discharge, such as Delaware Bay, lower Chesapeake Bay, Albemarle Sound, and the Cape Fear River. The occurrence of a deep transition zone in New Jersey and Maryland and water considerably fresher than seawater offshore is attributed to sea-level changes in past geologic time. In New Jersey and Maryland, past sea level probably was lower than present sea level, resulting in wide extension of the transition zone offshore; in Virginia and North Carolina, past sea level probably was near land surface, resulting in a shallower transition zone than in New Jersey and Maryland (Meisler, 1980, 1989).

The effect of eustatic sea-level fluctuations on the location and development of the saltwater-freshwater transition zone in New Jersey was analyzed with a finite-difference cross-sectional flow model. The sedimentary wedge from the Delaware River to the Continental Slope was simulated as a highly anisotropic porous medium. (A ratio of simulated lateral to vertical hydraulic conductivity of 30,000:1 provided the best results in the model.) Simulated sea-level fluctuation was from 50 to 150 ft below present sea level. The model was found to be sensitive to the altitude of sea level and the degree of anisotropy. The best match of simulated and observed chloride concentrations was obtained with sea level 50 to 100 ft below present sea level. Simulation results indicate that the aquifer system in New Jersey has not reached equilibrium with the rising of sea level. The transition zone is probably moving slowly landward and upward toward equilibrium with present sea level (Meisler and others, 1985).

Figure 29. Study area of the Northern Atlantic Coastal Plain regional aquifer-system analysis.

Anomalously high bicarbonate concentrations occur in water from aquifers consisting of nonmarine sediments in the Northern Atlantic Coastal Plain. The concentrations of bicarbonate are several times higher than could be generated by reactions involving carbon dioxide gas in recharge water entering the aquifers. To explain this anomaly it was hypothesized that the carbon dioxide gas must be generated within the aquifers. During the RASA study, Chapelle and Knobel (1985) suggested that such carbon dioxide gas must be generated by bacterially mediated processes in the aquifer. A test hole was drilled near Waldorf, Maryland, to test this hypothesis. Nineteen cores of unconsolidated Coastal Plain sediments from the Aquia aquifer were obtained from 47 to 545 ft below land surface and analyzed for metabolically active anaerobic bacteria. They concluded that the metabolic processes of fermentative and methanogenic bacteria produced carbon dioxide gas in the Aquia aquifer in Maryland. This research of microbially mediated oxidation process of sedimentary organic matter has been extended to other areas of Coastal Plain sediments (Chapelle and McMahon, 1991; McMahon and Chapelle, 1991).

The Northern Atlantic Coastal Plain regional aquifer-system analysis was started in 1979 and completed in 1987. As of early 1993, 35 reports had been completed, including 13 chapters in Professional Paper 1404 (Sun and Weeks, 1991). Seven Professional Paper chapters have been printed; six are being processed for printing.

NORTHERN GREAT PLAINS

The Northern Great Plains regional aquifer system underlies about 250,000 mi^2 of the Great Plains and Central Lowlands physiographic provinces. It includes North Dakota and parts of South Dakota, Nebraska, Montana, and Wyoming (fig. 30). The study area is bounded on the west by the central and northern Rocky Mountains, on the east by the Red River of the North, on the south by the central High Plains, and on the north by the United States–Canadian border. Sedimentary rocks underlying the area originated as erosional products from mountains to the west that were deposited to a thickness of more than 16,000 ft in the subsiding Williston and Powder River basins and surrounding areas. Subsequently, several hundred feet of sedimentary rocks were eroded, leaving remnants of more resistant rocks.

The principal aquifers, which are areally extensive, underlying the northern Great Plains are exposed along the flanks of the Bighorn and Powder River basins and other structural features. Ground water generally flows northeastward across the study area. The source of recharge is precipitation on a topographically high area near the Black Hills uplift, the Bighorn Mountains, the eastern flank of the northern Rocky Mountains, and other major structurally high areas (fig. 31). Ground water discharges mostly into topographically low areas of eastern North Dakota and South Dakota and as outflow into Canada. Some ground-water discharge occurs as diffuse upward leakage into overlying aquifers through confining units.

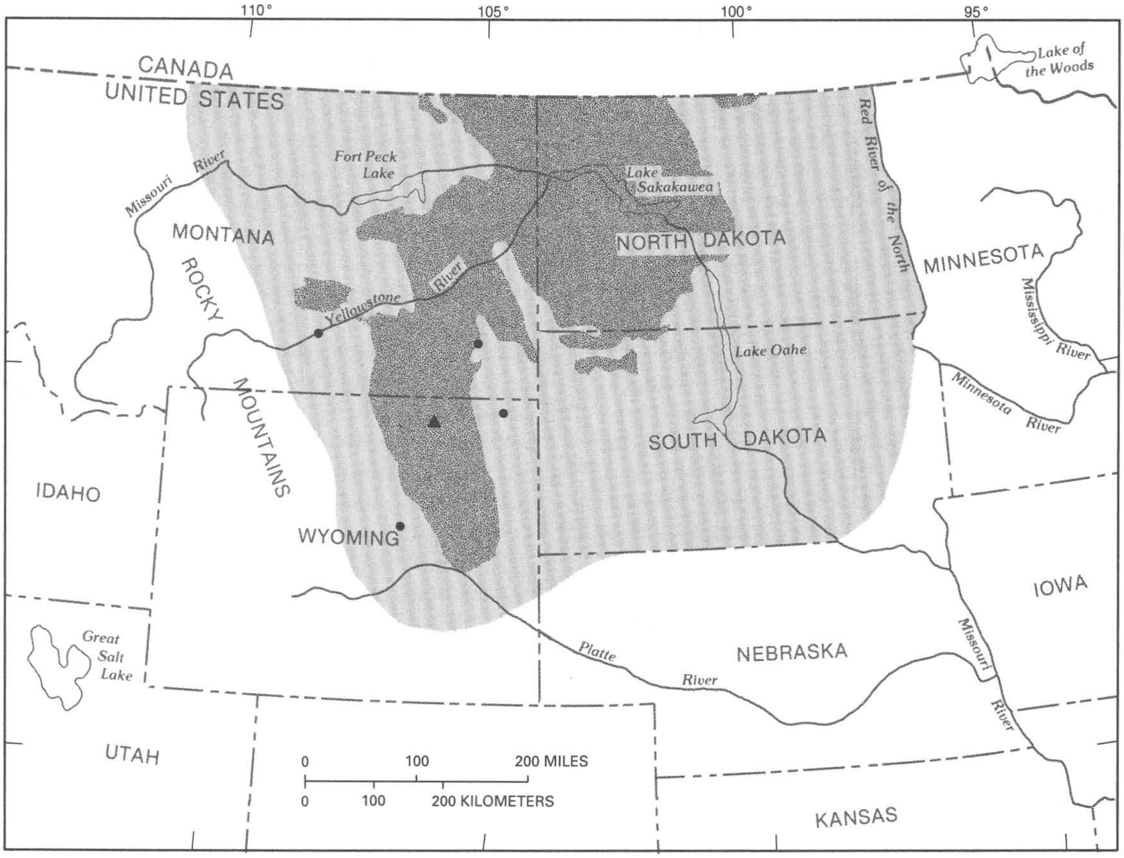
Five major aquifer systems were identified during this RASA study. In descending order, they are the Upper Cretaceous aquifer system, which mostly includes sediments of Late Cretaceous age but includes surficial glacial and Tertiary sediments; the Lower Cretaceous aquifer system; the Pennsylvanian aquifer system; the Mississippian (Madison Limestone) aquifer system; and the Cambrian-Ordovician aquifer system. Flow characteristics of the aquifer systems vary significantly between the dominantly carbonate aquifers (such as the Madison Limestone) and the dominantly clastic aquifers (such as the Dakota Sandstone). The major aquifers also are petroleum reservoirs within much of the study area. The hydrodynamic forces involved in the regional ground-water flow system have contributed to the accumulation of petroleum in the Williston basin (Downey, 1988).

All aquifer systems crop out and receive recharge in the highlands in the western part of the study area. However, a large part of the recharge water in outcrop areas discharges within short distances as springs and seeps along the flank of the mountains; only a small part of the recharge water flows downward to the deep, regional flow systems and flows eastward to discharge areas. On the basis of model simulation and conceptualized flow patterns in the aquifer systems, it has been deduced that water in the Upper Cretaceous aquifer system discharges to the Missouri River or upward to overlying surficial aquifers. Discharge from the Lower Cretaceous aquifer system is mainly upward to the overlying Upper Cretaceous aquifer system in eastern North Dakota and South Dakota and to the subcrop of the Lower Cretaceous aquifer system in the glacial Lake Agassiz Plain in North Dakota.

Discharge from the aquifer systems consisting of Paleozoic rocks—the Pennsylvanian aquifer system, the Mississippian aquifer system (Madison Limestone), and the Cambrian-Ordovician aquifer system—principally is upward to overlying aquifer systems and to the Red River of the North. However, in eastern North Dakota, water in the Pennsylvanian aquifer system flows downward into the Cambrian-Ordovician aquifer system, then discharges to the Red River of the North, or to land surface as springs.

A body of brine is present in the deeper aquifers along the eastern flank of the Williston basin, where water movement is sluggish. Three hypotheses have been developed concerning the movement of brine and ground water: (1) the brine is static, (2) the brine is moving slowly with regional ground-water flow (a sluggish segment of regional flow), and (3) the brine is moving due to the adjustment of the flow system following the melting of Pleistocene ice. Origin of the brine appears to have been the dissolution of halite. As the density of the saline water increased, it caused fresher water to be diverted around the saline water body to the north and south, or above it into the overlying Cambrian-Ordovician and Mississippian aquifer systems. The second hypothesis seems to agree best with model simulation and field data; however, the third hypothesis cannot be ruled out completely. The distribution of the saline water may still be adjusting in response to changes in recharge and discharge at the end of the Pleistocene (Downey, 1988).

The Northern Great Plains regional aquifer-system analysis was started in 1978 as an extension of the Madison aquifer (the Mississippian aquifer system) study. The Madison study was started in 1975 to address the problems of water supplies associated with development of coal resources and proposed coal-slurry pipelines in the Fort Union coal region. The Northern Great Plains RASA was completed in 1982 and resulted in 75 reports (Sun and Weeks, 1991), including 9 reports completed during the Madison aquifer study and 6 chapters of Professional Paper 1402. Professional Paper 1402–A (Downey and Dinwiddie, 1988) summarizes the general geology and hydrology of the regional aquifer systems underlying the northern Great Plains. Professional Paper 1402–B (Anna, 1986) discusses the geologic framework of the aquifer systems. Professional Paper 1402–C (Henderson, 1985) discusses geochemistry of water in the Kootenai Formation in the Judith basin of Montana, and in the Lance Formation and Fox Hills Sandstone in the Powder



EXPLANATION

Fort Union coal region

Test well drilled by the U. S. Geological Survey

● Well penetrating the Madison aquifer

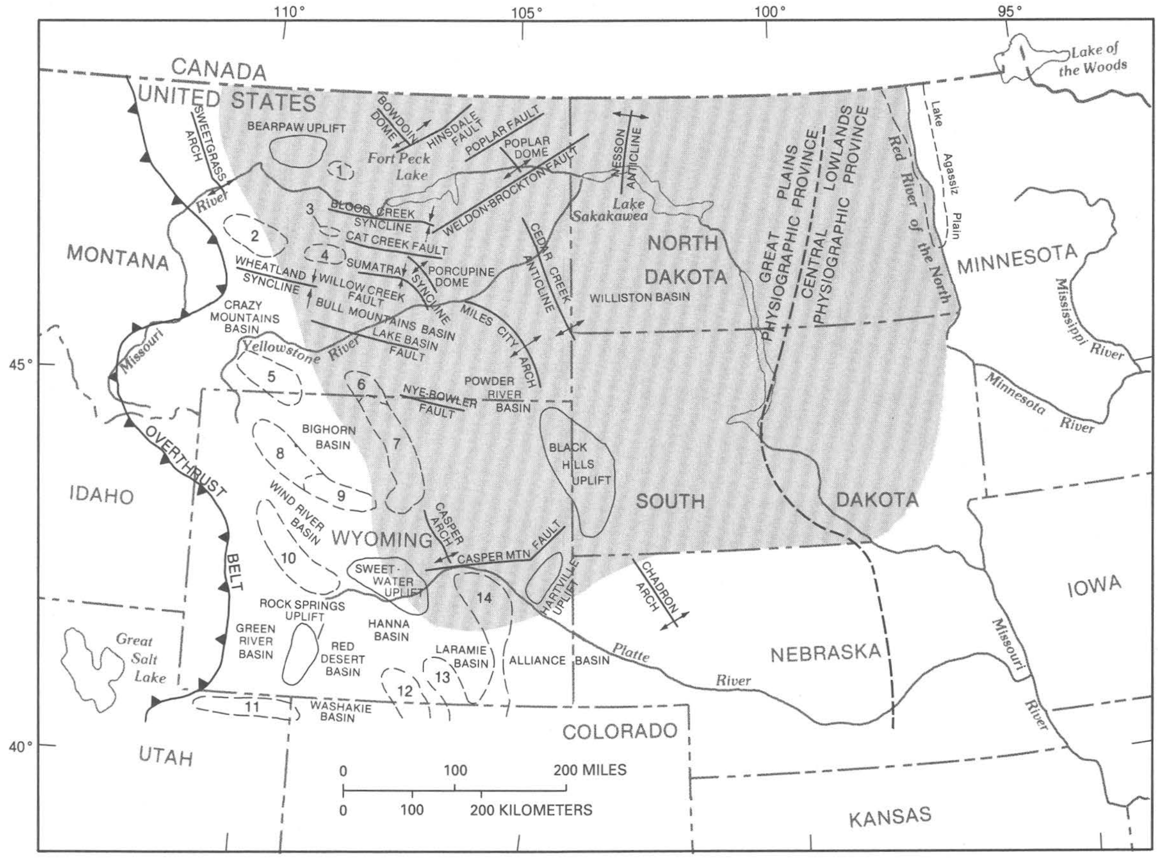
▲ Well penetrating the Pierre Shale

Approximate study area of the Northern Great Plains Regional Aquifer System

Figure 30. Study area of the Northern Great Plains regional aquifer-system analysis.

River basin of Wyoming. These formations consist of two important sandstone aquifers in the northern Great Plains region. Professional Paper 1402–D (Lobmeyer, 1985) describes the distribution of freshwater heads and ground-water temperatures in Cretaceous and Tertiary aquifers. This chapter also describes a method used to convert bottom-hole shut-in pressure to equivalent freshwater head by correcting for density variations resulting from temperatures observed during drill-stem tests. Professional Paper 1402–E (Downey, 1986) describes the geohydrology, aquifer hydraulic parameters, and regional flow system on the basis of simulation results. Professional Paper 1402–F (Busby and others, in press) discusses the geochemistry of waters in the aquifer systems and their related confining units.

Information obtained during the Madison aquifer study is summarized in Professional Papers 1273–A through –G. The stratigraphy and sedimentary facies of the Madison Limestone and associated rocks are described in Professional Paper 1273–A (Peterson, 1984). The correlation of paleostructure and sediment deposition in the Madison Limestone and associated rocks is described in Professional Paper 1273–B (Brown and others, 1984). Thayer (1984) discussed the relation of porosity and permeability to the petrology of the Madison Limestone in Professional Paper 1273–C.



EXPLANATION

Mountain ranges of the eastern flank of the northern Rocky Mountains

1 Little Rocky	6 Pryor	11 Uinta
2 Little Belt	7 Bighorn	12 Sierra Madre
3 Judith	8 Absaroka	13 Medicine Bow
4 Big Snowy	9 Owl Creek	14 Laramie
5 Beartooth	10 Wind River	

Approximate study area of the Northern Great Plains Regional Aquifer System

Figure 31. Structural and physiographic features of the northern Great Plains and vicinity (from Downey and Dinwiddie, 1988).

Apparent water resistivity, porosity, and temperatures of the Madison Limestone are discussed in Professional Paper 1273–D (MacCary, 1984). Potentially favorable areas for developing large-yield wells in the Red River Formation and Madison Limestone are suggested in Professional Paper 1273–E (MacCary and others, 1983). The geochemical evolution of water in the Madison aquifer is described in Professional Paper 1273–F (Busby and others, 1991). Geohydrology of the Madison and associated aquifers is presented in Professional Paper 1273–G (Downey, 1984).

SOUTHEASTERN COASTAL PLAIN

The Southeastern Coastal Plain aquifer system underlies about 120,000 mi^2 in parts of South Carolina, Georgia, Alabama, and Mississippi, and adjacent areas of northern Florida and southeastern North Carolina (fig. 32). The Southeastern Coastal Plain aquifer system is located among four adjacent regional aquifer systems investigated during the RASA Program: the Northern Atlantic Coastal Plain regional aquifer system to the northeast, the Floridan aquifer system to the south and southeast, the Gulf Coastal Plain regional aquifer system to the west, and the Appalachian Valleys and Piedmont regional aquifer system to the west of the Fall Line.

The Southeastern Coastal Plain aquifer system consists of a thick wedge of unconsolidated to consolidated clastic and carbonate rocks of Cretaceous to Holocene age. These rocks extend and thicken seaward from the inner Coastal Plain margin (the Fall Line) to the Atlantic Ocean, Gulf of Mexico, or Florida peninsula. Except where covered by younger strata, rocks comprising the aquifer system crop out in adjacent bands from Mississippi to South Carolina. In outcrop areas, most of the water that enters the aquifer system discharges to nearby local streams; only a small part of the recharge moves downward and enters the deeper, confined system. In gulfward areas, deeply buried clastic

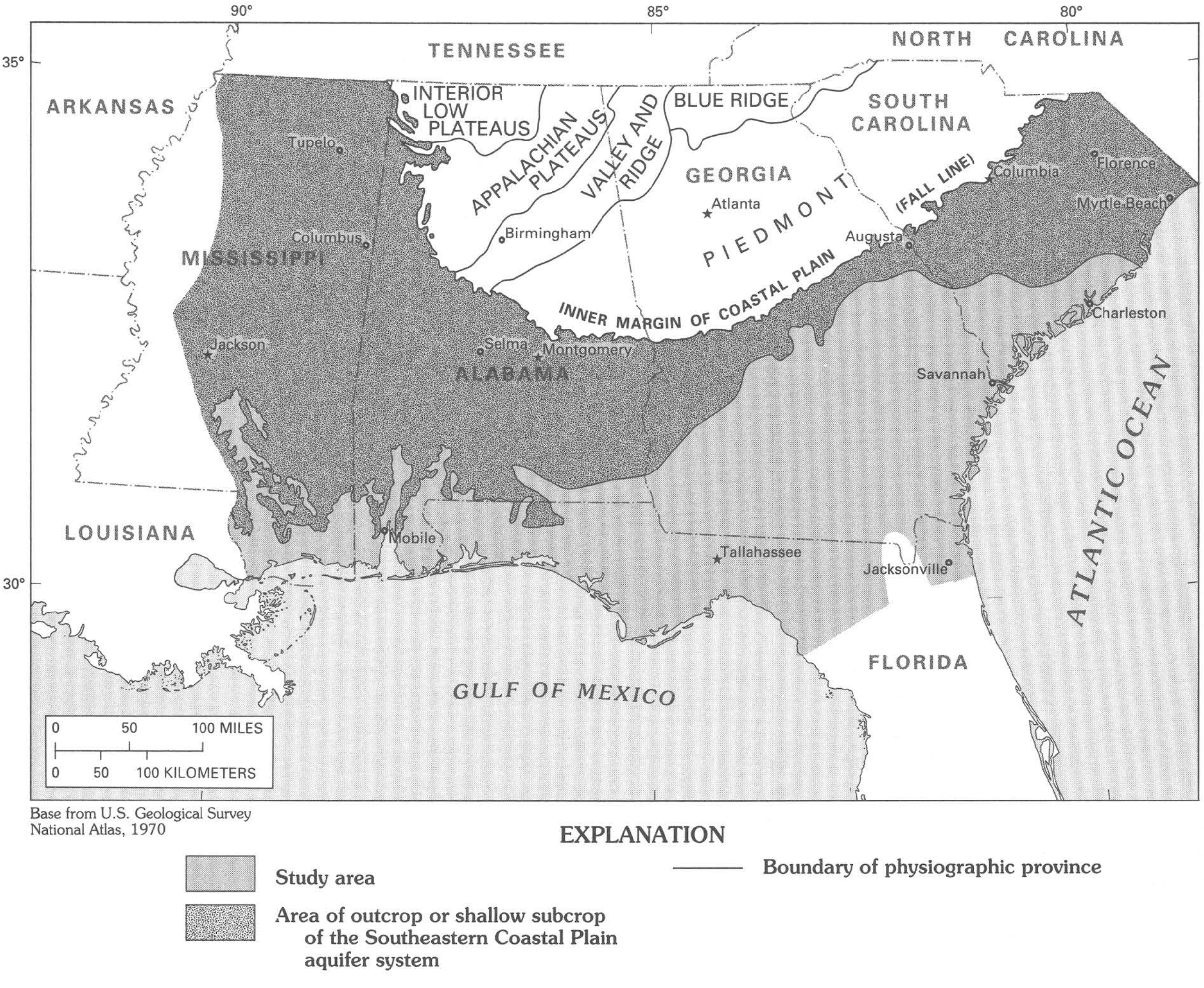


Figure 32. Study area of the Southeastern Coastal Plain regional aquifer-system analysis (from Miller, 1992).

and carbonate rocks contain saline water and are not considered as part of the aquifer system. In landward areas, the system is underlain by metamorphic, sedimentary, and igneous rocks of Paleozoic and early Mesozoic age that have very low permeability. The lower limit of the Southeastern Coastal Plain regional aquifer system is designated as the top of the freshwater-saltwater interface in the seaward and gulfward areas, and at the top of the low-permeability rocks of Paleozoic and early Mesozoic age in the landward area.

Sediments of the aquifer system were grouped into four regional aquifers and three confining units. The regional aquifers consist of sand, sandstone, gravel, and minor limestone. The regional confining units consist of clay, mudstone, marl, and chalk that separate the regional aquifers. The regional aquifers are named after major rivers along which they crop out. From shallowest to deepest, they are the Chickasawhay River aquifer, Pearl River aquifer, Chattahoochee River aquifer, and Black Warrior River aquifer. The regional confining units are named for the regional aquifer the confining unit overlies. They are the Pearl River confining unit, Chattahoochee River confining unit, and Black Warrior River confining unit (Miller and Renken, 1988). Regional hydrogeologic units are discontinuous within the study area. For example, the Black Warrior River aquifer is absent in updip areas of South Carolina and eastern Georgia. The Chattahoochee River aquifer is absent in a large area in western Alabama and southeastern Mississippi. Some of the hydrogeologic units of the Southeastern Coastal Plain aquifer system grade into units that are part of adjacent regional aquifer systems owing to facies change. For example, there is a facies change from clastic rocks of the Southeastern Coastal Plain aquifer system into the predominantly carbonate rocks of the Floridan aquifer system.

Almost all of the recharge is from precipitation that falls on the outcrop areas of the aquifer system; however, some recharge does occur in confined parts of the system by downward leakage, mostly where the shallower aquifer is unconfined or less confined. Flow in outcrop areas is predominantly vertical and becomes horizontal in middip confined parts of the aquifer system. Farther downdip, discharge occurs as upward leakage to shallower aquifers. Upward leakage primarily results from a combination of decreased permeability and abrupt increases in concentrations of dissolved solids of the water. Although rates of upward leakage are small, leakage occurs over a broad area, resulting in a large amount of leakage.

A simulated water budget of the Southeastern Coastal Plain regional aquifer system is as follows: annual precipitation, 51 in/yr; evapotranspiration, 32 in/yr; overland runoff, 12 in/yr; and ground-water recharge, 7 in/yr. More than 90 percent of the recharge (6.4 in/yr) moves along short flow paths to nearby streams, becoming baseflow; the remaining 10 percent (about 0.6 in/yr) percolates to deeper (confined) regional aquifers. About 80 percent of the regional flow (0.5 in/yr) discharges to large rivers; the remaining 10 percent (0.1 in/yr) discharges upward as diffuse leakage into shallower aquifers such as the Floridan (Miller and others, 1987).

Withdrawal of water from the aquifer system started in about 1900, and by 1985 pumpage was about 495 Mgal/d. About 320 Mgal/d was pumped from the Chattahoochee River aquifer, and 113 Mgal/d from the Black Warrior River aquifer. Simulation indicated that about 45 percent of the pumpage was derived from reduction in ground-water discharge to streams (reducing baseflow in streams), about 31 percent of the pumpage was water removed from aquifer storage, and the remaining 24 percent of the pumpage was derived from the adjacent aquifer systems (mostly from the Upper Floridan aquifer). Simulated upward leakage to the Upper Floridan decreased in many places, and downward leakage from the Upper Floridan increased in other places. There was no change in recharge because pumping occurred in middip confined parts of the Southeastern Coastal Plain aquifer system. Except in a few places, water levels in outcrop areas have not been affected by pumping. However, in downdip, confined parts of the Chattahoochee River and Black Warrior River aquifers, cones of depression have developed around pumping centers, with head declines exceeding 100 ft locally.

Water chemistry changes along ground-water flow paths as a result of water-rock mineral reactions. In outcrop areas, concentrations of dissolved solids in ground water are less than 50 mg/L, and the water is mostly calcium bicarbonate type. Downgradient from outcrops, water is mostly sodium bicarbonate type, and concentrations of dissolved solids range from 100 to 200 mg/L. Farther downgradient, concentrations of dissolved solids are from 300 to 500 mg/L, and chloride increases with depth. Farthest downgradient, concentrations of dissolved solids are from 1,000 to 30,000 mg/L, and sodium chloride type water is dominant, indicating that freshwater is mixing with saltwater in these areas (Miller and others, 1987).

The Southeastern Coastal Plain regional aquifer-system analysis was started in 1979 and completed in 1988. As of May 1991, 61 reports had been completed (Sun and Weeks, 1991), including 8 chapters in Professional Paper 1410. Professional Paper 1410–A (Miller, 1992) summarizes the important aspects of the aquifer system, and Professional Papers 1410–B through –D respectively describe the regional hydrogeologic framework, regional hydrology and simulation of deep ground-water flow, and ground-water chemistry; Professional paper 1410–E through –H discuss the aquifer system on a subregional basis for South Carolina, Georgia, Mississippi, and Alabama, respectively.

SOUTHWEST ALLUVIAL BASINS

Hundreds of isolated alluvial basins exist in the southwestern United States. Some of the basins have surface-water outflow, while others do not. It was impossible to study all basin aquifers under the RASA Program. Therefore, only some of the basins were selected for study to determine the occurrence, movement, and geochemistry of ground water in basin aquifers. Study results indicate that certain hydrologic and geologic information can be transferred from the studied basin aquifers to other basin aquifers. Geographically, the study was divided into two parts. One was in parts of Colorado, New Mexico, and Texas; the other was in southern and central Arizona and small parts of adjacent States.

The 70,000 mi^2 study of parts of Colorado, New Mexico, and Texas includes 22 basins (fig. 33). Two types of basins occur in the study area: (1) open basins that have a surface-water outlet and are within the Rio Grande rift, and (2) closed basins that have no surface-water outlet and are predominantly in southwest New Mexico and west Texas. The Rio Grande rift is a fault-bounded structural feature with uplifted blocks on the east and west. Uplifted blocks east of the basins generally rise several thousand feet above the valley floor of the basins. The basins are bounded on the north, east, and west mainly by Quaternary and Tertiary volcanic rocks, and Mesozoic and Paleozoic rocks. Alluvial sediments in the basins were derived from the surrounding highlands and mountains. These sediments are composed of flood-plain deposits and the Santa Fe Group that consists of unconsolidated to moderately consolidated lenticular deposits of gravel, sand, and clay interbedded in places with volcanics. Most wells are completed in the Santa Fe Group and individually produce as much as 3,000 gal/min.

Precipitation on the mountains on the east and west sides of the basins is the principal source of recharge to basin aquifers. Surface water runs off from mountainous areas and infiltrates the basin aquifers near mountain fronts; little surface water flows onto the alluvial fans because of high rates of infiltration in arroyos. The second source of recharge in open basins is seepage from the Rio Grande and return flow of applied irrigation water from surface-water sources.

Ground water flows from east and west sides of the basins toward basin axes and then flows southward, except in the Animas basin and the lower part of the Salt basin, where ground-water flow is northward.

Quality of ground water changes areally and vertically. Generally, concentrations of dissolved solids are less than 1,000 mg/L in water several hundreds of feet below the water table in flood-plain areas. However, concentrations increase and range from 3,000 to 10,000 mg/L in water 2,000 ft or more below the water table.

The study of alluvial basins in parts of Colorado, New Mexico, and Texas was started in 1978 and was completed in 1985. As of May 1991, 30 reports had been completed (Sun and Weeks, 1991). As of mid-1992, chapter C of Professional Paper 1407 was published and chapters A and B were in press.

The study of alluvial-basin aquifers in southern and central Arizona and parts of California, Nevada, and New Mexico covers an area of 82,000 mi^2 that contains 72 basins (fig. 34). The area is characterized by sharply rising mountains that separate wide and flat basins. The basins are filled with alluvial deposits, ranging from a few thousand feet to more than 10,000 ft in thickness. The basins

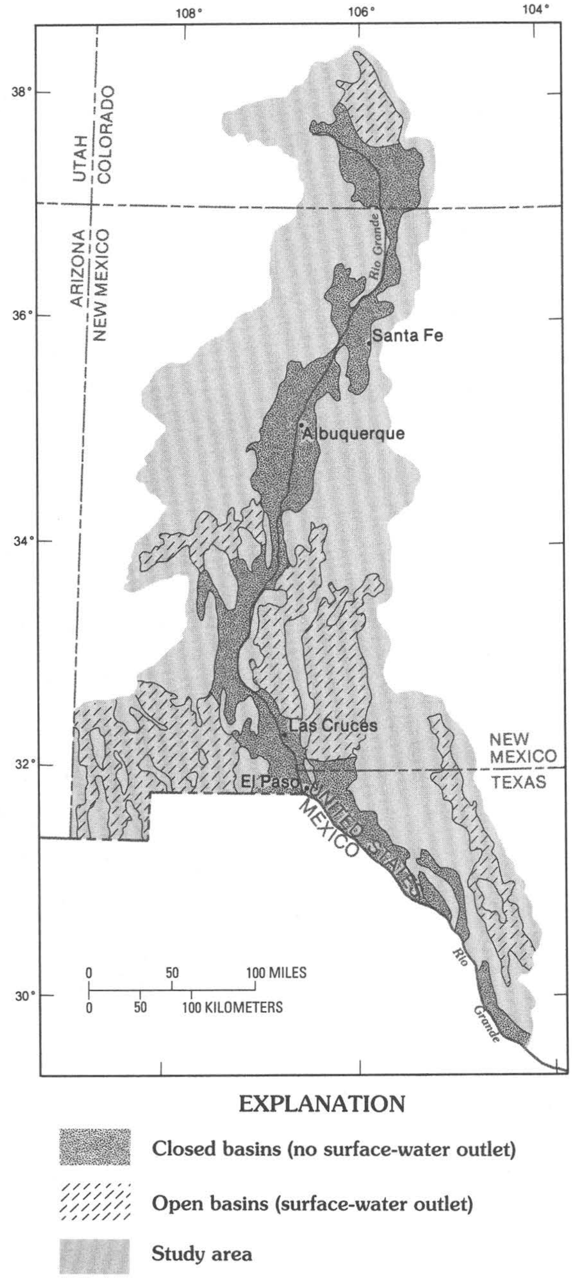


Figure 33. Study area and types of alluvial basins in parts of Colorado, New Mexico, and Texas (modified from Wilkens, 1986).

were formed 10 to 15 million years ago when movement along high-angle normal faults downdropped the basins in relation to the mountain masses. The result was a series of generally northwest-trending basins. The formation of basins was a gradual process that was accompanied by deposition of locally derived sediments. In almost all basins, the vertical sequence of sediments, in descending order, are stream alluvium, upper and lower basin fill, and sedimentary rocks deposited prior to the formation of the Basin and Range topography.

The sedimentary rocks deposited before the development of Basin and Range topography consist of moderately to highly consolidated continental deposits, including clay to gravel and some volcanic rocks. These sedimentary rocks are deeply buried and were faulted and tilted with the underlying bedrock. Except near basin margins, very few wells have been drilled into these sedimentary rocks.

The basin-fill sediments, which are the principal aquifers in most basins, were deposited during and after the development of Basin and Range topography. The lower

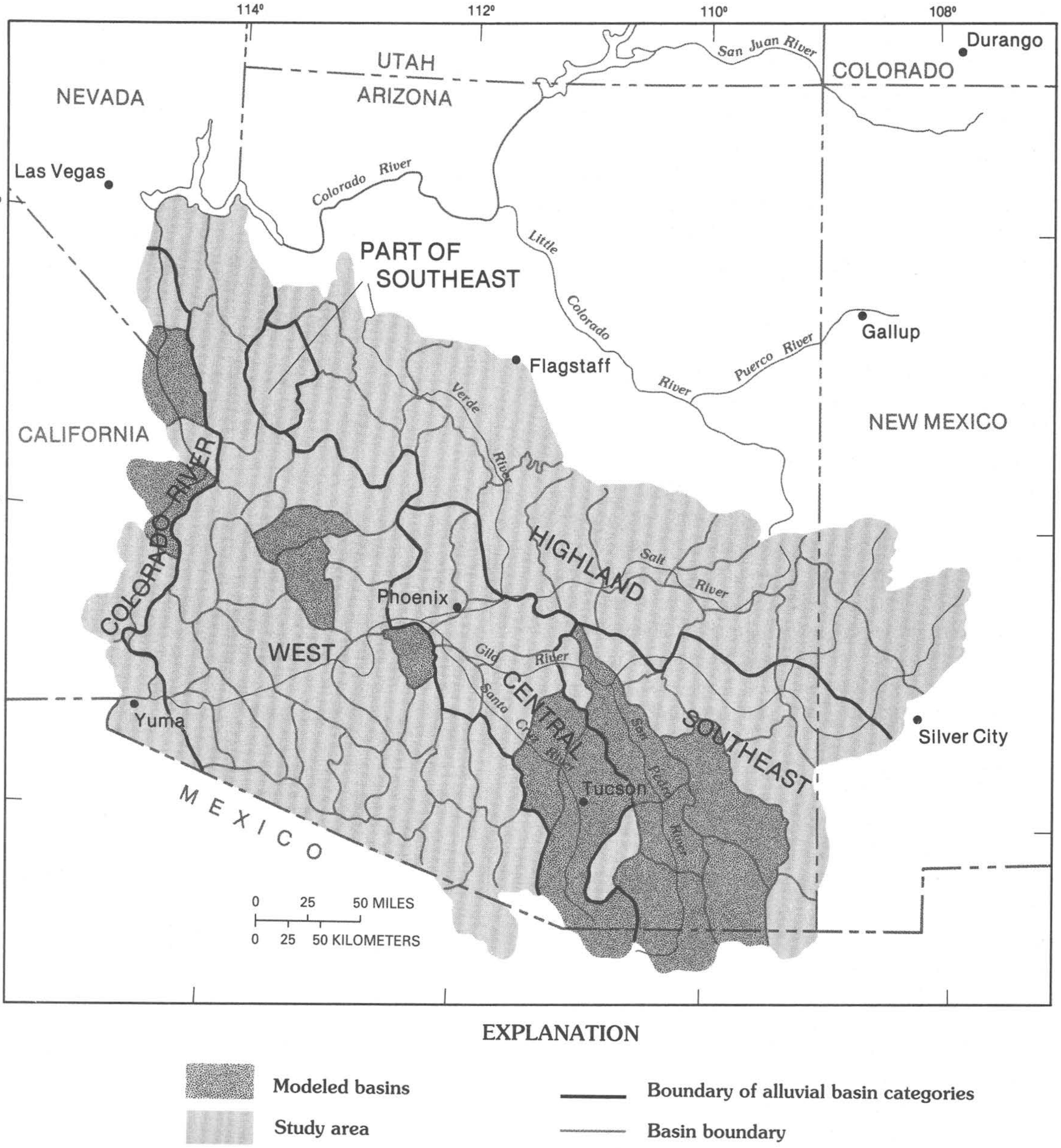


Figure 34. Study area and categories of alluvial basins in southern and central Arizona, and parts of California, Nevada, and New Mexico (from Anderson and others, 1992).

basin fill is moderately to highly consolidated fine-grained materials and contains evaporites. The upper basin fill was deposited during a transitional period when the basins changed from closed basins to an integrated drainage system. The upper basin fill is less consolidated, generally is thinner, and contains less fine-grained materials than the lower basin fill. Both the lower and upper basin fill grade laterally from coarse-grained sediments at basin margins to fine-grained sediments near basin centers.

The alluvium was deposited by the present surface drainage system and ranges from clay to boulders. Where saturated, the alluvium is the most productive aquifer.

Recharge to aquifers occurs mainly from runoff along mountain fronts or as seepage from major streams. In some basins, subsurface inflow from adjacent basins also contributes recharge. Ground water generally discharges as springflow, to streams, through evapotranspiration, or to downgradient adjacent basins as subsurface outflow. Water quality in the basin aquifers generally is good; concentrations of dissolved solids are less than 1,000 mg/L in most places. Ground-water development principally is for irrigation and has resulted in depletion of streamflows and water-level declines (from 50 to 400 ft) in some heavily developed basins. Pumpage increased from 1.7 million acre-ft in 1942 to 4.8 million acre-ft in 1962. During 1950–80, an average of 4.8 million acre-ft of water per year was pumped.

On the basis of total downvalley flow and lithology of basin aquifers, the alluvial basins were grouped into five categories by Anderson and others (1992) and named geographically as (1) southeast, (2) central, (3) west, (4) Colorado River, and (5) highland basins (fig. 34).

Aquifers in basins of the southeast category consist of at least two saturated units, as well as upper basin fill and lower basin fill, separated by a low-permeability fine-grained confining unit. The major recharge is infiltration of streamflow along mountain fronts and along major stream channels. Ground-water discharge, before development, was mainly through evapotranspiration, to streams, and subsurface outflow to downgradient basins. Ground-water development has resulted in reduction of natural discharge, increase of seepage from streamflow, and a small change in aquifer storage. Computer models of basin aquifers in the southeast category should be multilayered and designed to allow flow through leaky confining units.

Aquifers in basins of the central category consist of as much as 5,000 ft of lower basin fill and less then 1,000 ft of upper basin fill. Alluvium along major streams is as much as 300 ft thick. Fine-grained sediments commonly comprise more than 60 percent of the sediments near the centers of the basins. Evaporites typically are found in lower basin fill. Recharge consists of small to moderate amounts of mountain-front recharge and streamflow infiltration. Subsurface inflow from upstream basins may be significant in some basins. Before development, most ground-water discharge occurred as evapotranspiration. Discharge to streams is small. In some basins, subsurface outflow to a downgradient basin may be significant. Development can decrease evapotranspiration and discharge to streams. Most pumpage is supplied by a reduction in aquifer storage. Computer models of aquifers in the central category should be multilayered.

Pre-Basin and Range sediments occur at shallow depths in basins of the west category and are overlain by moderate- to coarse-grained lower basin fill (Anderson and others, 1992). Lower basin fill is the principal aquifer in this category. Upper basin fill is thin and occurs mostly above the water table. Alluvium is present only along the lower Gila River. Both recharge and discharge are small. Pumpage from wells is almost entirely from aquifer storage. Multilayered computer models are recommended for studying basin aquifers in this category.

Aquifers in the Colorado River category consist of fanglomerate overlain by marine estuarine deposits of the same age as the lower basin fill. Lower basin fill, in turn, is overlain by upper basin fill. Alluvium that overlies and occupies channels cut into the basin fill, and the flood-plain area is the principal aquifer. Flow in aquifers of this category is totally dominated by flow in the Colorado River. Seepage of water from the Colorado River is the principal source of recharge. Before development, ground-water discharge occurred mainly as evapotranspiration by phreatophytes and riparian vegetation. Pumpage has little effect on the aquifers because of the immensity of induced recharge from the Colorado River. Away from the river, small amounts of water may be withdrawn from aquifer storage locally. However, when the hydraulic gradient reaches the river, eventually all pumpage will be supplied by induced flow from the river. Aquifers in this category can be simulated with two-dimensional models.

Aquifers in the highland category consist of thin basin-fill deposits of small areal extent that are present in flood plains of streams draining the area. These alluvial deposits are superimposed on a sequence of older, consolidated sedimentary rocks. Many of the streams are perennial. Recharge occurs as underflow from adjacent consolidated-rock aquifers and from infiltration of streamflow. Mountain-front recharge occurs only locally. Ground-water discharge occurs as evapotranspiration or to streams. Pumpage effects are dependent upon the magnitude and location of the development. Pumpage could be supplied by induced infiltration of streamflow or by reduction in aquifer storage and discharge to streams. Aquifers in the highland category can be simulated with two-dimensional models.

During this RASA study, it was observed that in certain basins in southern and central Arizona, earth fissures are caused by land subsidence in response to water-level declines from pumping (fig. 24). Earth fissures create problems in maintenance of structures, canals, roads, and irrigation and drainage systems. Determination of cause-effect relations between pumping and fissure formation is critical to management of ground-water resources. The geochemical evolution of ground-water quality in basins with land subsidence has some unique features. Therefore, the study of basin aquifers in southern and central Arizona was extended to further investigate earth fissures and water chemistry. Computer models were developed to simulate land subsidence related to pumping (Leake, 1990, 1991), and earth-fissure movement associated with fluctuations of water levels were interpreted by Carpenter (1991). Geochemical models were also developed to determine the chemical evolution of water in these basins (Robertson, 1991).

The study of basin aquifers in southern and central Arizona, and parts of Nevada, New Mexico, and California, was started in 1978 and completed in 1990. As of May 1991, 53 reports had been completed (Sun and Weeks, 1991). Chapters B and C of Professional Paper 1406 have been printed and chapters A and D are in press as of mid-1992.

COMPLETED REGIONAL AQUIFER-SYSTEM ANALYSIS STUDIES; SOME REPORTS ARE IN PREPARATION OR IN REVIEW

The 12 regional studies that were completed as of mid-1992 are summarized in this section of the report. The data compilation and investigative activities have been completed and final reports are either in review or preparation.

CARIBBEAN ISLANDS

The Caribbean Islands regional aquifer-system analysis includes Puerto Rico, its adjacent islands (Vieques, Culebra, and Mona), and the U.S. Virgin Islands (St. Croix, St. Thomas, and St. John) as shown in figure 35. The most important sources of ground water in Puerto Rico are the limestone aquifers underlying the northern coast and the alluvial fan–delta aquifers underlying the southern coast. The Kingshill aquifer of St. Croix is the only significant aquifer in the U.S. Virgin Islands. Therefore, the Caribbean Islands regional aquifer-system analysis focused on these aquifers.

The Island of Puerto Rico is about 3,300 mi^2, with a central core of east-west mountain ranges flanked by foothills. The mountain ranges have a maximum altitude of about 4,400 ft and separate the island into north and south sides. Extensive coastal plains, as much as 8 mi wide, are present along the north and south sides of the island. Rainfall ranges from 200 in/yr on the rain forests of the northeast to 20 in/yr on the lowlands of the southwest. Annual average precipitation on the island is about 75 in.

The geology of Puerto Rico is complex and varied. The central core of the island consists largely of volcanic and intrusive rocks of Cretaceous and early Tertiary age. Limestone, minor dolomite, and clastic sediments of Oligocene to Pliocene age were deposited north and south of the central mountain core. The clastic sediments consist of poorly sorted mixtures of gravel, sand, and fine-grained materials. On the northern coastal plain, minor clastic sediments grade upward into thick beds of relatively pure

Figure 35. Study area of the Caribbean Islands regional aquifer-systems analysis.

limestone. Ground water moving through joints and fractures in the limestone has formed solution channels and cavities. In outcrop areas along the north coast, a mature karst topography has developed. Along the southern coast, conglomeratic gravel, sand, mudstone, and limestone beds of Oligocene to Pliocene age are not an important source of water. Calcareous cement has effectively reduced the porosity of the clastic strata, and the limestone beds have not undergone extensive solutioning. Overlying the Tertiary age beds are deltaic deposits of gravel, sand, and silt and alluvium of Pleistocene to Holocene age. These deposits compose the principal aquifers along the south coast. Permeability distribution in the aquifers is related to the depositional patterns of sand and gravel.

Rocks composing the northern coastal aquifer system of Puerto Rico were grouped into three hydrogeologic units: (1) an upper unconfined aquifer, (2) a confining unit, and (3) a lower confined aquifer (Rodriquez-Martinez, 1991). The upper unconfined aquifer consists of the Aymamon Limestone and underlying Los Puertos Formation. Locally, along the north coast, the upper unconfined aquifer also includes the uppermost rocks of an unnamed upper member of the Cibao Formation. In coastal areas where this aquifer is confined by surficial deposits, the aquifer contains saline water. The unconfined freshwater aquifer, is 130 to 240 ft thick in the north-central coastal area but becomes thinner east of Manati. East of Dorado, both the saline water and freshwater sections decrease in thickness. The aquifer pinches out in the vicinity of San Juan. If it exists locally farther to the east, it is very thin and contains brackish water. Near Isabela, the freshwater zone gradually decreases to 25 ft in thickness (fig. 35).

The confining unit of the northern coastal aquifer system consists largely of an unnamed member of the Cibao Formation, the Quebrada Arenas and Rio Indio Limestone Members of the Cibao Formation, a mudstone unit, and the lower part of the Los Puertos Formation. The confining unit underlies most of the upper confined aquifer west of San Juan. Between Manati and Arecibo, the confining unit locally contains a water-yielding zone under artesian conditions (Rodriquez-Martinez, 1991).

The lower aquifer is the principal artesian aquifer of the northern coastal aquifer system and attains its maximum transmissivity in the area between Arecibo and Manati. The lower aquifer consists of the Lares Limestone, the Montebello Limestone Member, and the lowermost strata of the unnamed upper member of the Cibao Formation. Water in the lower aquifer is potable, and well yields range from several hundred to several thousand gallons per minute. However, in San Juan and to the east, the quality of water varies from fresh to brackish.

The southern coastal aquifer system consists of six fan-deltas that coalesce to form a narrow but continuous alluvial plain that extends eastward for about 45 mi from Ponce to Patillas. The alluvial plain is bordered on the north by intensively faulted Cretaceous and Tertiary highlands. Tributaries in the mountains and foothills transport the poorly sorted material that comprises the alluvial deposits. Fan-delta deposits form a coastward-thickening sequence of bedded cobble, gravel, sand, and silt of Quaternary age. In the deep subsurface, these deposits may be as old as Miocene age. Bedrock hills protrude through thinner parts of the alluvial plain, especially along the northern margin (Renken and others, 1991).

The east-west mountain range effectively cuts off much of the precipitation from the northeast trade winds and creates a rainshadow on the leeward (southern) side of the island. Annual precipitation is less than 40 in. on the southern side and is about 20 in. near the coast and at the westernmost part of the alluvial plain. Recharge to the southern coastal aquifer system is principally by infrequent rainfall and by seepage of streamflow near the fan apexes. Ground-water discharge occurs as seepage to the sea and to streams, or through evapotranspiration where water levels are near land surface. The alluvial aquifers are predominantly unconfined at inland locations and confined near the coast. Development of water resources in the eastern coastal plain in 1914, where water from surface reservoirs is used to irrigate sugarcane fields, considerably altered the ground-water flow system. Recharge to the alluvial aquifers is increased by irrigation return flow of surface water used for irrigation. About 30 percent of the applied irrigation water was estimated to become recharge. In 1964, reported use of irrigation water was 68,000 acre-ft. However, the irrigation demand has declined since 1964. In 1989 the reported use for irrigation was 40,000 acre-ft. Recharge to the aquifers was reduced accordingly. New industrial development on the east coast may require pumping ground water for different water uses. Less profit from raising sugarcane has resulted in a reduction of surface-water irrigation, and thus recharge, and may create new problems for management of ground water on the east coast. These problems include ground-water level declines and possibly saltwater intrusion at major pumping centers (Quinones-Aponte, 1991).

The Kingshill aquifer underlying St. Croix consists of the Kingshill Limestone, the Mannings Bay Member of the Kingshill Limestone, and the Blessing Formation. The most permeable zone of the Kingshill aquifer is the Mannings Bay Member of the Kingshill Limestone and the Blessing Formation. Alluvial deposits of Holocene and Pleistocene age are associated with stream channels cut into the Kingshill Limestone. Ground water in the Kingshill aquifer mainly is unconfined. Yields to wells are as much as 100 gal/min but usually are about 30 gal/min. Ground-water withdrawals increased from 50,000 gal/d in the early 1960's to 800,000 gal/d in the late 1980's. Further increase in ground-water withdrawals may induce saline-water intrusion.

The Caribbean Islands regional aquifer-system analysis was started in 1984 and completed in 1990. As of

May 1991, 22 reports had been completed (Sun and Weeks, 1991).

CENTRAL VALLEY, CALIFORNIA

The Central Valley of California (fig. 36) is a long, narrow structural trough containing an aquifer system composed mostly of alluvial deposits of sand, gravel, silt, and clay. The valley occupies about 20,000 mi^2 of flatland between the Sierra Nevada range on the east and the Coast Ranges on the west. The climate is arid, with precipitation totals ranging from 14 to 20 in/yr in the northern part (Sacramento Valley) and from 5 to 14 in/yr in the southern part (San Joaquin Valley). To support the high level of agricultural production, a combination of intensive ground-water pumpage and large imports of surface water is required.

The Central Valley is filled with low-permeability marine deposits overlain by more permeable continental deposits. The continental deposits (of post-Eocene age) contain most of the freshwater and constitute a major aquifer system. The base of the aquifer system is considered to be the base of the post-Eocene continental deposits; however, this is not strictly true everywhere (Bertoldi and others, 1991). Thickness of the aquifer system averages about 2,400 ft and increases from north to south (fig. 36). The continental deposits consist predominantly of lenses of gravel, sand, silt, and clay with fine-grained sediments making up about 50 percent of the sequence. An important contribution of the Central Valley RASA was mapping the texture (proportion of fine-grained to coarse-grained sediments) of the continental deposits by Page (1986). He noted that the post-Eocene deposits "constitute a heterogenous mixture in which texture differs over short distances and depths from chiefly fine-grained to chiefly coarse-grained sediments and vice versa."

Prior to the RASA study, investigators generally conceptualized the Sacramento Valley as containing one water-table aquifer, and the San Joaquin Valley as containing a two-aquifer system separated by a regional clay confining unit. However, a slightly different concept of the aquifer system was proposed by Williamson and others (1989) based on an analysis of ground-water levels, texture of the sediments, and ground-water flow simulations made during the RASA study. The new conceptual model, which is shown in figure 37, assumed that "the entire thickness of the continental deposits is one aquifer system that has varying vertical leakance and confinement depending on the proportion of fine-grained sediments." This conceptual model was used as the basis for a regional computer model of the flow system that simulates recharge, irrigation return flow, pumpage from wells, and discharge as evapotranspiration and to streams (fig. 37). Williamson and others (1989) state that the model "simulates the heterogeneity of the aquifer system by (1) varying the aquifer properties from block to block and (2) averaging values to represent the aggregate of the heterogeneity within each block." The model utilized a three-dimensional finite-difference code (Trescott, 1975) modified to simulate the effects of land subsidence due to inelastic compaction of clay beds.

Ground-water development began in the Central Valley in about 1880, and pumpage for irrigation sharply increased during the 1940's and 1950's. During the 1960's and 1970's, ground-water withdrawals averaged about 11.5 million acre-ft/yr (10 Bgal/d) and provided about 50 percent of the irrigation water supply (Williamson and others, 1989). The intensive pumpage caused ground-water levels to decline 200 to more than 400 ft throughout the western San Joaquin Valley from predevelopment time to the late 1960's. However, the importation of surface water beginning in 1968 replaced much of the former ground-water pumpage there.

The combination of large ground-water pumpage and large imports of surface water completely changed the regional ground-water flow system and ground-water budget (see fig. 14 and discussion in an earlier section). The effects of development are summarized in Williamson and others (1989) as follows:

1. Ground-water flow is now largely from areas recharged by imported surface water toward areas of irrigation pumpage from wells.
2. Most ground-water discharge is now from pumping wells rather than as evapotranspiration or discharge to streams.
3. An estimated 60 million acre-ft loss of aquifer storage has occurred since predevelopment time.
4. The construction of about 100,000 wells, many with long intervals of perforated casing, has increased the effective vertical leakage of the aquifer system by about an order of magnitude.
5. In the western and southern San Joaquin Valley, the large decline of hydraulic head caused inelastic compaction of fine-grained sediments, resulting in the largest volume of land subsidence in the world.

More than one-half of the San Joaquin Valley (or about 5,200 mi^2) has undergone land subsidence of more than 1 ft (fig. 22). Subsidence due to ground-water withdrawals in the valley has been extensively studied by the USGS since the 1950's. The pioneer work by Joseph F. Poland and his colleagues of the USGS established many of the principles of the mechanics of land subsidence and techniques used for field measurements. A brief discussion of the mechanics of land subsidence (due to inelastic compaction of fine-grained beds) is presented in the earlier section entitled "Evaluation of Ground-Water Development Effects." The maximum subsidence (about 30 ft) has occurred on the western side of the San Joaquin Valley near the town of Mendota (fig. 23). Subsidence in the valley has been greatest where pumpage from wells is greatest and

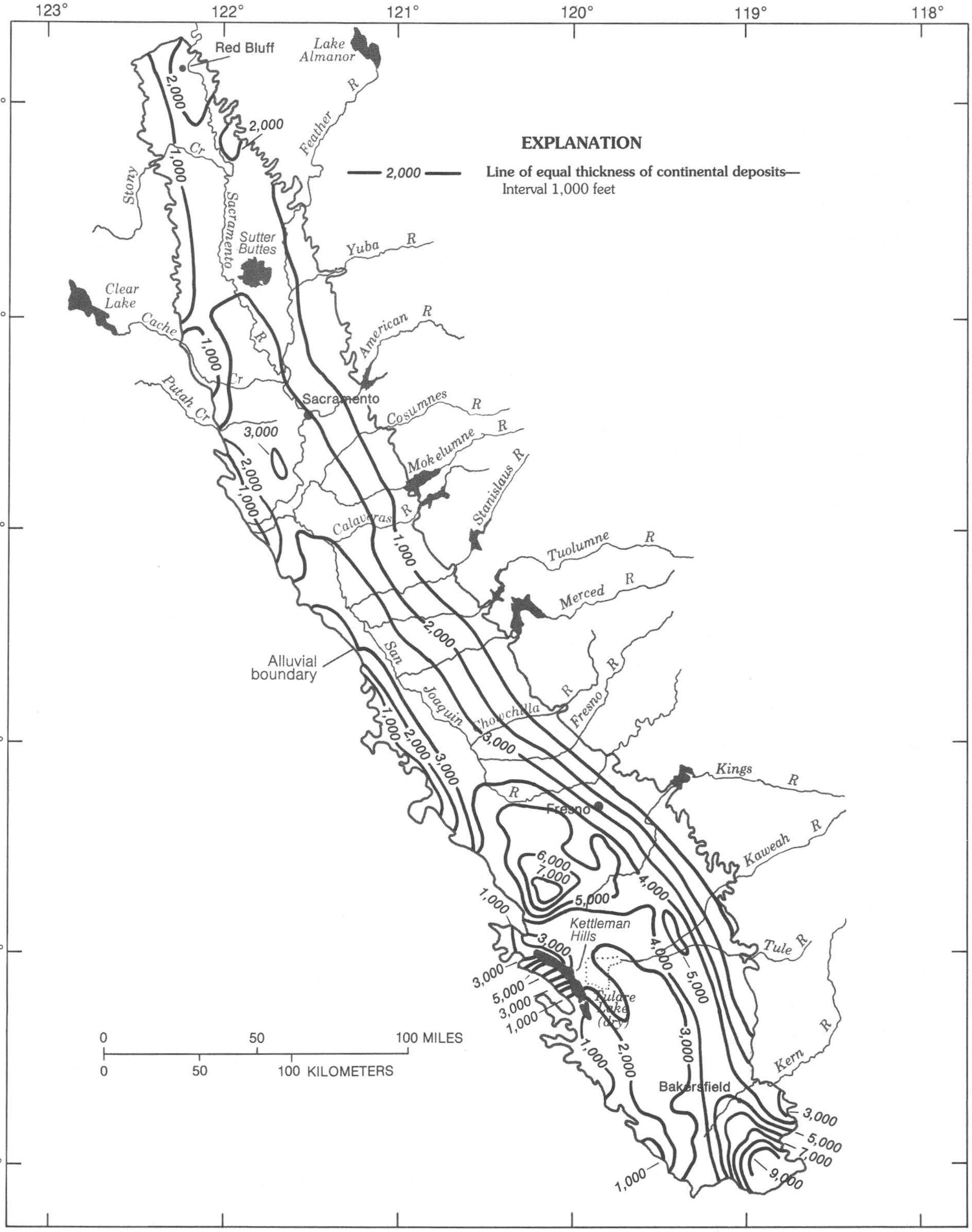


Figure 36. Thickness of the Central Valley aquifer system (largely post-Eocene continental deposits) (from Bertoldi and others, 1991).

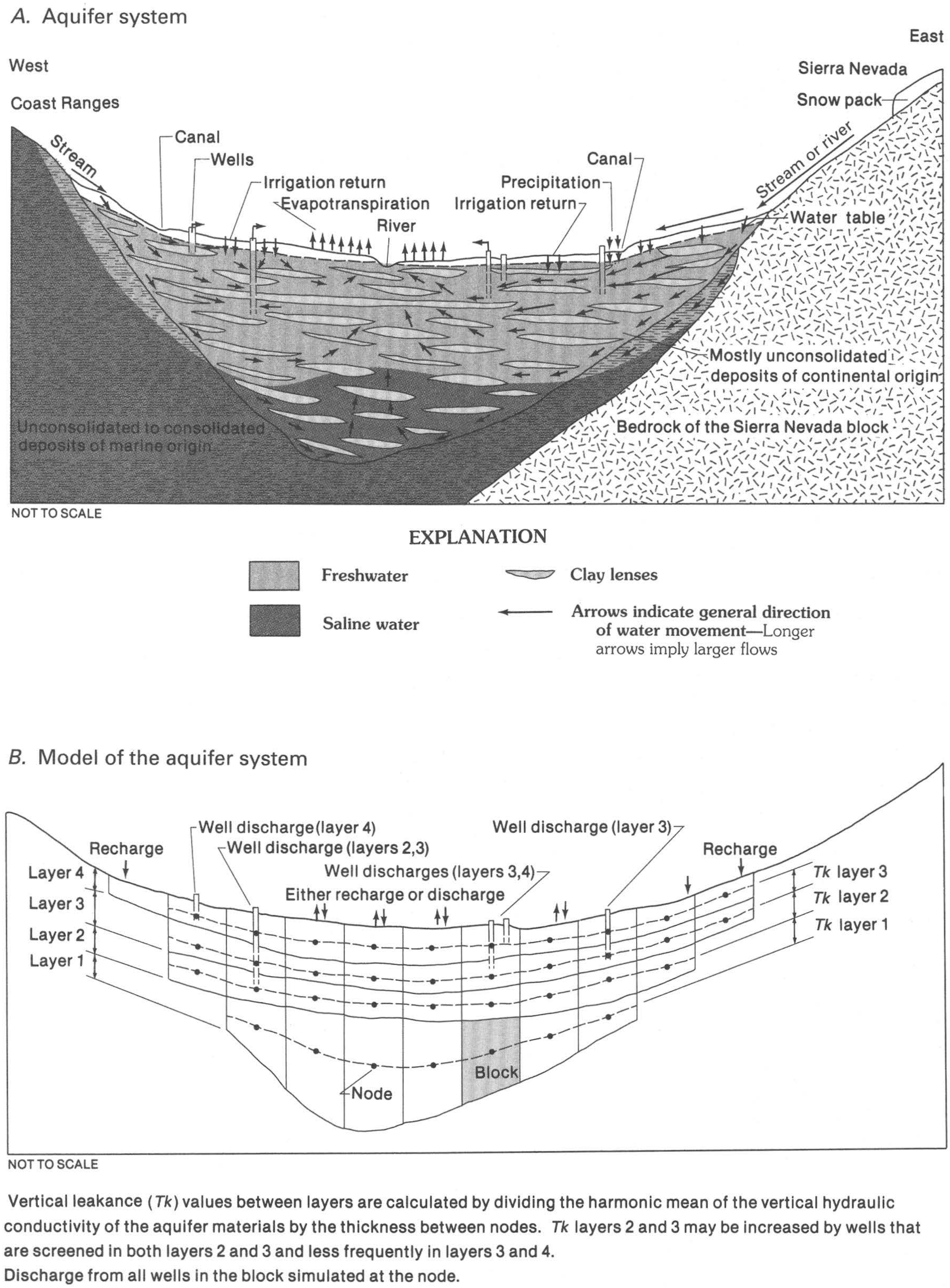


Figure 37. Central Valley aquifer system. *A*, Concept of a single homogeneous aquifer system. *B*, Structure of computer flow model of the aquifer system (from Williamson and others, 1989).

where the aquifer system contains thick sections of montmorillonite clay. The importation of surface water into the western San Joaquin Valley in the late 1960's has largely replaced the ground-water pumpage there. However, during the drought of 1976–77, intensive pumpage from wells resumed, accompanied by a sharp decline of water levels and a short period of renewed compaction. Land subsidence could resume in the future with increased pumpage from wells if water levels decline below previous lows.

Ground-water quality in the Central Valley is influenced by the quality of water in streams that are a major source of recharge (Bertoldi and others, 1991). Generally, concentrations of dissolved solids are lower in the northern part (Sacramento Valley) than in the southern part (San Joaquin Valley). Concentrations of boron, chloride, and nitrate in the ground water are large enough locally to be a problem to crops and humans.

Selenium, which is toxic to humans and animals at very low concentrations, occurs naturally in soils and ground water on the west side of the San Joaquin Valley. In 1983, it was determined that selenium in subsurface tile drains in the western part of the valley was having toxic effects on water fowl in Kesterson Reservoir located there. As a result, a phase II RASA was started to investigate the sources, distribution, and mobility of selenium in soils and ground water of the San Joaquin Valley. It was determined that the present areal distribution of selenium in shallow ground water reflects the natural distribution of saline soils. However, the distribution of selenium in the subsurface results from the long history of irrigation during which soluble forms of selenium have been redistributed from the soil into ground water. Further concentration of selenium in the shallow ground water has occurred owing to evapotranspiration. The rising water table required artificial drainage of ground water containing high concentrations of selenium. Gilliom and others (1989) concluded that the large volume of high-selenium ground water should be left where it is rather than brought to the surface and allowed to move elsewhere.

The study of the Central Valley aquifer system was started in 1978, and Phase I (hydrogeologic framework definition and simulation of ground-water flow and land subsidence) was completed in 1982. Phase II (geochemical investigations and evaluation of selenium mobility) was completed in 1990, and additional reports are still in preparation or review. As of May 1991, 59 reports had been completed. The principal findings of Phase I are presented in U.S. Geological Survey Professional Paper 1401, which consists of the following chapters: Chapter A (Bertoldi and others, 1991) summarizes important aspects of the geologic framework, regional ground-water flow, and ground-water quality in the Central Valley; Chapter B (Hull, 1984) describes the geochemistry of ground water in the Sacramento Valley; Chapter C (Page, 1986) describes the geologic framework of the Central Valley; Chapter D (Williamson and others, 1989) discusses ground-water hydraulics with emphasis on an analysis of regional ground-water flow.

CENTRAL MIDWEST

The Central Midwest regional aquifer-system analysis was an investigation of three major aquifer systems underlying about 370,000 mi^2 in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 38). The study area extends from the foothills of the Rocky Mountains in Colorado to the Mississippi River in eastern Missouri, and from South Dakota to the Ouachita, Arbuckle, and Wichita Mountains of Arkansas and Oklahoma. The study area is informally divided into the Plains subregion and the Ozark subregion. The study is limited to sedimentary rocks ranging from Cambrian through Cretaceous age and does not include the overlying High Plains aquifer, which was studied by the High Plains regional aquifer-system analysis project.

Many of the boundaries of the study area are areas of complex geologic structure, and some are characterized by several structural deformations. Large structural features bounding the study area include the Rocky Mountains on the west, the Sioux Ridge on the northeast, and a series of uplifts on the south. The Mississippi and Missouri Rivers form the eastern and northeastern boundaries. The rivers and their associated alluvial aquifers are regional discharge areas of the aquifer systems (Signor and Imes, 1989).

The rocks, except those included in the High Plains aquifer, are grouped into three aquifer systems and three confining units (fig. 39). The three aquifer systems are (1) the Great Plains aquifer system, (2) the Western Interior Plains aquifer system, and (3) the Ozark Plateaus aquifer system. The Western Interior Plains aquifer system is laterally adjacent to the Ozark Plateaus aquifer system. These two aquifer systems consist of equivalent geologic strata; however, they have distinctly different regional flow systems and have a common boundary along a regional topographic low that parallels the boundary between the Plains and Ozark subregions. Except at the upper part of the Great Plains aquifer system, both the Great Plains and the Western Interior Plains aquifer systems contain mostly saline water. However, the Ozark Plateaus aquifer system contains mostly freshwater. The three confining systems were named for the underlying aquifer systems; they are, in descending order, (1) the Great Plains confining system, which separates the High Plains aquifer from the underlying Great Plains aquifer system; (2) the Western Interior Plains confining system, which separates the Great Plains aquifer system from the underlying Western Interior Plains aquifer system; and (3) the basement confining unit, the lowermost boundary of the Western Interior Plains and Ozark Plateaus aquifer systems (figs. 39 and 40).

The Great Plains confining system consists of Upper Cretaceous shale and extends throughout the northwestern one-half of the study area. It increases from near zero thickness along its southern and eastern margins to more than 8,000 ft in the basin areas of southeastern Wyoming and eastern Colorado. Where the High Plains aquifer is absent, the confining system generally is the surficial unit. The thick shale of the confining system effectively restricts flow between the High Plains aquifer and the underlying Great Plains aquifer system. The small vertical leakage through the confining system is from the High Plains aquifer (high head) to the Great Plains aquifer system (low head). The known head difference in western Nebraska, southeastern Wyoming, and northern Colorado exceeds 1,600 ft. Two extensive but minor aquifers, the Greenhorn Limestone and Niobrara Chalk, are in the confining system.

The Great Plains aquifer system consists of two aquifers: the Maha and Apishapa aquifers. In most places these two aquifers are separated by the Apishapa confining unit. Where the confining unit is missing, the two aquifers merge into a single aquifer. The Great Plains aquifer system consists mainly of sandstone, siltstone, and shale, with wide variations in texture, degree of fracturing, and thickness. Total thickness of the aquifer system generally is from 200 to 800 ft, being greatest in north-central Nebraska (Helgesen and Leonard, 1989). The Great Plains aquifer system includes the Dakota Sandstone and equivalent beds that were recognized early as a major artesian reservoir by Darton (1905). The Great Plains aquifer system is one of the most extensive aquifer systems in North America and extends over most of the northwestern one-half of the study area. Ground water generally flows from west to east and recharges in large outcrop areas in southeastern Colorado, along the front range of the Rocky Mountains in southern Colorado, near the Black Hills in southwestern South Dakota, and in east-central Kansas. Ground water discharges at outcrops where the Missouri River incises

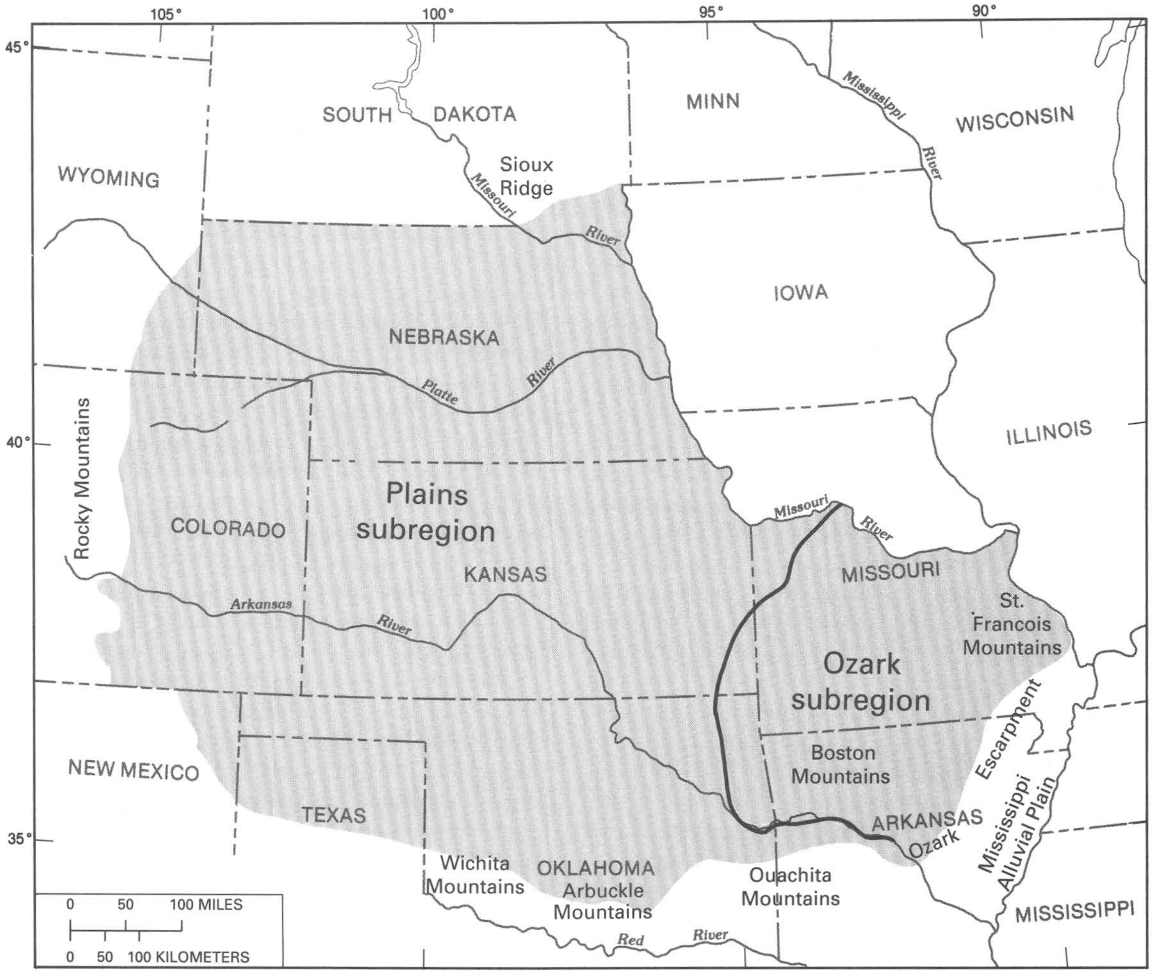


Figure 38. Study area (shaded) of the Central Midwest regional aquifer-system analysis.

the aquifer system in southeastern South Dakota, eastern Nebraska, and western Iowa. Simulation of regional flow in the Great Plains aquifer system suggests that withdrawals during the 1970's were more than twice the natural recharge rate. (See discussion of the aquifer system in the earlier section entitled "Regional Ground-Water Budgets.") Concentrations of dissolved solids range from 500 mg/L or less in the outcrop areas to more than 100,000 mg/L in oil-field brines in the Denver basin. In much of the aquifer system, water is brackish (1,000 to 10,000 mg/L of dissolved solids).

The Western Interior Plains confining system consists mostly of (1) shale with lesser amounts of limestone and sandstone of Pennsylvanian age and (2) shale with evaporite deposits and sandstone/limestone of Permian age. The confining system exists everywhere in the study area except along the easternmost part of the border between South Dakota and Nebraska and in the Ozark subregion. The thickness of the confining system ranges from near zero in northeastern Nebraska and along the western and southern margins of the Ozark subregion to more than 24,000 ft in southwestern Oklahoma. Locally, sandstone and limestone in the confining system are aquifers.

The Western Interior Plains aquifer system consists of aquifers composed of permeable limestone, dolostone, and sandstone of Cambrian to Mississippian age. These aquifers are separated by shale or dolostone of low permeability; thus, the aquifer system can be subdivided into an upper permeable unit and a lower permeable unit. The aquifer system extends from the Rocky Mountains eastward to the western boundary of the Ozark Plateaus aquifer system, but it is not present in large areas of Nebraska and Colorado. The aquifer system contains mostly brackish water (1,000 to 10,000 mg/L of dissolved solids). A potentiometric surface map based on equivalent freshwater heads indicates that ground water flows from outcrop areas to the east and southeast.

The Ozark Plateaus aquifer system consists of rocks that are laterally equivalent to those of the Western Interior Plains aquifer system. However, the Ozark Plateaus aquifer system contains freshwater and exists as a separate regional ground-water flow system. The extent of the Ozark Plateaus aquifer system is approximately coincident with the extent of the Ozark Plateaus. Rocks making up the Ozark Plateaus aquifer system are grouped into three aquifers and two confining units. In descending order, they are (1) the Springfield Plateau aquifer, (2) the Ozark confining unit, (3) the Ozark aquifer, (4) the St. Francois confining unit, and (5) the St. Francois aquifer. The Ozark Plateaus aquifer system consists mainly of limestone, dolostone, and sandstone of Late Cambrian through Late Mississippian age.

The Springfield Plateau aquifer is the uppermost aquifer of the Ozark Plateaus aquifer system and consists of Mississippian-age limestone. The aquifer is used only for domestic and stock water supply owing to low well yields.

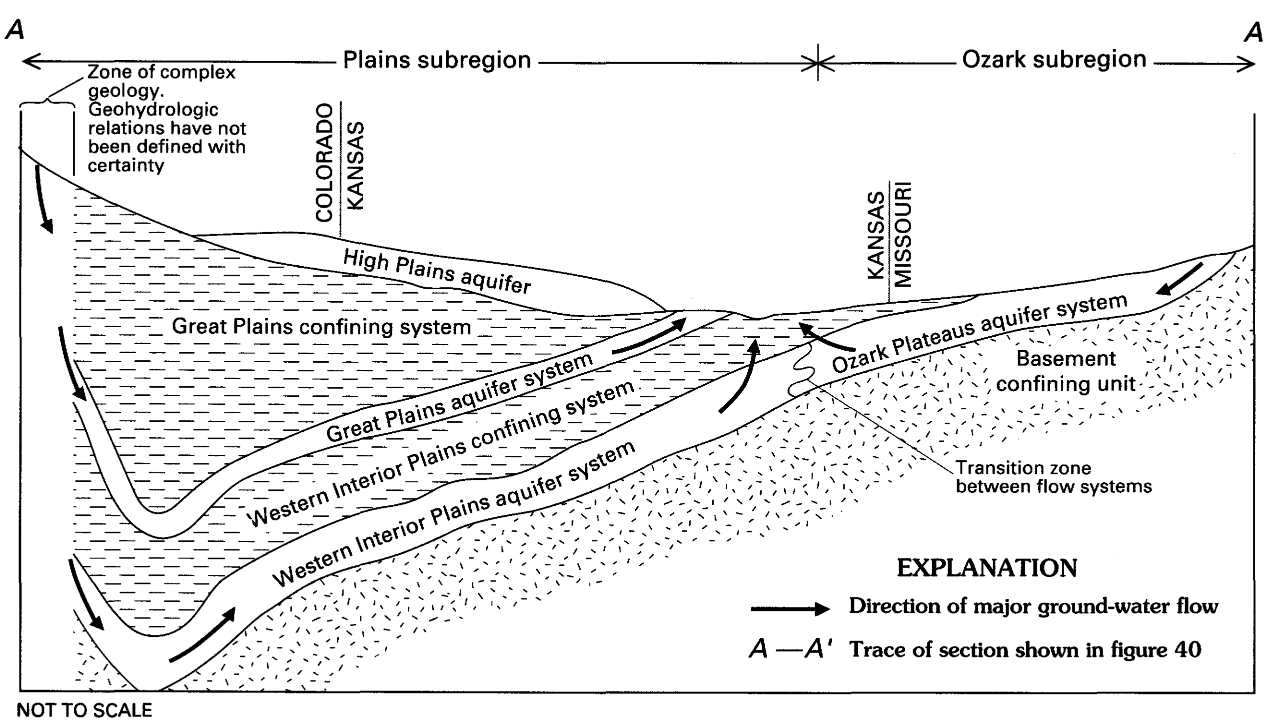


Figure 39. Geohydrologic section showing regional aquifer systems and confining systems in the central midwestern United States (from Signor and Imes, 1989).

The thickness of the aquifer ranges from 100 to 400 ft. The aquifer acts as a sink and source for the underlying Ozark aquifer. The Ozark confining unit, consisting of the Maquoketa Shale of Late Ordovician age and the Early Mississippian-age Chouteau Limestone, overlies the Ozark aquifer, thus separating the Springfield Plateau aquifer from the underlying Ozark aquifer. The thickness of the confining unit ranges from near 0 to 1,500 ft. However, in most of the study area the thickness is less than 100 ft.

The Ozark aquifer is the most areally extensive and widely used aquifer in the Ozark subregion. The aquifer consists of dolostone, limestone, and chert of Late Cambrian through Middle Devonian age. The thickness of the Ozark aquifer ranges from about 800 to 1,500 ft. Yields of deep wells may exceed 1,000 gal/min. Dissolution of the mainly carbonate rocks along fractures and bedding planes has produced a substantial karst terrane, with hundreds of springs in the upper few hundred feet of the aquifer. Water in the aquifer is generally a calcium bicarbonate type with concentrations of dissolved solids ranging from 200 to 500 mg/L.

The St. Francois confining unit restricts flow between the Ozark aquifer and the St. Francois aquifer. The confining unit has significant vertical permeability and is considered to be a leaky unit, consisting of shale, siltstone, dolostone, and limestone of Late Cambrian age. The confining unit is exposed at land surface in a narrow, nearly circular band about 400 mi^2 in area that surrounds a central core of older rocks in the St. Francois Mountains. Thickness of the confining unit ranges from near zero to 730 ft.

The St. Francois aquifer is the lowermost aquifer of the Ozark Plateaus aquifer system and consists mainly of dolostone, siltstone, and sandstone of Late Cambrian age. These permeable rocks overlie the Basement confining unit. The aquifer crops out in the St. Francois Mountains of southeast Missouri. Beyond the 590 mi^2 outcrop area,

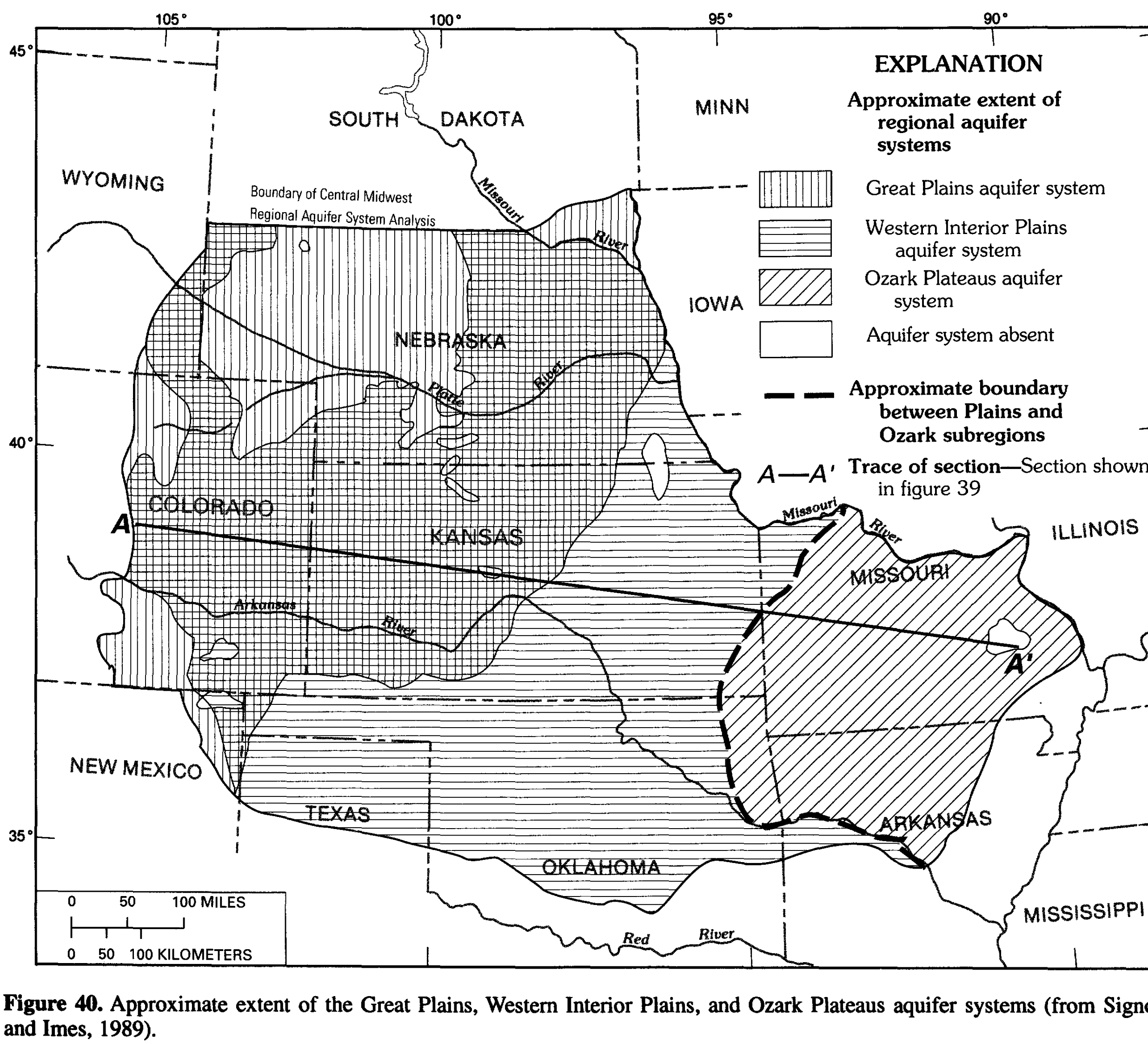


Figure 40. Approximate extent of the Great Plains, Western Interior Plains, and Ozark Plateaus aquifer systems (from Signor and Imes, 1989).

the aquifer dips into the subsurface and is buried beneath younger, more permeable rocks. The depth of burial generally is between 800 and 1,400 ft in the central and western part of the Ozark subregion and is deeper elsewhere. The aquifer is more than 300 ft thick in northern Arkansas; however, in western and southwestern parts of the Ozark subregion, the aquifer is less than 300 ft thick and thins toward the west.

The St. Francois aquifer is primarily used in and near its outcrop area. Wells 200 to 300 ft deep may yield less than 10 gal/min; however, some wells are reported to yield 50 gal/min. Water in the aquifer is a calcium magnesium bicarbonate type with concentrations of dissolved solids ranging from 200 to 400 mg/L.

Underlying the Ozark Plateaus and Western Interior Plains aquifer systems is the basement confining unit, consisting mostly of crystalline rocks of Precambrian age. These rocks may be fractured and yield water to wells locally, as in east-central Colorado, southeastern South Dakota, and southeastern Missouri, although regionally they are assumed to have low permeability and to form the base of the aquifer systems in both the Plains and Ozark subregions. The top of the basement confining unit ranges from more than 1,000 ft above sea level in southeastern Missouri to about 34,000 ft below sea level in central Oklahoma.

The Central Midwest regional aquifer-system analysis was started in 1980 and completed in 1989. As of May 1991, 63 reports had been completed (Sun and Weeks, 1991). As of mid-1993, chapters B, D, and E of Professional Paper 1414 were approved for publication and chapters A and C are in review.

COLUMBIA PLATEAU, WASHINGTON, OREGON, AND IDAHO

The Columbia Plateau is in central and eastern Washington, northern Oregon, and a small part of Idaho. The plateau covers about 63,200 mi^2 entirely within the drainage of the Columbia River and is bordered on the west by the Cascade Range, on the north and east by the Rocky Mountains, and on the south by the Blue Mountains (fig. 41). Extensive hydrologic evaluation and flow simulation was done in about 32,700 mi^2. The study area is underlain everywhere by massive basalt flows with an estimated maximum thickness of 16,000 ft in a structural low near the center of the plateau. Basalt flows overlie sedimentary, igneous, and metamorphic rocks with low permeability. This prebasalt rock is considered the lowermost confining unit of the Columbia Plateau regional aquifer system. Over a very large area of the plateau, the basalt is overlain by sedimentary rocks of Holocene through Miocene age. These sedimentary rocks are the major sources of ground water for all uses in the study area. During this study, all sedimentary rocks overlying the basalt with a thickness of 50 ft or more were collectively named the "overburden aquifer."

Rocks that comprise the Columbia River Basalt Group were emplaced by extrusion of numerous individual lava flows through fissures. Individual flows range in thickness from a few inches to more than 300 ft and average about 110 ft. The structure of a lava flow generally consists of three units (fig. 42): flow top, entablature, and colonnade (Swanson and Wright, 1978). The flow tops also include the basal part (flow bottom) of the overlying flow that consists of pillow-palagonite complexes. Groundwater flow is predominantly horizontal within interflow zones (the tops of one flow and bottoms of the overlying flow), which average about 5 to 30 ft in thickness. In general, the entablature and colonnade are dense with vertical fractures.

Ground-water flow through fractures in the entablature and colonnade is predominantly vertical. Locally, the basalt flows are interbedded with sediments that function either as confining units or aquifers. The interbeds vary from shalely material to sand and gravel, with fine-grained materials predominating. Generally, more interbeds are present in the younger basalt than in the older basalt.

The Columbia River Basalt Group has been subdivided into five formations and numerous members. The five formations, from oldest to youngest, are the Imnaha Basalt, Picture Gorge Basalt, Grande Ronde Basalt, Wanapum Basalt, and the Saddle Mountains Basalt (Swanson and others, 1979). The Imnaha Basalt is present in northeastern Oregon and adjacent Washington and Idaho, where it is exposed chiefly in valleys of the Imnaha, Snake, Salmon, and Clearwater Rivers. The Picture Gorge Basalt is exposed only in north-central Oregon, mostly within the John Day basin south of the Blue Mountains uplift, where it is interlayered locally with Grande Ronde Basalt. Because of small areal extent and occurrence at edges of the plateau, the Imnaha and Picture Gorge Basalts are not considered important aquifers; therefore, they were included with the Grande Ronde Basalt. On the basis of these assumptions, the Columbia River Basalt Group was subdivided into three basalt aquifers: in descending order, the Saddle Mountains, Wanapum, and Grande Ronde Basalt units (Drost and Whiteman, 1986). These basalt aquifers are separated by two confining units, the Saddle Mountains–Wanapum and Wanapum–Grande Ronde interbed confining units.

The interbeds are areally extensive but thin compared with the basalt formations. The interbeds locally function as aquifers, but regionally they act as confining units. The Saddle Mountains–Wanapum interbed confining unit consists mainly of clay, silt, claystone, or siltstone. Thickness of the confining unit averages about 50 ft but may be nearly 0 to 200 ft. The Wanapum–Grande Ronde interbed confining unit is most extensive and thickest in the northern part of the plateau, where it varies from nearly 0 to 100 ft in thickness and averages about 25 ft. It consists chiefly of claystone and siltstone, with minor beds of sand, gravel, and sandstone. The Wanapum–Grande Ronde thins to the south. Where absent, a thin saprolite commonly marks the interval.

Model-derived hydraulic conductivity for the overburden aquifer is from 5×10^{-4} to 1.3×10^{-2} ft/s with a median of 5×10^{-4} ft/s. Hydraulic conductivity of basalt is from 1×10^{-6} to 1×10^{-4} ft/s, with a median of 1.6×10^{-5} ft/s for the Saddle Mountains Basalt unit and 3×10^{-5} ft/s for the Wanapum Basalt unit. The Grande Ronde Basalt unit was simulated as two zones. Model-simulated median hydraulic conductivity is 1.6×10^{-5} ft/s for the upper Grande

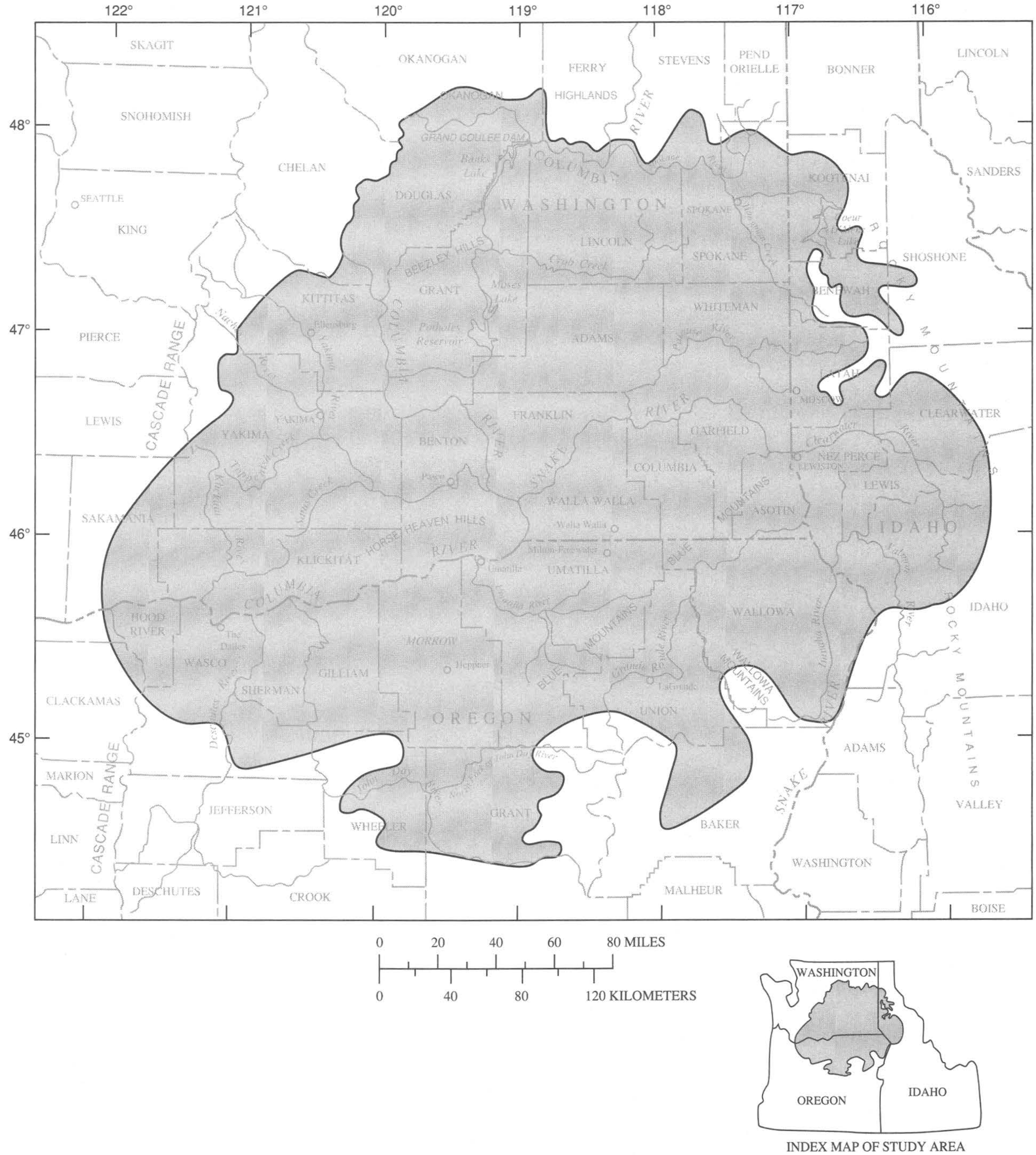


Figure 41. Study area of the Columbia Plateau regional aquifer-system analysis.

Ronde basalt unit and 1.4×10^{-5} ft/s for the lower Grande Ronde Basalt unit. Median vertical hydraulic conductivity of the overburden aquifer is about 2×10^{-5} ft/s and for the basalt units is 1.5×10^{-8} ft/s.

Water in the overburden aquifer flows toward discharge points at surface-water bodies. Water in the overburden aquifer is in direct hydraulic connection with water in the immediately underlying basalt unit. The potentiometric surface for the Saddle Mountains Basalt unit indicates that water in the basalt flows primarily toward major streams. This flow pattern also exists for the Wanapum and Grande Ronde Basalt units where not overlain by younger basalts. If they are deeply buried, as in the south-central part of the plateau, the potentiometric surfaces are less influenced by surface-drainage features and consequently have a smooth configuration. Regional discharge is toward the Columbia and Snake Rivers.

Recharge to the aquifers primarily is from precipitation on the plateau. However, this natural condition was disturbed by irrigation with surface water imported to the plateau under the Columbia Basin Irrigation Project (CBIP), starting in the early 1950's. Since then, part of the recharge is supplied by excess irrigation water (irrigation return flow).

Ground water was developed mostly after World War II, increased rapidly from 1965 to 1979, but has decreased somewhat since then. For example, pumpage was about 56,000 acre-ft in 1945, it was 78,000 acre-ft in 1960, then increased to about 940,000 acre-ft in 1979, and decreased to 813,000 acre-ft in 1983. The combination of imported surface water and withdrawals of ground water for irrigation, and municipal and industrial uses, caused ground-water levels in the plateau to rise in some places and decline in other places. In the CBIP area, water levels rose as much as 300 ft and averaged about 12 ft owing to the importation of surface water for irrigation. Water-level declines in the Wanapum Basalt units were as much as 400 ft and averaged about 60 ft due to pumping of ground water. Irrigation with imported surface water increased recharge about 50 percent; ground-water discharge increased accordingly. During the 1980's, only about 15 percent of the pumpage was supplied from aquifer storage.

Water in the basalt units generally is of good quality and suitable for most uses. However, in areas of surface-water irrigation and where the overburden is less than 200 ft thick, water from shallow wells drilled into the Saddle Mountains Basalt unit may have increased concentrations of dissolved solids due to induced recharge from irrigation return flow that has high concentrations of dissolved solids. Nitrogen concentrations (nitrate plus nitrite as N) of 2 mg/L or more occur in water from the Saddle Mountains Basalt unit in surface-water-irrigated areas where the overburden is thin or absent. However, nitrogen concentrations are less than 2 mg/L in water from wells deeper than 500 ft.

The Columbia Plateau regional aquifer-system analysis was started in 1982 and completed in 1989. As of mid-1992, 24 reports had been completed. Chapter B of Professional Paper 1413 has been approved for publication and three other chapters are in preparation.

GREAT BASIN, NEVADA AND UTAH

The Great Basin regional aquifer-system analysis covers an area of about 140,000 mi^2 in parts of Nevada, Utah, and adjacent states (fig. 43). The area is characterized by generally north-trending mountain ranges 5 to 15 mi in width, which rise 1,000 to 5,000 ft above adjoining valleys. The width of valleys is about the same as the width of the adjacent mountain ranges. The valleys are

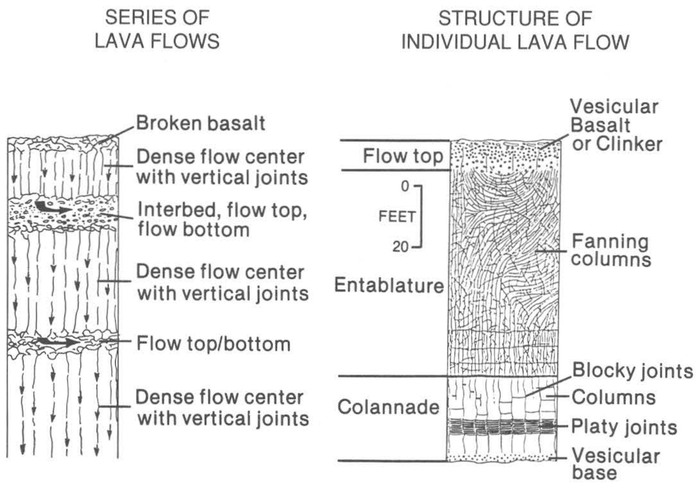


Figure 42. Basalt interflow structures (from Swanson and Wright, 1978).

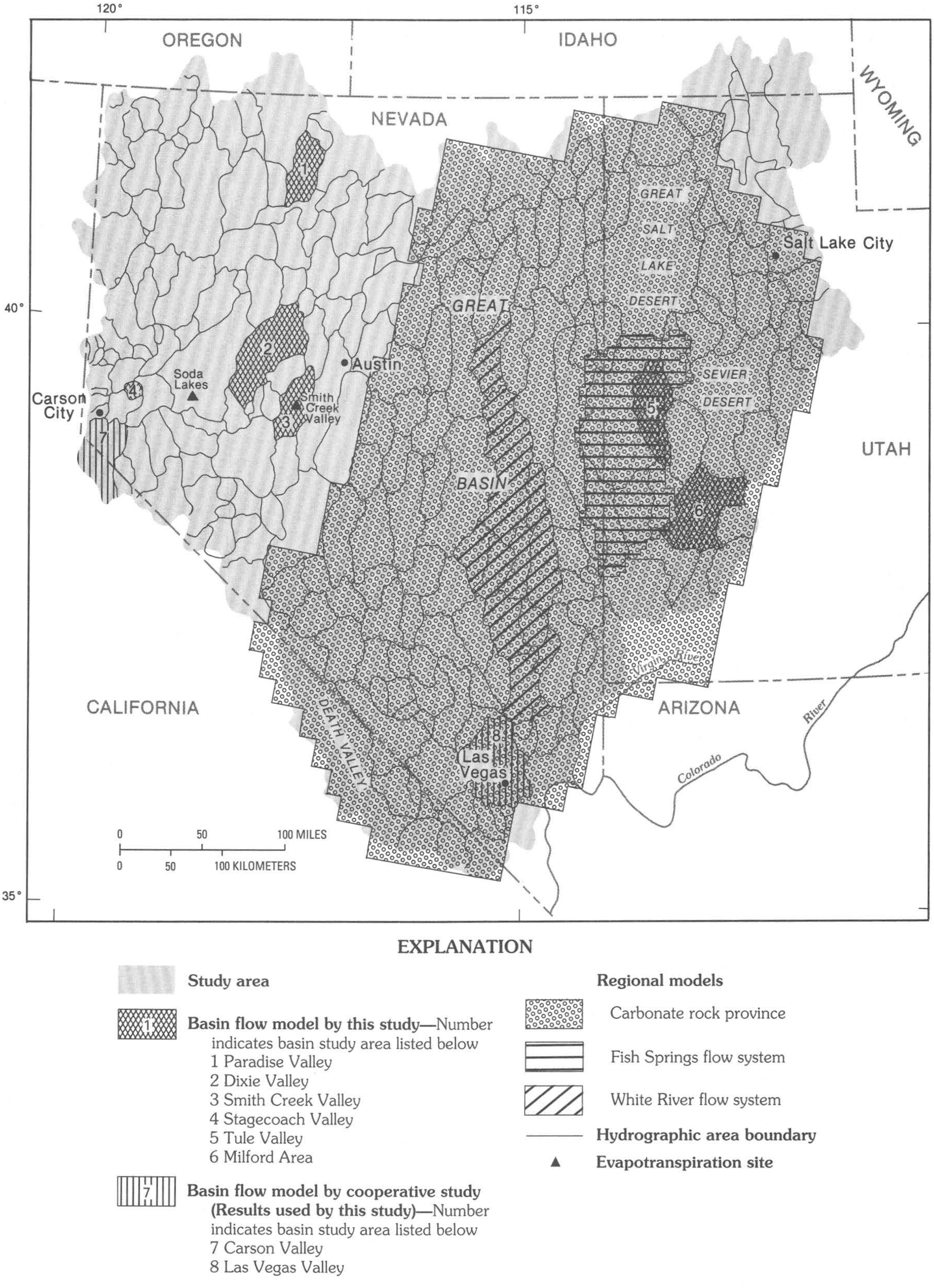


Figure 43. Study area and types of ground-water flow models, Great Basin regional aquifer system (from Harrill, 1986).

typically elongated, and many extend more than 50 mi 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 that formed the basin and range topography. The Great Basin regional aquifer-system analysis study has grouped 242 hydrographic areas that share many common geologic and hydrologic characteristics. Most of the grouped hydrographic areas include one or more structural basins and associated basin-fill aquifers. A special situation is found in eastern Nevada and western Utah, where permeable carbonate rocks underlie the basin-fill deposits and form a complex ground-water flow system that reflects the characteristics of both basin-fill and carbonate aquifers. Selected basins were studied and simulated with ground-water flow models (fig. 43).

The study included investigation of recharge and evapotranspiration processes at selected sites. Recharge-process studies involved a mass balance of chloride between precipitation and ground water (Dettinger, 1989). Evapotranspiration studies used the Bowen-ratio technique and eddy correlation measurement (Carman, in press). Eight basins were selected for computer-based model simulations, which collectively represent most conditions present in the study area. Three regional flow models were also made: One simulates flow in the carbonate rock province between the Great Salt Lake Desert and Death Valley, and the others are smaller scale models of the Fish Springs flow system and the White River flow system (fig. 43). The purpose of the regional flow models is to test the validity of the conceptualized flow systems. All models were run for steady-state conditions. The carbonate rock province simulation indicates that flow in the carbonate rocks can be subdivided into five deep-flow regions. These regions, named after the terminal sinks of the regional flows, are (1) Death Valley, (2) Colorado River, (3) Bonneville, (4) Railroad Valley, and (5) Upper Humboldt River. Superimposed over the deep-flow regions are 17 shallow-flow regions that approximately coincide with flow systems delineated from topography, water-level data, and discharge areas. Flow in the carbonate rocks generally is from south to north toward the Great Salt Lake Desert (Bonneville region) and the Humboldt River in the eastern and northern parts of the province; elsewhere, flows are from north to south toward either Death Valley or the Virgin and Colorado Rivers. Recharge is principally precipitation on mountain ranges. About 3 percent of precipitation recharges the carbonate rocks. Discharge is mainly evapotranspiration and flow to springs and terminal sinks, particularly in the Colorado River region (Prudic and others, in press).

The 242 hydrographic areas were grouped into 39 major flow systems (fig. 44). Of these, 14 are single-basin flow systems, and the remainder are multibasin flow systems. Large multibasin flow systems outside the carbonate rock province are generally coincident with major drainage systems. Large multibasin flow systems within the carbonate rock province typically have little surface flow. Ground water from multibasins in the carbonate rock province, where there is little surface water, discharges to large springs and is consumed by evapotranspiration in the vicinity of the springs.

The Great Basin regional aquifer-system analysis was started in 1980 and completed in 1988. As of late 1992, 48 reports had been completed. One chapter of Professional Paper 1409 has been printed, four are in press, and others are in review or in preparation.

GULF COASTAL PLAIN

The Gulf Coastal Plain regional aquifer-systems analysis covers about 230,000 mi^2 onshore in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Mississippi, Missouri, Tennessee, Texas, and all of Louisiana (fig. 45). The study also includes 60,000 mi^2 offshore between the coast and the edge of the Continental Shelf. 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 water in parts of several states. The bottom of the Gulf Coastal Plain aquifer systems is specified at either the top of the Midway Group of Paleocene age, which consists of low-permeability sediments (mostly marine clays), or at the top of the zone of geopressure. The sediments are thin in and near outcrop areas but thicken to several thousand feet gulfward in downdip areas. None of the individual aquifers are continuous throughout the study area; some underlie only a few hundred square miles. Some of the aquifers in sediments of Eocene age are present in 8 of the 10 States studied and supply large quantities of freshwater for all uses. The unconsolidated to semiconsolidated sediments are complexly interbedded sequences of sand, silt, and clay with minor beds of lignite, gravel, and limestone.

Salt-dome basins occur across the area from southern Texas to southwestern Alabama. The domes penetrate most or all Tertiary strata at any given location; however, only a few are at or near land surface. Salt domes penetrating aquifers and permeable zones in the Gulf Coastal Plain have been mapped by Beckman and Williamson (1990). Faulting associated with the domes is localized, and the domes typically are 1 to 3 mi in diameter. The effects of salt domes on regional freshwater flow are localized. However, the dissolution of salt in the deep part of the salt basins may affect ground-water flow in sediments that contain highly mineralized water. Regional fault zones that parallel the coastline seem to have less influence on regional ground-water flow; however, they may have significant impact locally.

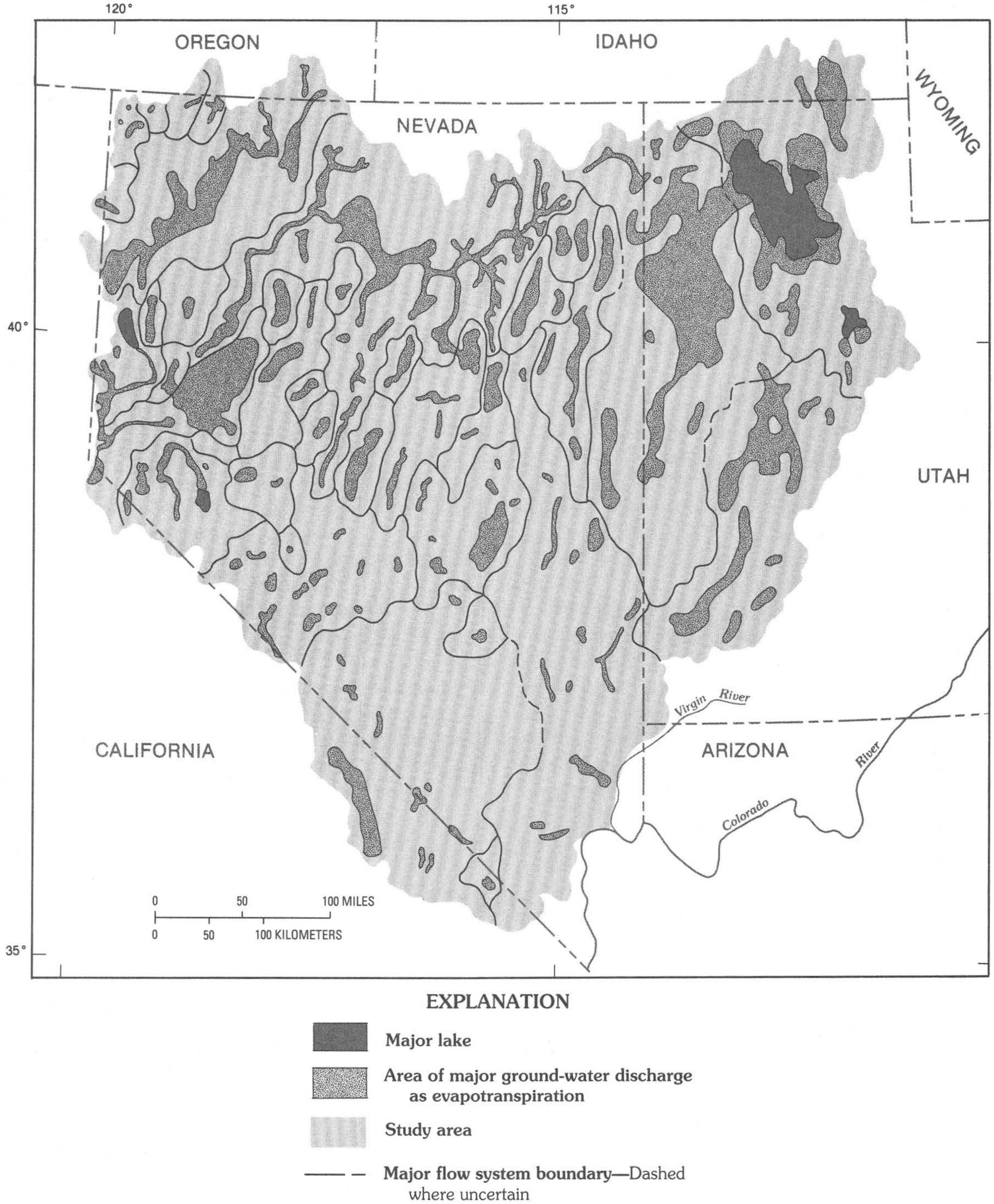


Figure 44. Major flow systems and major ground-water discharge areas of the Great Basin regional aquifer system (from Harrill, 1986).

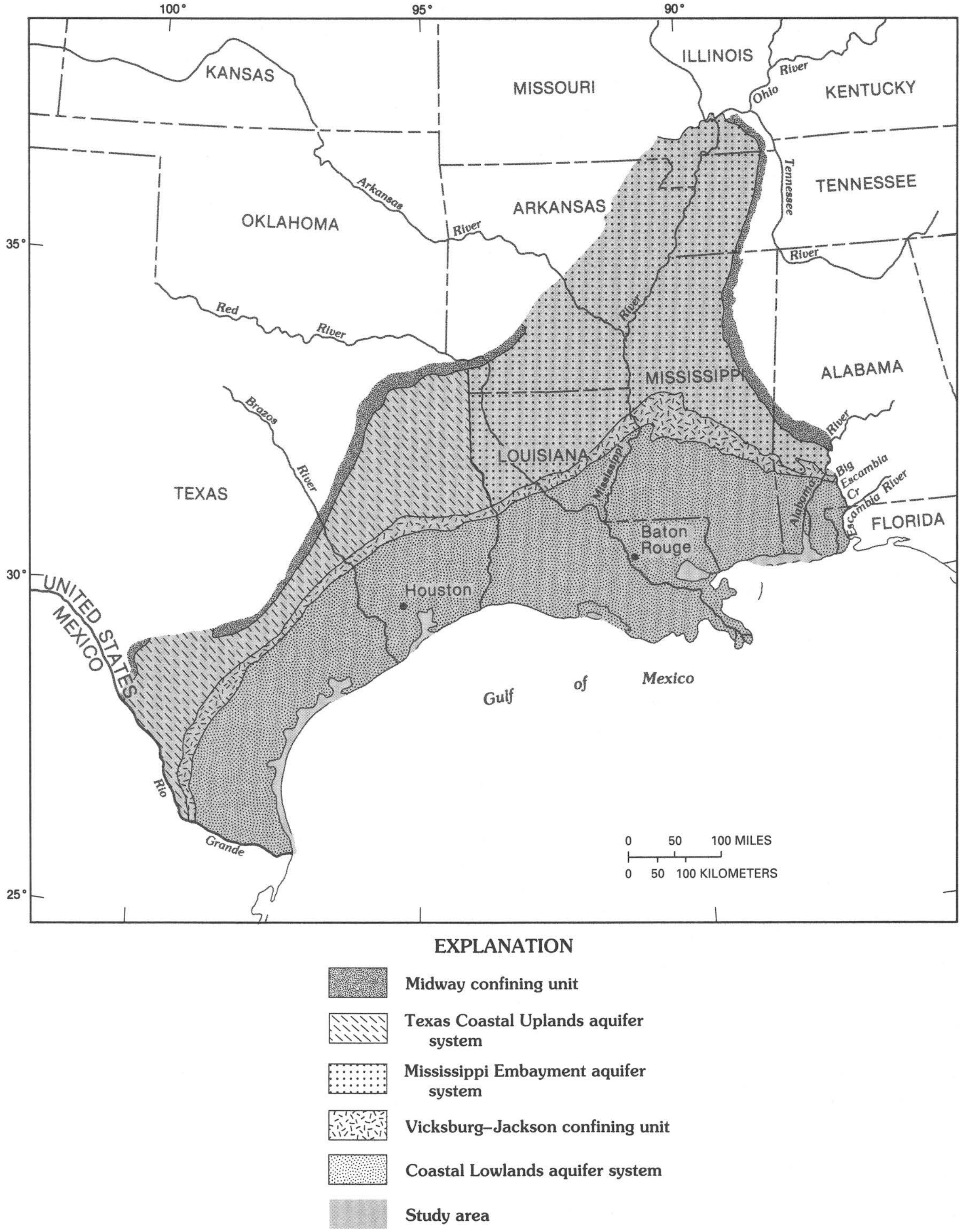


Figure 45. Study area and outcrops of regional aquifer systems and confining units, Gulf Coastal Plain regional aquifer-systems analysis (modified from Mesko and others, 1990).

On the basis of differences in regional ground-water flow patterns and sediment characteristics, three aquifer systems were delineated during this RASA study: (1) the Mississippi embayment aquifer system, (2) the Texas coastal uplands aquifer system, and (3) the coastal lowlands aquifer system (fig. 45). These aquifer systems were further divided vertically into six regional aquifers, five permeable zones, and six confining units (fig. 46). The aquifers range in areal extent from about 32,000 mi^2 (the Mississippi River Valley alluvial aquifer) to about 170,000 mi^2 (the middle Wilcox aquifer). The average thickness of the Mississippi River Valley alluvial aquifer is least (140 ft), and permeable zone C (lower Pliocene–upper Miocene deposits) has the greatest average thickness (2,000 ft). Average percentage of sand ranges from 34 percent in the middle Wilcox aquifer to 70 percent in the Mississippi River Valley alluvial aquifer.

Water in the aquifer systems is fresh in and near outcrop areas. Except for a few areas in southern Texas, concentrations of dissolved solids are less than 2,000 mg/L in outcrop areas. Elsewhere the concentrations of dissolved solids of water in outcrop areas are generally less than 1,000 mg/L. Concentrations of dissolved solids generally increase toward the Gulf of Mexico and toward principal discharge areas. Increase in concentrations from 10,000 to 35,000 mg/L typically occur over distances of 10 to 40 mi. Aquifers of the Mississippi embayment aquifer system contain more freshwater than aquifers of the Texas coastal uplands aquifer system primarily because the embayment

Mississippi Embayment aquifer system / **Texas coastal uplands aquifer system**

Geologic unit			Mississippi Embayment aquifer system: Geohydrologic units	Texas coastal uplands aquifer system: Geohydrologic units
System	Series	Group		
Quaternary	Pleistocene and Holocene		Mississippi River Valley alluvial aquifer	Not present
Tertiary	Eocene and Oligocene	Jackson and Vicksburg	Vicksburg-Jackson confining unit[1]	Vicksburg-Jackson confining unit[1]
Tertiary	Eocene	Claiborne	Upper Claiborne aquifer	Upper Claiborne aquifer
Tertiary	Eocene	Claiborne	Middle Claiborne confining unit	Middle Claiborne confining unit
Tertiary	Eocene	Claiborne	Middle Claiborne aquifer	Middle Claiborne aquifer
Tertiary	Eocene	Claiborne	Lower Claiborne confining unit	Lower Claiborne confining unit
Tertiary	Eocene	Claiborne / Wilcox	Lower Claiborne–upper Wilcox aquifer	Lower Claiborne–upper Wilcox aquifer
Tertiary	Eocene	Wilcox	Middle Wilcox aquifer	Middle Wilcox aquifer
Tertiary	Eocene / Paleocene	Wilcox	Lower Wilcox aquifer	Not present
Tertiary	Paleocene	Midway	Midway confining unit[1]	Midway confining unit[1]

Coastal lowlands aquifer system

Geologic unit			Geohydrologic units
System	Series	Group	
Quaternary	Holocene		Permeable zone A
Quaternary	Pleistocene		Permeable zone A
Quaternary / Tertiary	Pleistocene / Pliocene		Permeable zone B
Tertiary	Pliocene / Miocene		Permeable zone C
Tertiary	Miocene		Zone D confining unit
Tertiary	Miocene		Permeable zone D
Tertiary	Miocene		Zone E confining unit
Tertiary	Miocene / Eocene and Oligocene	/ Jackson and Vicksburg	Permeable zone E
Tertiary	Eocene and Oligocene	Jackson and Vicksburg	Vicksburg-Jackson confining unit[1]

[1] The confining units are defined as the massive clay section (with interbedded sands) of the Midway Group and the undifferentiated Jackson and Vicksburg Groups that are recognizable on geophysical logs. The recognizable lithologic unit may not be equivalent to the geologic unit as determined by fossils or other means of correlation and dating, because the upper and lower part of either the Midway Group or the undifferentiated Jackson and Vicksburg Groups may be sandy and therefore included in the adjacent aquifer or permeable zone. The Midway confining unit was referred to as the Coastal Uplands confining system and the Vicksburg-Jackson confining unit was referred to as the Coastal Lowlands confining system by Grubb (1984, p. 11).

Figure 46. Geohydrologic and geologic units of the Gulf Coastal Plain aquifer systems (from Grubb, 1987).

aquifers have a greater areal extent updip of the Vicksburg-Jackson confining unit, and perhaps secondarily because there is less rainfall in the western part of the study area than in the eastern part. Permeable zones of the coastal lowlands aquifer system in southern Texas are only a few hundred square miles in areal extent where concentrations of dissolved solids are less than 1,000 mg/L.

In 1985, about 9,000 Mgal/d of water was pumped from the Gulf Coastal Plain aquifer systems. About 75 percent was for irrigation, 15 percent was for municipal supply, and 10 percent was for industrial uses.

The base of the Mississippi embayment aquifer system is the Midway confining unit except along a narrow band, as much as 20 mi wide, across southern Louisiana, where the top of the geopressure zone is above the top of the sediments comprising the confining unit. The confining unit has a maximum thickness of about 3,500 ft in Louisiana and an average thickness of about 750 to 850 ft. Extensive and massive sand beds, especially in the updip freshwater part, are characteristic of the Mississippi embayment aquifer system. Some aquifers are separated by areally extensive confining units; others are not separated by areally extensive confining units but are defined on the basis of differences in lithology. The resistance to vertical flow among the aquifers is provided by interbedded fine-grained sediments (Grubb, 1987).

The Texas coastal uplands aquifer system consists of sediments that are laterally equivalent to those of the Mississippi embayment aquifer system, except that the sediments comprising the Mississippi River Valley alluvial aquifer and the lower Wilcox aquifer are missing from the Texas coastal uplands aquifer system (Grubb, 1987). The other aquifers of the Mississippi embayment aquifer system are also present in the Texas coastal uplands aquifer system and are called by the same names (fig. 46).

The base of the coastal lowlands aquifer system is the Vicksburg-Jackson confining unit, except in the Continental Shelf area and a narrow band onshore along the coast of Texas and Louisiana where the top of the geopressure zone is above the top of the sediments comprising the Vicksburg-Jackson confining unit. The confining unit has a maximum thickness of about 6,000 ft in eastern Louisiana and an average thickness of about 500 ft. Five permeable zones and two confining units were grouped within the coastal lowlands aquifer system. Because of the complexity of the interbedded sediments and the absence of areally extensive marker beds that have hydrologic significance, the permeable zones were delineated on the basis of differences in hydraulic heads between permeable zones (Grubb, 1987). No names were given to the permeable zones, which are labeled by letters from A through E for purposes of discussion (fig. 46).

Regional predevelopment flow in the Mississippi embayment aquifer system was from high-water-level areas along the eastern side of the study area to the Mississippi Alluvial Plain in Missouri, Arkansas, northwestern Mississippi, and northeastern Louisiana. Some flow paths may be as long as 200 to 300 mi, extending from east-central Mississippi southward from aquifer outcrop areas beneath the Vicksburg-Jackson confining unit, and then northwestward toward large discharge areas in northeastern Louisiana (fig. 45). Regional flow in the Texas coastal uplands aquifer system was from high-water-level areas between the major rivers to narrow discharge areas in the vicinity of the rivers. Flow paths in this aquifer system are only tens of miles in length. The circulation of freshwater gulfward from the outcrop of the Vicksburg-Jackson confining unit occurred in only a small part of the Rio Grande embayment. Regional flow in the coastal lowlands aquifer system generally was from high-water-level areas between the major rivers and adjacent to the outcrop band of the Vicksburg-Jackson confining units to the major rivers. In addition, flow was to regional discharge areas that are parallel to the shoreline and centered about midway between the recharge areas and the shoreline. Discharge of freshwater to the Gulf of Mexico probably occurred only along the coast of Mississippi, Alabama, and Florida, where areas of high water levels were within a short distance of the shoreline. The extensive flat topography with little relief throughout many coastal areas in Louisiana and Texas offered little opportunity to develop local flow systems (Grubb, 1987).

Ground-water pumpage for cities or for agriculture since the late 1800's has modified the flow system in places. For example, most of the onshore predevelopment discharge areas have become net recharge areas. As discussed in the earlier section on regional ground-water budgets, most of the current pumpage is supplied by increased percolation to the regional flow system. Due to the abundance of water in streams, lakes, and swamps, and their hydraulic connection with water-table aquifers, the potential for induced recharge to the underlying aquifers is substantial. Therefore, the potential for future development of ground water from the three Gulf Coastal Plain aquifer systems is good. Areas with potential for further development of ground-water supplies have been delineated by Ackerman (1990), Ryder and Ardis (1991), and Martin and Whiteman (1991).

The Gulf Coastal Plain regional aquifer-systems analysis study was started in 1980 and completed in 1991. As of late 1992, 68 reports had been completed. Two chapters of Professional Paper 1416 have been printed, six are in press, and three others are either in review or in preparation.

NORTHEAST GLACIAL AQUIFERS

The Northeast Glacial Aquifers study differs from most RASA studies. It involves many sand-and-gravel aquifers deposited by meltwater in the glaciated Northeast that do not constitute a single, continuous aquifer system. Almost all glacial aquifers are in valleys bounded by low-permeability bedrock, thus limiting aquifer width to a few thousand feet or less and limiting aquifer length to several thousand feet or less. These valley aquifers are independent hydrologic entities; they are related only in a regional sense in that they are widely distributed across the glaciated Northeast and their hydrogeologic characteristics are similar owing to common depositional conditions.

The study area includes most of the glaciated Northeast, extending approximately as far west as the edge of the glaciated Appalachian Plateau in Ohio. Long Island, New York, and Cape Cod, Massachusetts, are excluded from the study because the ground-water hydrology in these two areas has been studied extensively (fig. 47). The study area ranges from mountainous areas, such as the White Mountains of New Hampshire and Maine, the Green Mountains of Vermont, and the Adirondack and Catskill Mountains of New York, to low-lying areas along the Great Lakes, the St. Lawrence River valley, the Hudson and Mohawk River valleys; and the lowlands along the Atlantic Coast.

The study area has been divided into five hydrogeologic terranes for grouping and discussing aquifers that have similar characteristics (Randall and Johnson, 1988). These divisions or terranes, shown in figure 48, are based on geology of the glacial deposits and physiography. Most of the study area and most of the productive glacial aquifers are in type A terranes (fig. 48), where aquifers were formed largely in valleys that generally sloped or drained away from the ice sheets. The stratified deposits were largely laid down in lakes of modest extent. Coarse-grained sediment deposited

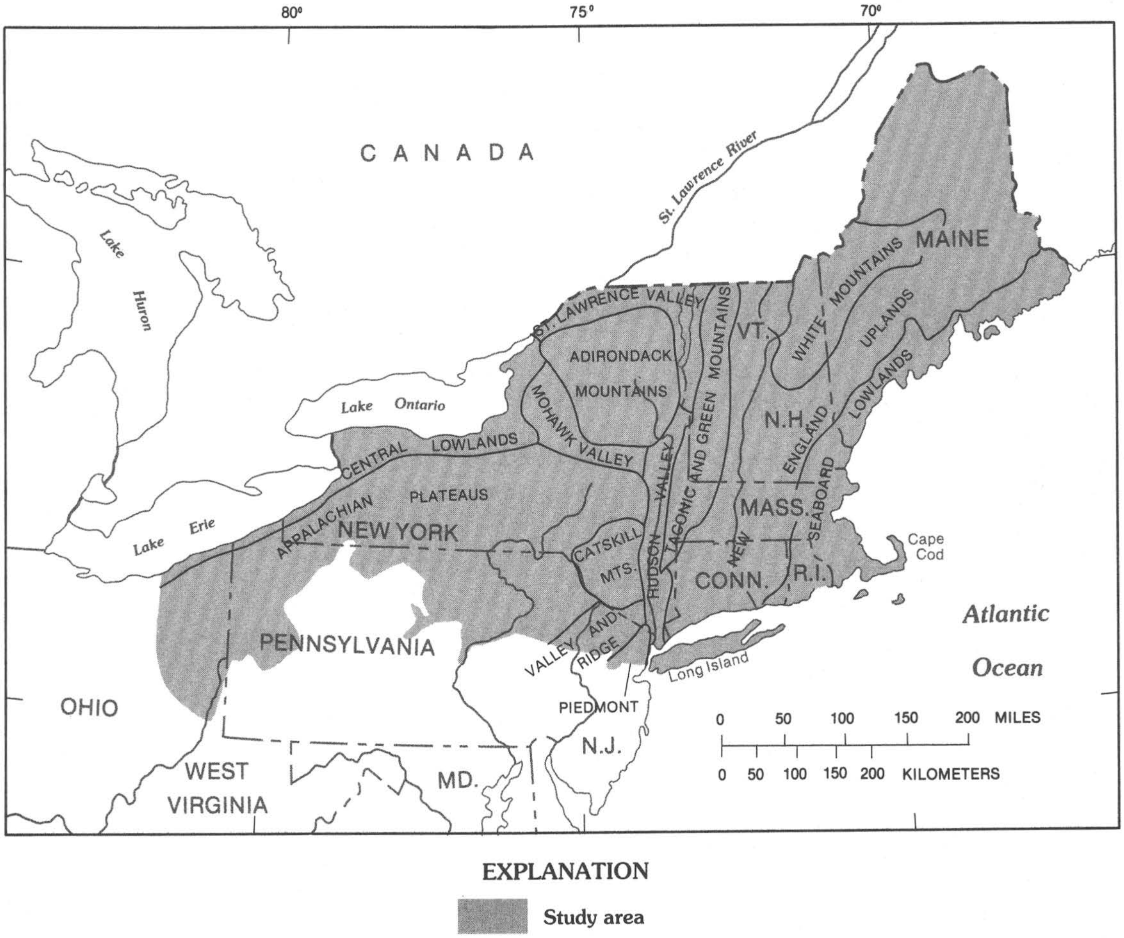


Figure 47. Study area and physiographic divisions of the Northeast Glacial Aquifers regional aquifer-system analysis.

near the ice margin commonly prograded southward as deltas across fine-grained sediments on the bottom of lakes. As the ice continued to melt, coarse-grained sediments that had been deposited on or against it collapsed and were overlapped by fine-grained lake-bottom sediments that settled later as the process was repeated farther north.

Glacial aquifers in type B terranes were formed in broad lowland areas inundated by large lakes or seawater as ice retreated. Some of the early ice-contact deposits are productive aquifers, but they are widely scattered. The fine-grained sediments deposited later are extensive. Where coarse sand caps the fine sediments, the sand commonly is

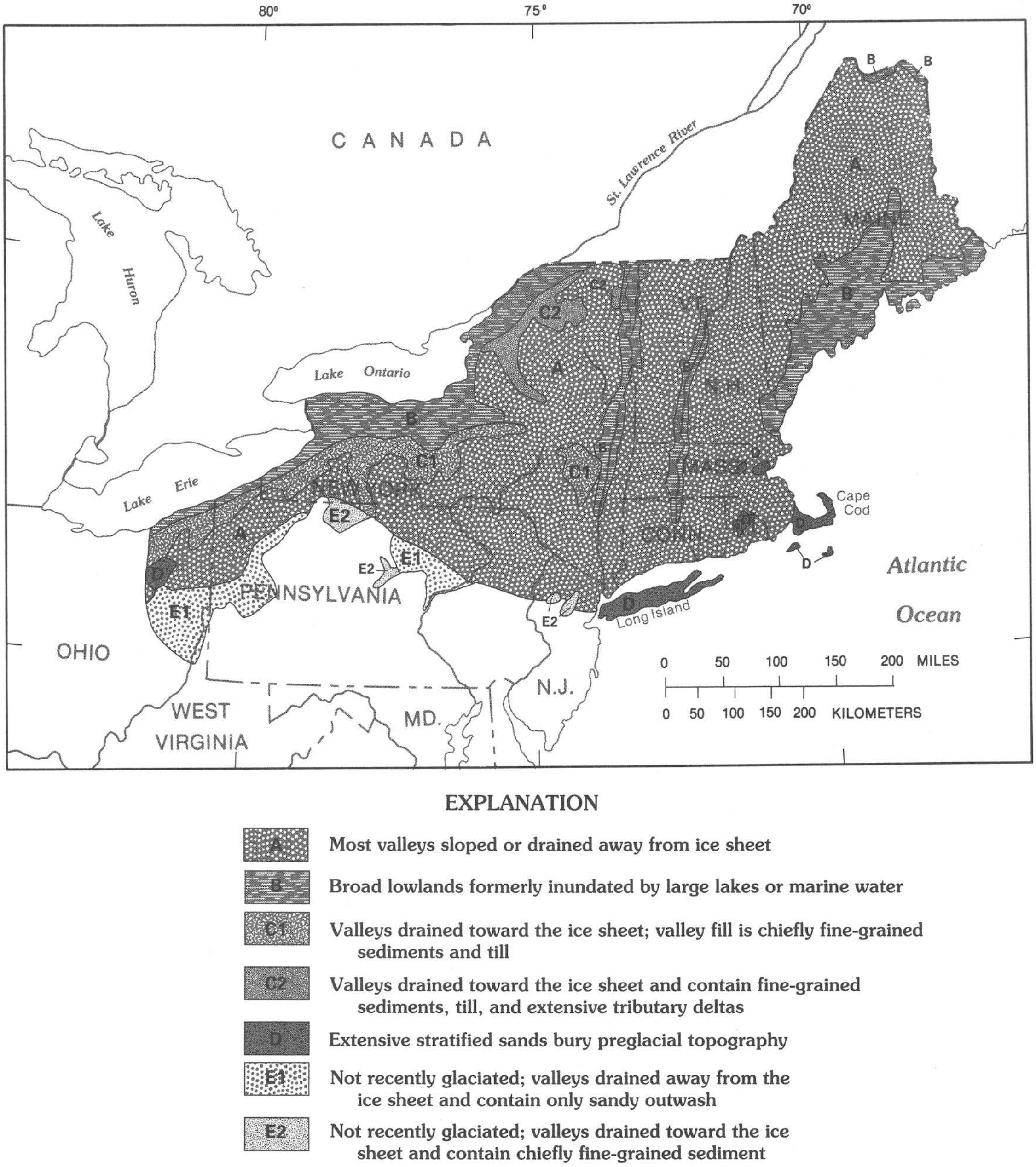


Figure 48. Hydrophysiographic terranes in glacial drift of the Northeastern United States (from Randall and Johnson, 1988).

thin or so deeply incised by postglacial streams that its saturated thickness is small. Coarse-grained stratified drift is sparse in type B terranes.

Glacial aquifers in type C terranes are characterized by valleys that drained toward ice sheets. Glacial drift commonly is several hundred feet thick and consists largely of lake-bottom silt and clay that are interlayered in places with till composed of reworked lacustrine sediments. Coarse-grained sediments, a minor fraction of the valley fill, may have originated in two ways: (1) as alluvium or possibly deltaic deposits of north-draining streams deposited during intervals between ice readvances, or (2) as local outwash deposited by meltwater at the base of an ice tongue during advance or retreat of ice.

In a few areas of low relief, chiefly in southeastern New England, broad outwash plains and ice-contact deposits (largely sand) bury the preglacial topography, not only filling the valleys but covering most of the ridges. These areas are grouped as type D terranes in figure 48.

Beyond the southern limit of the last major ice sheet, highly permeable, sandy outwash was deposited in numerous valleys that carried meltwater away from the ice. At the same time, fine-grained sediments were deposited in lakes ponded by ice in a few north-draining valleys. These areas are grouped as type E terranes in figure 48.

Knowing the aquifer geometry and the distribution of coarse-grained sediments is important in locating optimum well sites for ground-water development. Several geophysical techniques were evaluated during this study. Continuous seismic-reflection techniques, including marine seismic reflection, were tested. These surface geophysical techniques proved very useful for determining the thickness and lithology of stratified drift in the glaciated Northeast (Haeni, in press).

Previous workers suggested that most recharge to glacial aquifers in the Northeast is from precipitation on the valley floor. However, the findings of this RASA study suggest that over half of the recharge under natural conditions is from upland runoff, infiltration of streamflow, unchanneled runoff, and (or) lateral ground-water discharge from the adjacent uplands (Morrissey and others, 1988). Ground water in glaciated valleys mainly discharges to streams. The main streams that follow the axes of the larger valleys gain from ground water along nearly their entire length. However, ground-water development in the glaciated Northeast can completely disturb this natural hydrologic system. Wells drilled near large streams can intercept large quantities of water that otherwise would become streamflow. Near small streams, pumping from nearby large well fields may reduce streamflow significantly. For these reasons, the Northeast Glacial Aquifers RASA study used isotopes and temperature measurements to evaluate and observe the interaction between streamflow and water in glacial aquifers (Dysart, 1988; Lapham, 1989).

The Northeast Glacial Aquifers regional aquifer-systems analysis was started in 1981 and completed in 1989. As of May 1991, 27 reports had been completed (Sun and Weeks, 1991). The scheduled chapters of Professional Paper 1415 are either in review or in preparation, except for chapter C (Haeni, in press), which has been approved for publication.

NORTHERN MIDWEST

The Northern Midwest regional aquifer-system analysis was an investigation of the Cambrian-Ordovician aquifer system underlying 161,000 mi^2 in parts of Illinois, Indiana, Iowa, Minnesota, Missouri, and Wisconsin (fig. 49). The aquifer system consists of Cambrian and Ordovician rock (mainly sandstone and dolomite). The aquifer system is a primary source of water throughout most of its area of occurrence, except for Indiana, central and southern Illinois, and western Iowa, where the aquifer system contains saline water.

Rocks of the aquifer system were deposited in shallow seas that encroached on the Precambrian rock surface, which slopes generally southward from Minnesota and Wisconsin but eastward from eastern Wisconsin. Structural basins are located in southwestern Iowa, south-central Illinois, and Michigan. The rock strata of the aquifer system crop out in an arc around the Wisconsin arch and thicken toward the structural basins, where they are deeply buried by younger sedimentary rocks. The aquifer system contains three distinct aquifers—the St. Peter–Prairie du Chien–Jordan aquifer, the Ironton-Galesville aquifer, and the Mount Simon aquifer. The aquifers are primarily sandstone, separated by shale, shaly dolomite, or siltstone confining units. Where the Maquoketa Shale is present, it and the underlying dolomite and shale strata of the Galena Dolomite and the Decorah, Platteville, and Glenwood Formations form a major confining unit that overlies the three aquifers.

The Cambrian-Ordovician aquifer system is a leaky system, and ground-water flow is partly controlled by confining units. Much of the recharge is in upland areas and most discharge is to nearby streams through local flow paths. The remainder of the recharge moves slowly downward to deeper formations and downgradient to the regional flow system. Regional ground-water flow generally is away from high areas in the north toward low areas in the south and east. Principal discharge areas of the regional flow system are the Mississippi and Missouri Rivers, the Illinois and Michigan basins, and Lake Michigan.

Development of the aquifer system began in the 1860's near Lake Michigan in eastern Wisconsin and northeastern Illinois, and along the valleys of the Mississippi River and its nearby tributaries. Wells flowed initially. The initial hydraulic heads were 186 ft above the water level of Lake Michigan at Milwaukee and 130 ft at Chicago (Young and others, 1989b). By 1980, large-scale pumping had caused the hydraulic heads to decline as much as 425 ft at Milwaukee and 900 ft at Chicago (Young and others, 1989a). Projection of future water needs indicates continuing or increasing demands and, therefore, continuing water-level declines.

Simulation provided ground-water budgets for predevelopment and 1980 conditions (fig. 13) and indicated that the 1980 pumpage of 684 Mgal/d was supplied mostly by an increase in recharge and to a lesser extent by a decrease in discharge and loss of water from storage (see the earlier section on regional ground-water budgets).

The aquifer system contains highly mineralized water in several places, especially in its deepest parts, which generally coincide with regional discharge or structurally low areas. These areas are mainly in the southwestern, southern, and eastern parts of the study area. Water from highly mineralized zones may be introduced into freshwater zones by large withdrawals of freshwater, such as those withdrawals presently occurring in northeastern Illinois, southeastern Wisconsin, and central Iowa. Newly developed simulation techniques that account for multiaquifer well effects and water with variable density in space (but not with time)

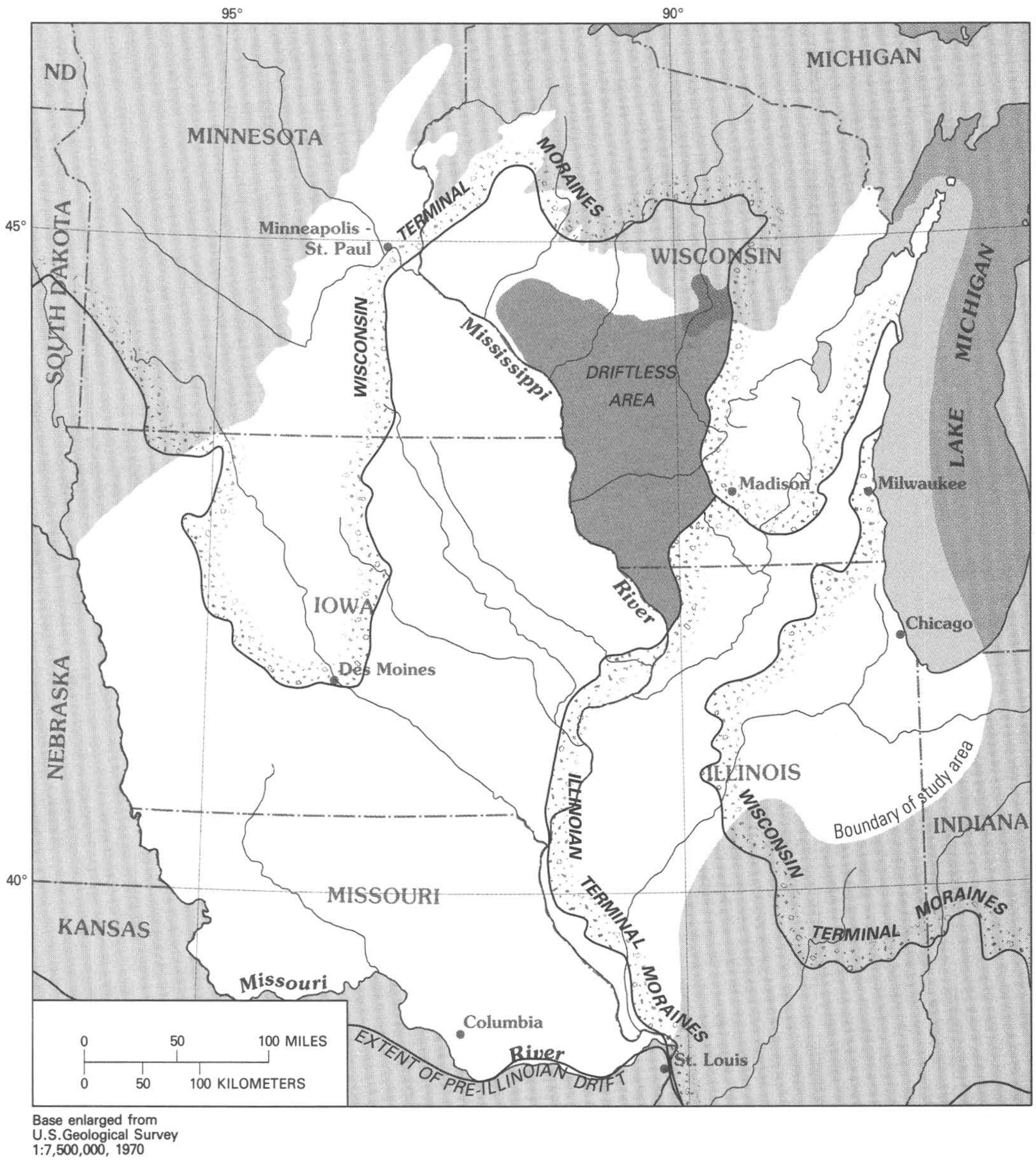


Figure 49. Study area of the Northern Midwest regional aquifer-system analysis and extent of major glaciation during the Pleistocene Epoch (from Young and others, 1989b).

were used in simulation of this aquifer system (Kontis and Mandle, 1988).

During the Northern Midwest RASA study, the hydrologic evidence and results of flow simulation of the Cambrian-Ordovician aquifer system indicated that most of the water is recharged in outcrop areas in Wisconsin and southern Minnesota, or through the leaky Maquoketa confining unit. Water then flows eastward to Lake Michigan or southeastward to the Illinois basin. However, the concentration of dissolved solids (fig. 50) suggests that ground-water flow in central Iowa is southwestward toward Missouri, which is approximately perpendicular to the flow direction interpreted from the potentiometric surface or simulated by the flow model. This different interpretation of flow direction in central Iowa was supported by isotope analyses of water from wells in Iowa. Siegel (1989) hypothesized that Pleistocene recharge probably was a factor in the occurrence of a plume of water having higher concentrations of dissolved solids (fig. 50). Water in the plume is isotopically depleted in $\delta^{18}O$ (standard expression of the ratio of the less abundant oxygen-18 ion with respect to modern precipitation). This observation indicates that water in the aquifer was precipitated in a climate similar to that hundreds of miles north of the study area and suggests that the water probably was recharged during Pleistocene glaciation. The northeast-to-southwest increase in concentration of dissolved solids in water in the St. Peter–Prairie du Chien–Jordan aquifer in central Iowa suggests that the direction of paleo-ground-water flow was perpendicular to present flow. This earlier flow path might be due to emplacement of subglacial meltwater under high hydraulic gradients from ice loading in areas such as the Great Lakes. This hypothetical explanation of paleo-recharge is further supported by concentrations of sulfur isotopes in water from wells in central Iowa (Siegel, 1989).

The Northern Midwest regional aquifer-system analysis was started in 1978 and completed in 1984. As of May 1991, 31 reports had been completed, of which 4 are Professional Papers 1405–A through –D (Sun and Weeks, 1991). Professional Paper 1405–A (Young, 1992a) summarizes the Cambrian-Ordovician aquifer system, 1405–B (Young, 1992b) discusses the hydrogeologic framework of the aquifer system, 1405–C (Mandle and Kontis, 1992) describes the simulation of the regional flow system, and 1405–D (Siegel, 1989) discusses geochemistry of the Cambrian-Ordovician aquifer system.

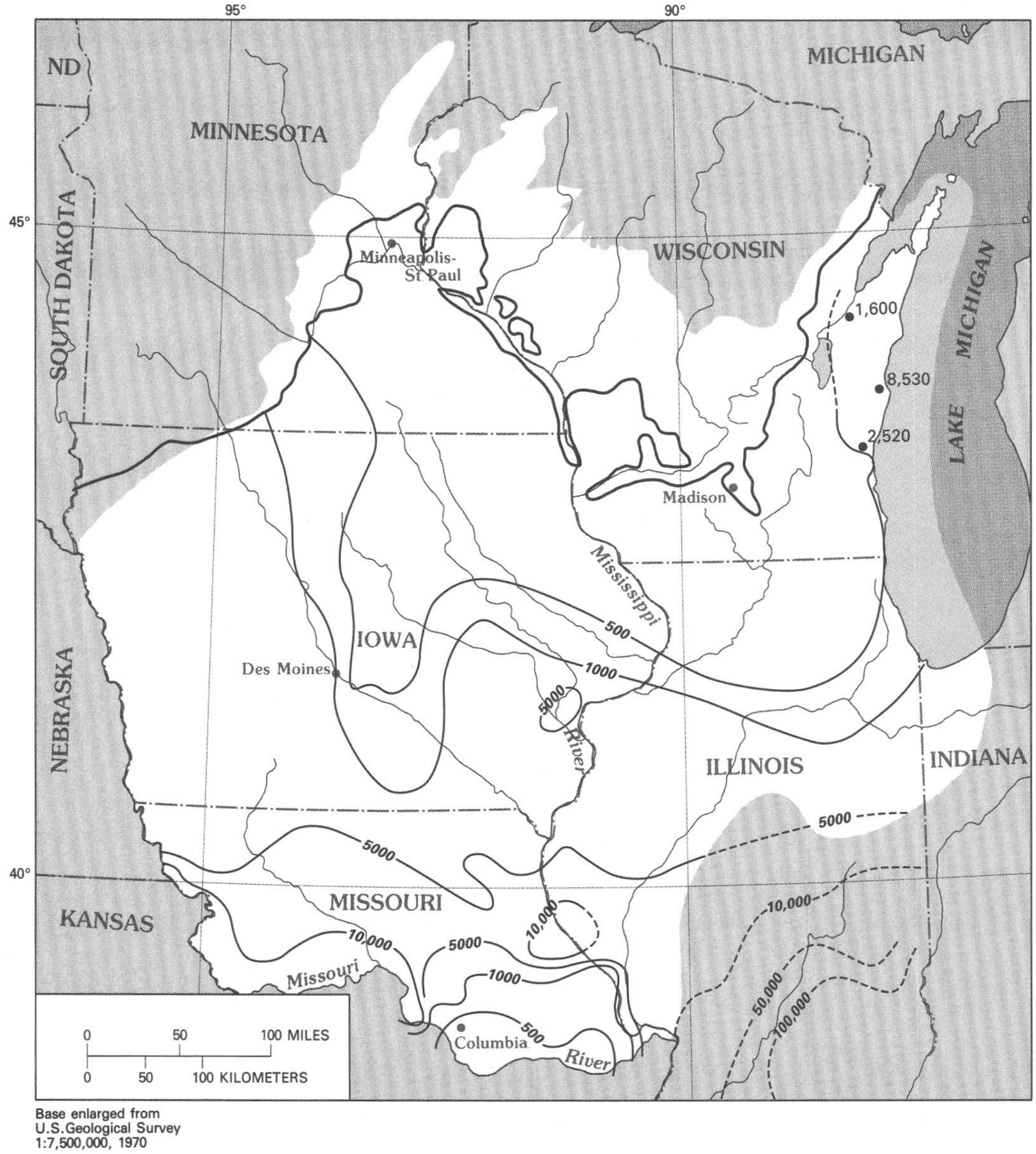
OAHU, HAWAII

The Oahu regional aquifer-system analysis investigated the aquifer system underlying 600 mi^2 of the island of Oahu in Hawaii (fig. 51). Oahu was formed through building and subsequent coalescing of two shield volcanoes, 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 initial mountain building. During quiescence, both volcanoes were deeply eroded. Waianae Volcano became dormant first, and westward-dipping flows of 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 connection with the surrounding ocean water. Shifts in sea level and erosion of the volcanic rocks allowed marine and terrestrial sediments to accumulate behind barrier reefs, forming coastal plains in some areas.

Due to the complexity of volcanic rocks and the island environment, local hydrologic terms were developed in Hawaii that are not generally used by ground-water hydrologists (Ewart, 1986). A body of ground water floating on and in hydrodynamic equilibrium with saltwater is termed "basal ground water," or "basal water body," in Hawaii. Ground water stored in lavas between low-permeability dikes is termed a "dike-impounded water body." Where water levels are much higher than the water table in a basal water body, but the geologic reason for the occurrence is not known (flow is either impeded by low-permeability dikes, ash beds, or other low-permeability rocks), the ground-water body is termed a "high-level water body." Ground water in dike-impounded or high-level water bodies eventually seeps through or overflows the low-permeability dikes or barriers and discharges into adjacent basal water bodies, leaks to streams in adjacent valleys, or discharges as springs. In places, perched ground water can be found. The perched water is unconfined and is separated from an underlying basal water body by an unsaturated zone owing to the presence of ash beds or other low-permeability materials. On the basis of the terminology used by hydrologists in Hawaii, the aquifer system underlying the island of Oahu is divided into 10 aquifers as shown in figure 51.

A significant amount of water is stored in the volcanic rocks of Oahu. Water is stored above sea level to an altitude of at least 2,000 ft in the Waianae Range, but most is stored below sea level. Depths of freshwater storage below sea level are from a few feet to 1,000 ft or more in the dike-free lavas, and probably to several thousand feet in the compartmentalized lavas between dikes. The dike-impounded water bodies that underlie interior mountainous areas (where rainfall and recharge are greatest) play an important role in the recharge, storage, movement, and discharge of all ground water on the island of Oahu (Takasaki and Mink, 1985).

A unique method of tapping ground water stored in dike-impounded water bodies is the use of tunnels dug into the lava formations at high altitudes. The earliest tunnel reported was dug in Waimanalo Valley in about 1888 for municipal use. About 25 tunnels have been dug in the



EXPLANATION

—500— — **Line of equal dissolved-solids concentration**—Dashed where approximate or inferred. Interval, in milligrams per liter, is variable

——— **Aquifer boundary**

● 2,520 **Well yielding water with dissolved-solids concentration that exceeds the concentrations on which the lines are based**—Number is dissolved-solids concentration, in milligrams per liter

Figure 50. Dissolved-solids distribution in the St. Peter–Prairie du Chien–Jordan aquifer of the Cambrian-Ordovician aquifer system in the Northern Midwest (from Young, 1992a).

Koolau Range for irrigation or municipal use, of which 21 tap water impounded in the main fissure zones and 4 tap water in the minor rift zones. The first well to exploit the dike-impounded water bodies in the Koolau Range was reportedly drilled in 1892 in Waimanalo Valley. Since then, 40 wells have been drilled as of 1978. Wells drilled at low altitudes in highly weathered rocks in the dike complex yield little water. Wells drilled in less weathered rocks, mostly in the margins of the dike zone, yield substantial quantities of water, ranging from about one to several tens of million gallons per day (Takasaki and Mink, 1985).

Computer models were used to simulate ground-water flow and evaluate the effects of development on ground-water levels and the movement of saltwater-freshwater interfaces. A finite-element cross-sectional model (Souza and Voss, 1986) was used to simulate the saltwater-freshwater transition zone in the aquifers of southern Oahu. During the steady-state simulation a regional ground-water discharge of 20 Mgal/d per mile of coastline was assumed, and constant freshwater recharge was input into nodes at the top part of the upstream boundary while the bottom of the same upstream boundary was assumed to be a no-flow boundary. The downstream sea water boundary is a specified-pressure head boundary that corresponds to the depth of the sea water at the respective position. The simulated contours of sea water percentage seem

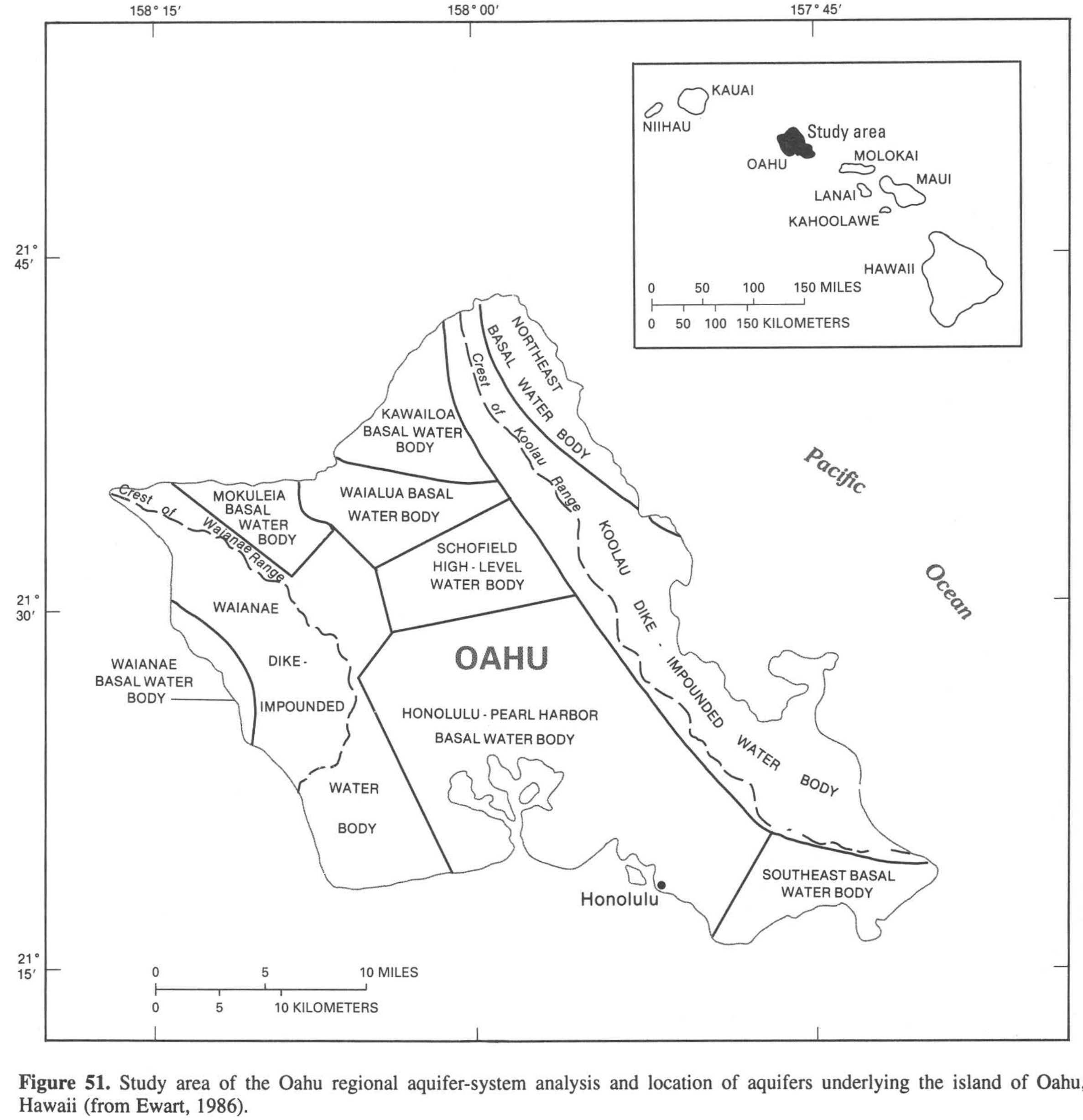


Figure 51. Study area of the Oahu regional aquifer-system analysis and location of aquifers underlying the island of Oahu, Hawaii (from Ewart, 1986).

consistent with contours based on observed data along the approximate position of the cross section. A cyclic pumping stress of 30 Mgal/d per mile of coastline was applied during a transient simulation. The cyclic stress involved pumping for 6 months, followed by 6 months of recovery. This cyclic pumping roughly corresponds to the schedule of agricultural and industrial water uses in southern Oahu. During the simulated 65 years of cyclic pumping, the freshwater lens in the aquifers shrank considerably, and the transition zone moved landward and upward to a significant degree (Voss and Souza, 1986; Souza and Voss, 1986). This conclusion is important for planners and managers concerned with the development of ground-water resources along coastal plain areas in Hawaii.

The Oahu regional aquifer-system analysis was started in 1982 and completed in 1988. As of May 1991, eight reports had been completed (Sun and Weeks, 1991).

SAN JUAN BASIN, ARIZONA, COLORADO, NEW MEXICO, AND UTAH

Two regional aquifer-system analyses were conducted in the Upper Colorado River Basin: the San Juan Basin RASA, and a RASA covering all of the Upper Colorado River Basin excluding the San Juan Basin. The San Juan Basin RASA in New Mexico, Colorado, Arizona, and Utah includes about 21,600 mi^2 (fig. 52). The regional aquifer system consists mainly of rocks of Jurassic through Tertiary age that underlie about 19,400 mi^2 of the San Juan Basin. Altitudes in the study area range from 4,500 ft above sea level in San Juan County, Utah, to about 11,000 ft in Cibola County, New Mexico. Annual precipitation on mountainous areas along the northern and eastern margins of the basin ranges from 20 to 45 in., whereas precipitation on the lower altitude central part of the basin is 10 in/yr or less. Mean annual precipitation is about 12 in.

The San Juan Basin is a northwest-trending asymmetric structural depression of Laramide age, located at the eastern edge of the Colorado Plateau, with a width of about 140 mi and a length of 200 mi. The basin contains a thick sequence (more than 14,000 ft) of sedimentary rocks ranging from Cambrian through Tertiary age. Volcanic rocks of Tertiary age and various deposits of Quaternary age are also present. The rocks dip from basin margins toward the troughlike basin center. Older rocks crop out around the basin margins and are successively overlain by younger rocks toward the basin center.

During the RASA study, 10 permeable hydrogeologic units were delineated. Two consist of Tertiary age rocks: (1) San Jose, Nacimiento, and Animas Formations; and (2) Ojo Alamo Sandstone. Seven units consist of Cretaceous age rocks, in descending order: (1) Kirtland Shale and Fruitland Formation; (2) Pictured Cliffs Sandstone; (3) Cliff House Sandstone; (4) Menefee Formation; (5) Point Lookout Sandstone; (6) Gallup Sandstone; and (7) Dakota Sandstone. The lowermost unit consists of the Morrison Formation of Jurassic age. Among the 10 hydrogeologic units, the Gallup Sandstone and Morrison Formation are the most productive; the Ojo Alamo Sandstone, Kirtland Shale and Fruitland Formation, and Cliff House Sandstone are the next most productive; the remaining units are less productive.

The principal uses of ground water in the basin are for municipal, domestic, and stock supplies. However, industrial water use has increased significantly since the late 1970's due to increased mining of uranium in the Morrison Formation. Water levels have declined in several areas because of dewatering of the Morrison Formation for mining operations. Competition has been great among electric-power companies in recent years for rights to use the limited ground-water resources in the basin.

The San Juan Basin RASA study was the first RASA study to use a Geographic Information System (GIS) to manipulate geologic and hydrologic data and to formulate these data as input for a three-dimensional finite-difference ground-water flow model. The model consisted of 12 layers that included the 10 hydrogeologic units plus the Lewis Shale of Cretaceous age, which acts as a thick confining unit, and the Entrada Sandstone, which acts as an aquifer. The base of the model is the Chinle Formation of Triassic age, which has very low permeability. The Entrada Sandstone is highly permeable and productive; however, concentrations of dissolved solids in waters in the Entrada Sandstone are very high, more than 10,000 mg/L in most areas. Therefore, this unit was not included among the 10 simulated hydrogeologic units. However, for modeling purposes it is possible that this brackish water may leak upward into the overlying aquifers.

Confining units separate the 10 hydrogeologic units, but they are not areally extensive. In places, the hydrogeologic units may merge together. In the model, confining units were treated by specifying a vertical leakance, except for the Lewis Shale, which was treated as an active confining layer.

The San Juan Basin regional aquifer-system analysis was started in 1984 and completed in 1990. As of May 1991, 14 reports had been completed (Sun and Weeks, 1991). Atlases of the hydrogeologic units were constructed by using GIS (Kernodle and Craigg, 1992). As of mid-1992, chapter B (geologic framework) of Professional Paper 1420 by Craigg (in press) was approved for publication and other chapters are either in preparation or in review.

SNAKE RIVER PLAIN

The 15,600 mi^2 Snake River Plain extends across southern Idaho into eastern Oregon. The Snake River descends 2,930 ft along its 502-mi course across the plain (fig. 53). The surface of the plain decreases in altitude from about 6,000 ft above sea level in the northeast to

2,100 ft in the west. Average annual precipitation on much of the plain is less than 10 in., one-third to one-half of which falls during the growing season from April through September. Most of the water available to the plain originates as snow on surrounding mountains, which are as much as 12,000 ft above sea level. Annual precipitation on the mountains is as much as 60 in. For study purposes, the Snake River Plain was divided into eastern and western parts on the basis of hydrology and geology, as shown in figure 53.

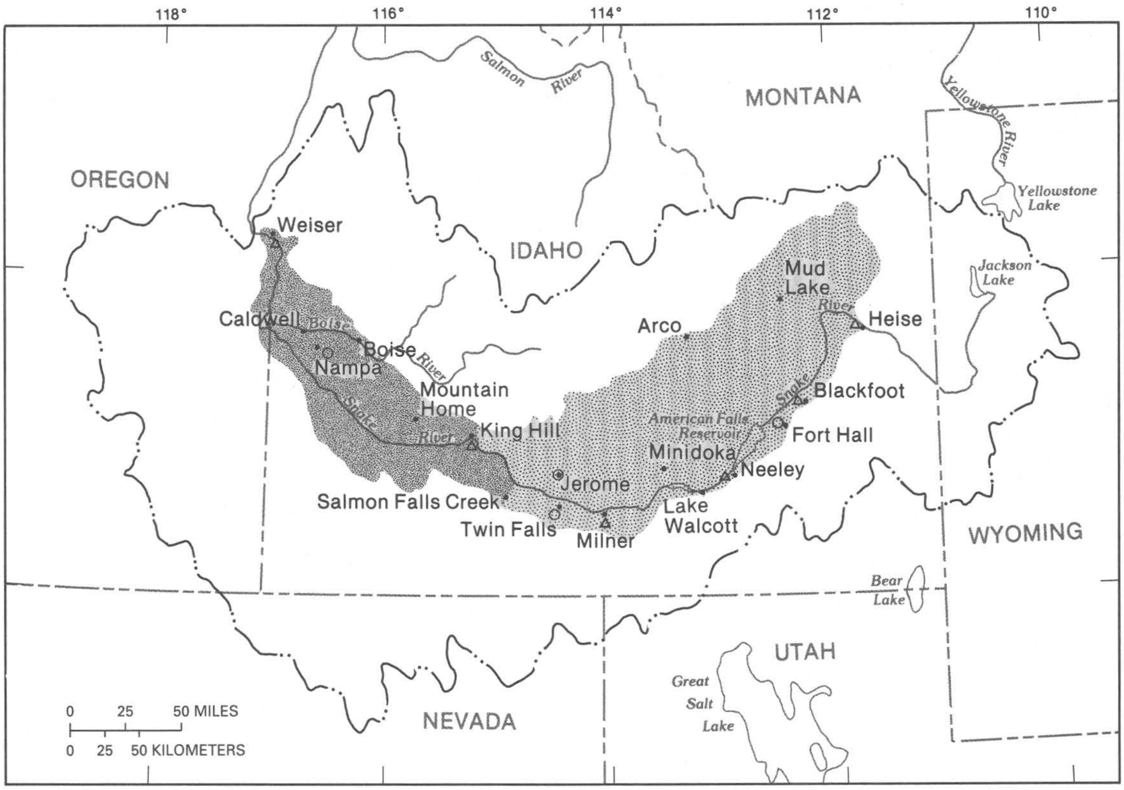
Geophysical studies indicate that the eastern Snake River Plain is a downwarp. Most of the fill consists of Quaternary basalt. Near the plain margins, unconsolidated sedimentary rocks overlie and are intercalated with the basalt. Tops of basalt flows are typically broken and have very high permeability. Consequently, thick sections of basalt, which include many flows, store and yield large quantities of water. In places, the basalt is several thousand feet thick; however, the upper 200 to 500 ft of the basalt are thought to be the most permeable (Lindholm,

Figure 52. Study area of the San Juan Basin regional aquifer-system analysis.

1986). An estimated 200 to 300 million acre-ft of water are stored in the top 500 ft of the basalt aquifer. In much of the eastern plain, the aquifer is unconfined. About two-thirds of the ground-water discharge from the eastern plain is from a series of springs, most of which issue from basalt forming the north wall of the Snake River canyon between Milner and King Hill (fig. 53). These springs include 11 of the 78 springs in the United States that discharge an average of more than 100 ft^3/s.

The western Snake River Plain is a graben bounded by well-defined high-angle faults. Quaternary and Tertiary sedimentary rocks of variable thickness are the predominant fill materials. In the Boise River valley, most ground water is obtained from unconsolidated alluvial sand and gravel. Elsewhere in the western plain, rocks are predominantly fine grained and the included aquifers are largely confined. Ground-water discharge to the Snake River in the western plain is small compared with ground-water discharge to the Snake River in the eastern plain. A geothermal aquifer system underlies much of the western plain.

Irrigation is the largest water use on the Snake River Plain. Irrigation started in about 1843 along the Boise River. Development was slow until the late 1880's, when Congress encouraged reclamation of desert lands and expansion of irrigated acreage in the arid West. By 1899, about 550,000 acres were irrigated with surface water. The Reclamation Act of 1902 stimulated further expansion by providing funds for construction of major instream storage facilities (reservoirs) and transmitting canals. By 1929, about 2.2 million acres were irrigated with surface water. Increases in land irrigated with surface water from 1929 through 1945 were moderate owing to depressed economic conditions, World War II, and full appropriation of surface-water rights.



EXPLANATION

Eastern Snake River Plain

Western Snake River Plain

Area of Snake River Plain

Boundary of Snake River basin

△ Stream gaging station

○ Well referenced in text and figure 54

Figure 53. Study area of the Snake River Plain regional aquifer-system analysis (modified from Lindholm, 1986).

After World War II, demand for irrigation water increased. Because surface-water rights were fully appropriated, ground water became a logical source of supply. By 1966, ground water was used to irrigate about 700,000 acres. In 1980, about 32 percent of the Snake River Plain, or about 3.1 million acres of land, were irrigated. In one area south of the Snake River near Twin Falls, ground-water levels rose as much as 200 ft in 5 yr after the start of irrigation with surface water (fig. 54). In much of the plain, water levels rose several tens of feet over tens of years as indicated by water levels observed in wells at Jerome and near Fort Hall. Water levels in the western plain were also affected by surface-water irrigation, as observed in wells near Nampa (fig. 54).

As ground-water levels rose, ground-water discharge to the Snake River increased. Long-term data on gaining reaches of the Snake River that include the major springs are the key to understanding changes in the ground-water flow system of the eastern plain. Kjelstrom (1986) documented changes in ground-water discharge to reaches of the Snake River that include major groups of springs.

Discharge from the group of springs between Blackfoot and Neeley (fig. 53) has been relatively constant over the period of record (1912–80). Upgradient from the springs, considerable acreage was irrigated prior to the start of data collection. Despite an increase in surface-water diversion of about 1.5 million acre-ft from 1912 through 1952, ground-water discharge remained stable. It is likely that by 1912, ground-water recharge and discharge affecting the reach from Blackfoot to Neeley were approximately in balance (Lindholm, 1986).

In the reach from Milner to King Hill, some increase in ground-water discharge probably occurred between the start of irrigation (1880's) and the start of data collection (1902). A 40-yr trend of increasing ground-water discharge started in 1912 owing to major increases in surface-water irrigated acreage following the completion of reservoirs and diversion structures on the Snake River. In the early 1950's, spring discharge stabilized, implying a temporary balance between recharge and discharge that lasted for several years (fig. 17). A period of overall decrease in ground-water discharge followed and continued to 1980. The decrease probably was due to several factors, including an increase in ground-water withdrawal, decrease in surface-water irrigation, and increase in irrigation efficiency (Lindholm, 1986).

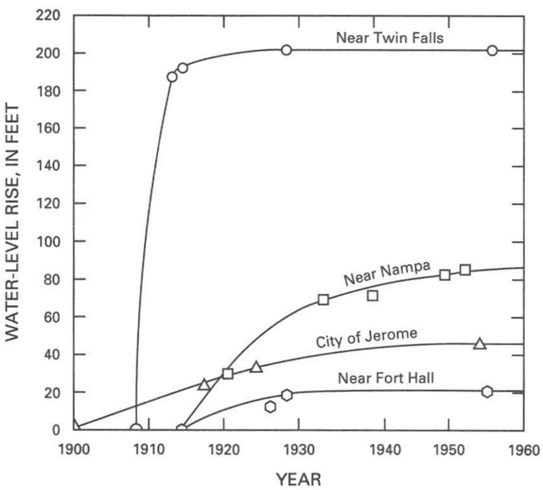


Figure 54. Changes in ground-water levels in the Snake River Plain due to surface-water irrigation (locations of wells shown in fig. 53) (from Lindholm, 1986).

The impact of the long history of surface-water diversions and ground-water withdrawals on the ground-water budgets of the eastern Snake River Plain is shown in figure 14 and discussed in the earlier section on regional ground-water budgets. In brief, flow through the aquifer system in the eastern plain increased by about 80 percent from predevelopment to 1980, and most recharge in 1980 was supplied by irrigation return flow.

Phase I of the Snake River Plain regional aquifer-system study was started in 1979 and completed in 1984. In Phase I, the study was divided into six parts; those parts are described in chapters B through G of Professional Paper 1408 as follows: (B) geohydrologic framework (Whitehead, 1992); (C) ground-water/surface-water relations and ground-water budgets (Kjelstrom, in press); (D) solute geochemistry (Wood and Low, 1988); (E) water use (Goodell, 1988); (F) hydrology and digital simulation, eastern Snake River Plain (Garabedian, 1993); and (G) geohydrology, western Snake River Plain (Newton, 1991). Chapter A of Professional paper 1408 by Lindholm (in press) summarizes Phase I study results.

During Phase I, several key local areas within the Snake River basin were identified as needing more detailed analysis than was possible in a regional study. These areas required additional data collection and detailed ground-water flow models to improve hydrologic understanding. Phase II was initiated in 1985 to study the American Falls Reservoir area, the Big Lost River basin, and the Thousand Springs area (fig. 55). In the American Falls and Thousand Springs areas, large quantities of ground water discharge to the Snake River. The Big Lost River basin is a major north-side tributary to the plain. Kjelstrom (1986) estimated that from 1934 through 1980, the Big Lost River basin annually yielded an average of 335,000 acre-ft of water to the Snake River Plain. A major objective of the Phase II studies was to provide a more accurate water budget for the Snake River Plain. Reports summarizing results of the three Phase II areal studies are currently in review.

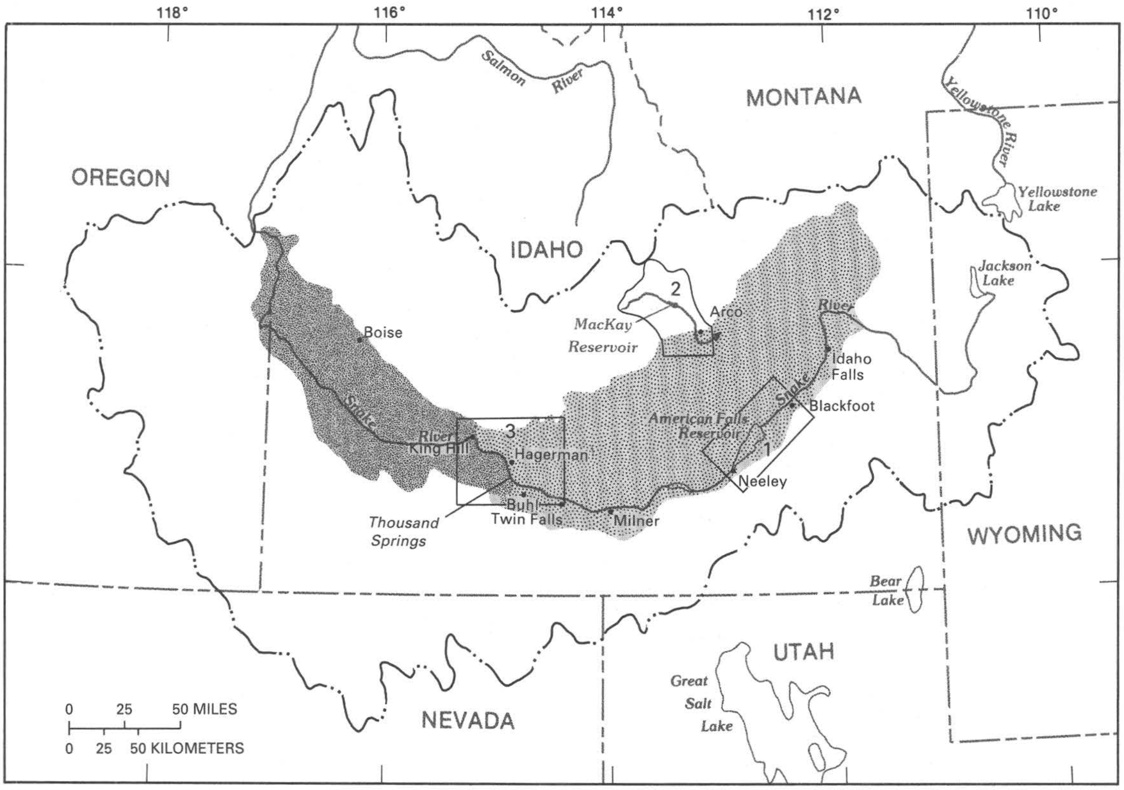
The Snake River Plain regional aquifer-system analysis was started in 1979 and completed in 1990. As of May 1991, 35 reports had been completed (Sun and Weeks, 1991).

UPPER COLORADO RIVER BASIN

The Upper Colorado River Basin has a drainage area of about 113,500 mi^2 in western Colorado, eastern Utah, southwestern Wyoming, northeastern Arizona, and northwestern New Mexico. The regional aquifer-system analysis of the Upper Colorado River Basin excludes the San Juan Basin, which was studied separately (see the previous section entitled "San Juan Basin, Arizona, Colorado, New Mexico, and Utah"). Therefore, the Upper Colorado River Basin RASA is about 92,000 mi^2 (fig. 56). The study 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 (fig. 57). Resulting structural relief is nearly 30,000 ft.

Tens of thousands of feet of consolidated sedimentary rocks of Paleozoic, Mesozoic, and Cenozoic age underlie the study area. Rocks consisting of fractured limestone, dolomite, and sandstone form aquifers. Low-permeability limestone, dolomite, shale, and evaporite form confining units. Rocks in the Upper Colorado River Basin have been classified into three major aquifer systems. They are, in descending order: (1) the Tertiary rock aquifer system, (2) the Mesozoic rock aquifer system, and (3) the Paleozoic rock aquifer system. Within each aquifer system, the rocks are subdivided into regional aquifers and confining units on the basis of lithology, depositional environment, and hydrologic characteristics. Igneous rocks, especially volcanic rocks, are also present in parts of the study area, but they are not regional aquifers.

The Cenozoic rocks are sediments of Tertiary age that overlie much of the northern half of the study area



EXPLANATION

1	American Falls Reservoir area		Eastern Snake River Plain
2	Big Lost River basin		Western Snake River Plain
3	Thousand Springs area		Area of Snake River Plain
		—··—	Boundary of Snake River basin

Figure 55. Study areas of the Snake River Plain regional aquifer-system analysis, Phase II.

(fig. 58). The rocks of the Tertiary rock aquifer system crop out in the Green River, Great Divide–Washakie, Piceance, and Uinta basins (figs. 57 and 58). Hydraulic properties of the Tertiary rocks vary markedly from basin to basin. For example, the Wasatch Formation includes water-yielding rocks in the Green River and Great Divide–Washakie basins but transmits little water to wells in the Piceance and Uinta basins. Lake deposits in the Green

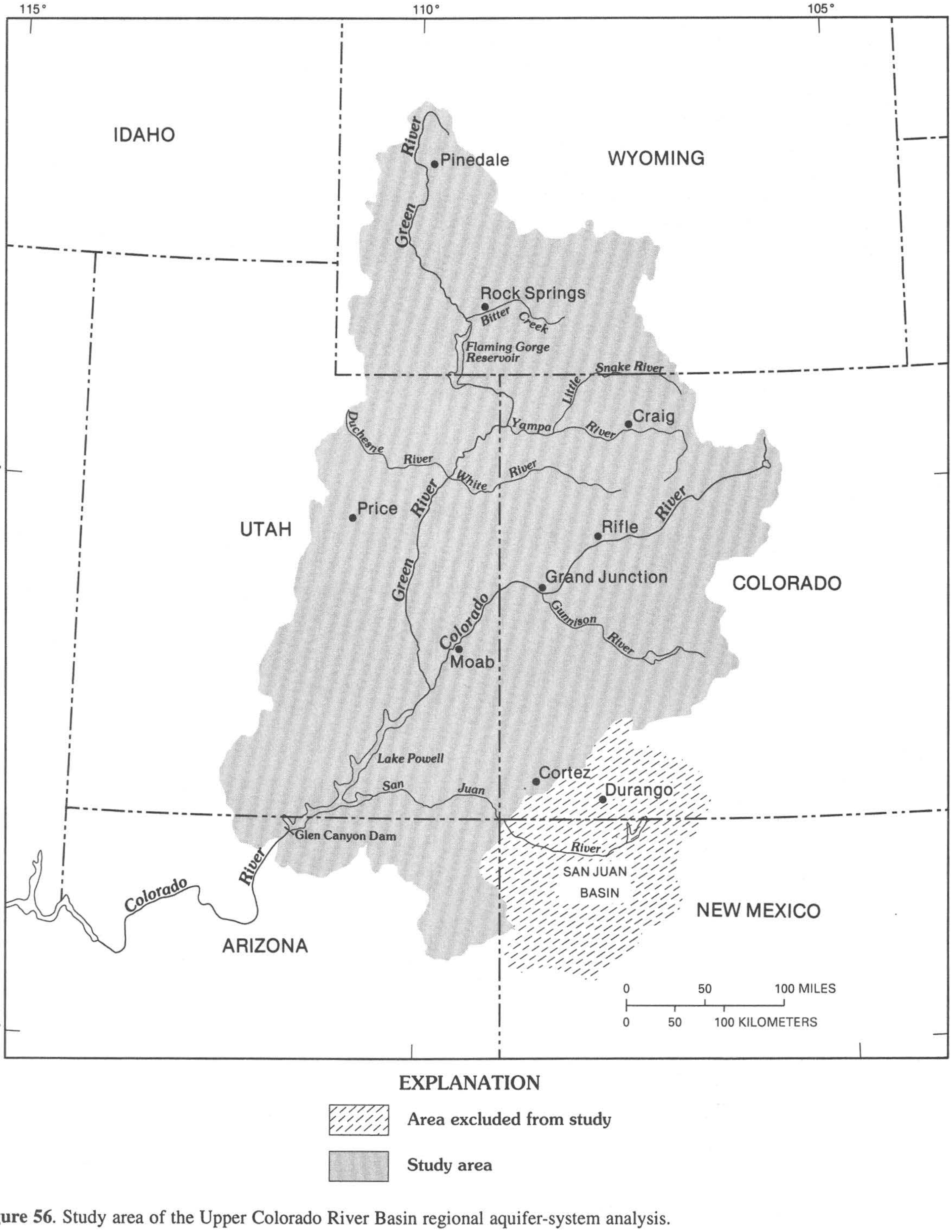
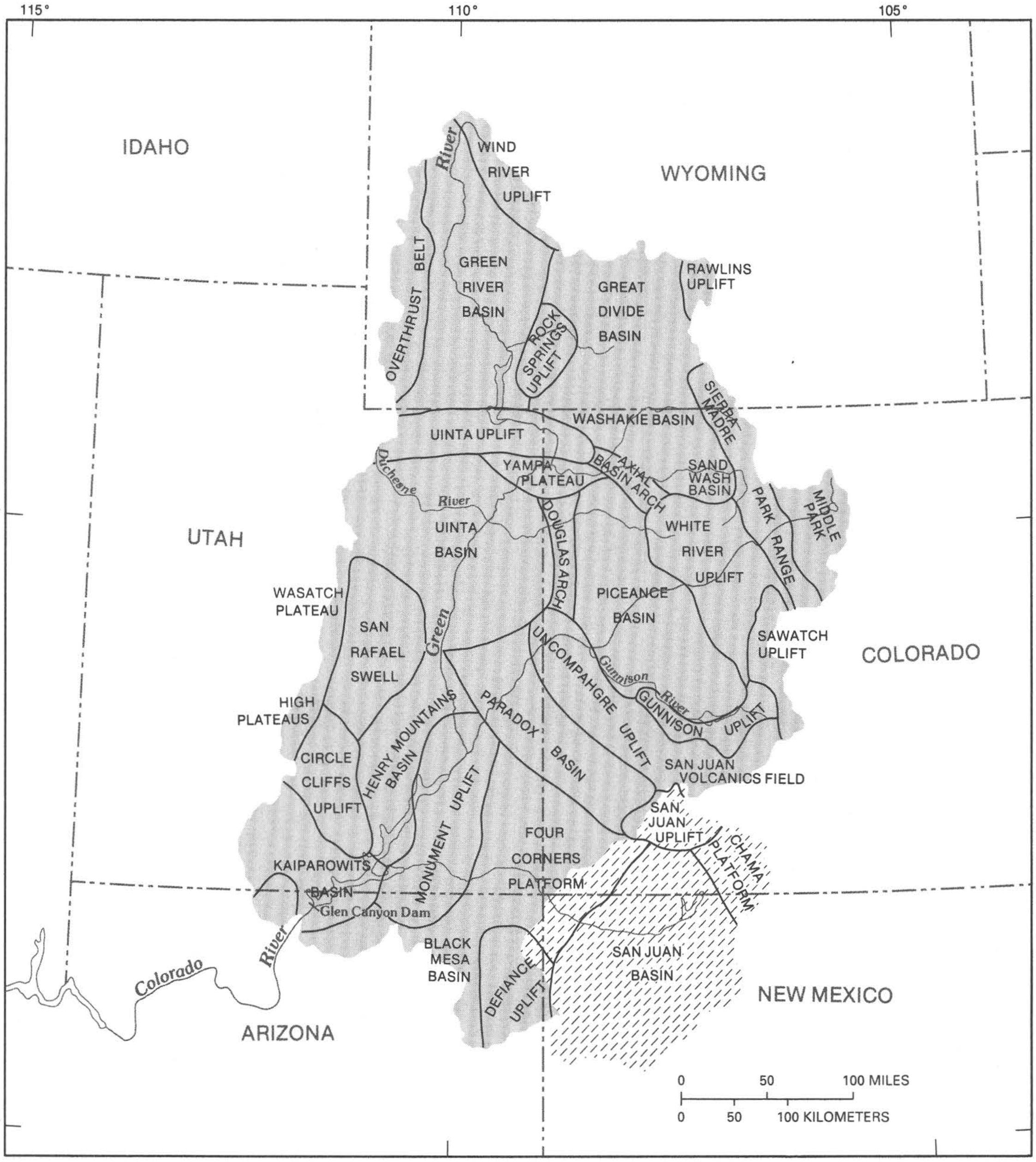


Figure 56. Study area of the Upper Colorado River Basin regional aquifer-system analysis.

River Formation are a regional aquifer in the Piceance basin where they are fractured; elsewhere, this hydrogeologic unit is confining. In the Uinta basin, the Duchesne River Formation of the Tertiary rock aquifer system is the most productive unit; however, this unit is limited to the northern half of the basin. A well inventory indicates that



EXPLANATION

Area excluded from study

Study area

Approximate boundary of uplifts and basins

Figure 57. Principal tectonic features in the Upper Colorado River Basin (modified from Grose, 1972).

the Uinta Formation is used extensively for water supply in the Uinta basin. The Piceance basin consists of one of the largest potential areas for oil-shale development in the Western United States. The important Tertiary aquifer in the Piceance basin consists of the Uinta Formation and parts of the Parachute Creek Member of the Green River

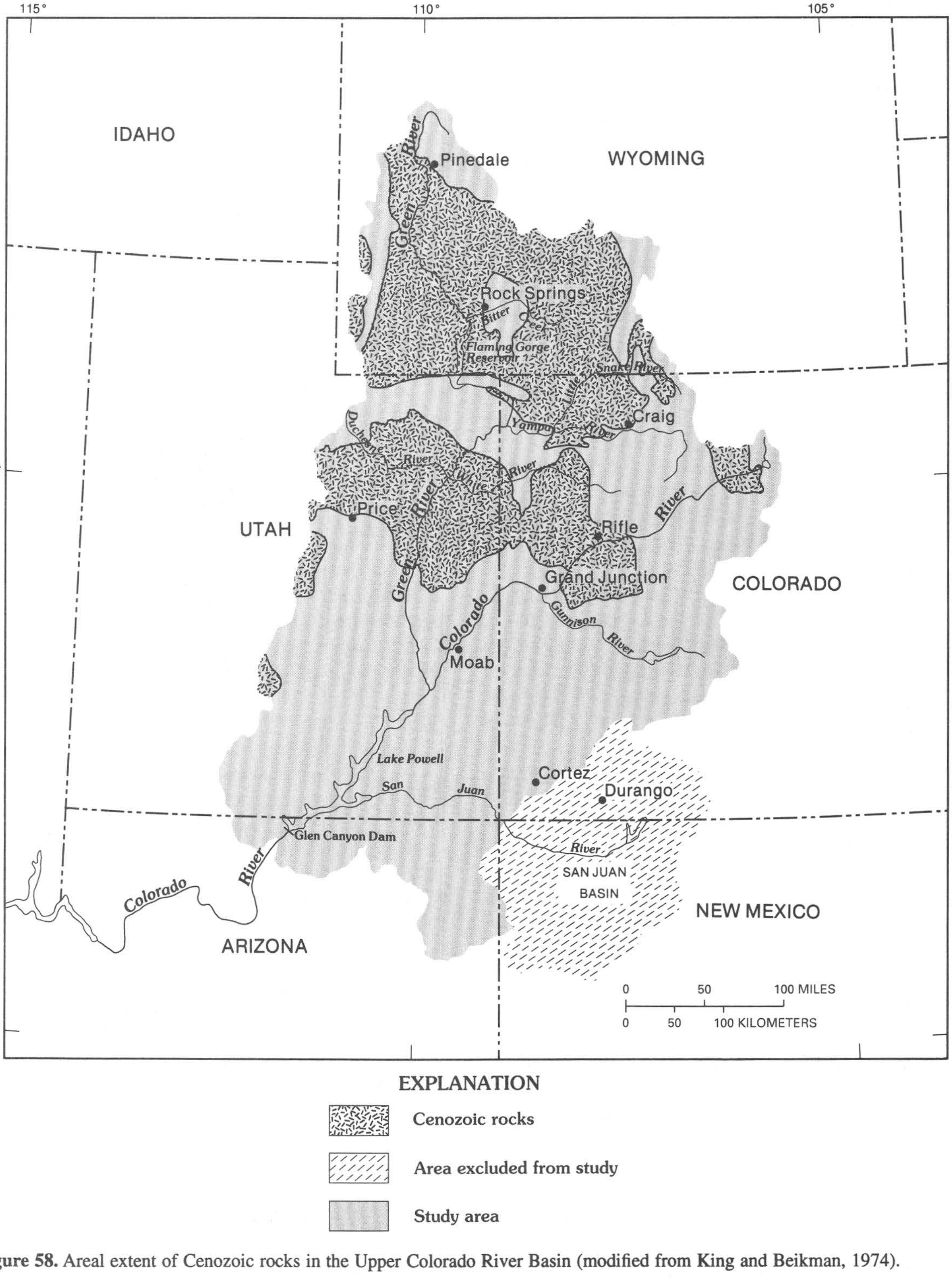


Figure 58. Areal extent of Cenozoic rocks in the Upper Colorado River Basin (modified from King and Beikman, 1974).

Formation. In Wyoming, the Fort Union Formation and the Wasatch Formation and their equivalents are the most important hydrogeologic units of the Tertiary aquifer system. Recharge to the Tertiary aquifer system occurs near the peripheries of basins and in the uplands; discharge is to streams in the central parts of basins. In the Great Divide basin, water in the Wasatch Formation discharges to salt flats and phreatophytes. The rate of evapotranspiration in these areas is large enough to prevent the formation of permanent lakes in the Great Divide basin.

The Mesozoic rock aquifer system consists mainly of sandstone sequences that extend across most of the study area (fig. 59). Sequences made up mostly of siltstone, claystone, and shale are grouped into confining units. The hydraulic conductivity of sandstone is highly variable, ranging from about 0.01 to 3 ft/d. The hydraulic conductivity of confining units is from about 0.03 to 0.1 ft/d. Thickness of Mesozoic rocks exceeds 10,000 ft over a large part of the northern basins; these rock sequences are less than 5,000 ft thick in the southern one-half of the study area. Recharge occurs mainly in outcrop and subcrop areas, in structural uplift areas, and in topographic uplands. Ground water discharges to major rivers—the Colorado, Green, San Juan, and Yampa Rivers—by means of springs located on walls and bottoms of canyons where aquifers are exposed and by upward leakage where aquifers are not exposed. Regionwide development of water in the Mesozoic rock aquifer system is negligible because deep drilling is required and aquifers contain brackish water. However, some development has occurred in the Navajo Sandstone locally.

The Paleozoic rock aquifer system consists of sedimentary rocks representing all periods of the Paleozoic Era except the Silurian and extends throughout most of the study area (fig. 60). The aquifer system includes two regional aquifers and several local aquifers and confining units. The two regional aquifers consist of (1) Devonian and Mississippian carbonate rocks, and (2) Pennsylvanian and Permian sandstone. Geldon (1988) concluded that the Devonian-Mississippian carbonate rock aquifer is the most permeable unit in the Paleozoic sequence. However, as shown previously in figure 6, the estimated transmissivity varies by several orders of magnitude.

Recharge to the Paleozoic rock aquifer system occurs mostly from precipitation on uplift areas where the rocks are exposed, leakage from overlying aquifers, and from streamflow losses in subcrop and outcrop areas. Ground water flows from structurally high areas to structural basins, to the incised canyons of the Colorado and Green Rivers and their tributaries, to the northeastern Great Divide basin, to the confluence of the Green and Yampa Rivers, to the San Juan Basin, to springs, and to overlying Mesozoic and Tertiary rocks. In some recharge areas, heads in the upper Paleozoic rock aquifer system are more than 1,500 ft higher than heads in the lower Paleozoic rock aquifer system.

Well yields from the Paleozoic rock aquifer system are small in most areas, generally less than 50 gal/min for wells pumped for domestic and stock supplies. However, in uplifted areas where the transmissivity is highest (fig. 6), a few wells yielding 100 to 3,000 gal/min were reported. Most of the ground water is pumped in oil and gas fields. In December 1986, the combined daily water production from the Rangely, Lost Soldier–Wertz–Mahoney, Ashley Valley, greater Aneth, Upper Valley Brady, and Lisbon oil fields and 23 smaller fields was about 63 ft^3/s, or 46,000 acre-ft/yr. Based on sparse data, cones of depression several hundred to 1,000 ft deep seem to have developed around some of these fields (Geldon, 1988).

The Upper Colorado River Basin regional aquifer-system analysis was started in 1981 and completed in 1989. As of mid-1992, 31 reports had been completed. One chapter of Professional Paper 1411 has been printed, three are in press, and the others are either in review or in preparation.

ONGOING REGIONAL AQUIFER-SYSTEM ANALYSIS STUDIES

Seven regional studies and the National Ground Water Atlas that were ongoing as of mid-1992 are summarized in this section. Data compilation and investigative activities were in progress and only a few reports had been printed by mid-1992. The individual project summaries are based on writeups prepared by the project chiefs.

APPALACHIAN VALLEYS AND PIEDMONT

The Appalachian Valleys and Piedmont regional aquifer-system analysis (APRASA) includes about 142,000 mi^2 in parts of Pennsylvania, New Jersey, Delaware, Maryland, the District of Columbia, Virginia, West Virginia, North Carolina, Tennessee, South Carolina, Georgia, and Alabama (fig. 61). The eastern and southern boundaries of the study area correspond to the Fall Line, beyond which is the Atlantic Coastal Plain. The western boundary corresponds to the western limit of thrust faults and folds in the Valley and Ridge physiographic province; the rocks along this boundary dip steeply. West of this boundary is the Appalachian Plateaus physiographic province, which is underlain by gently dipping Paleozoic rocks whose hydrologic characteristics differ from the rocks underlying the Valley and Ridge physiographic province. The northern boundary of the study area is a 1,000-ft-thick diabase sheet that exists along the Hudson River; elsewhere, the northern boundary is the state line between New York and New Jersey. The extreme northern part of the study area is locally mantled by glacial deposits. The hydrology of the glacial deposits was studied by the Northeast Glacial Aquifers RASA.

On the basis of hydrogeologic characteristics, the study area was divided into two subareas. The extreme western part of the Blue Ridge physiographic province and the entire Valley and Ridge physiographic province consist of carbonate rocks, sandstone, and shale, forming one of the subareas. The Piedmont physiographic province

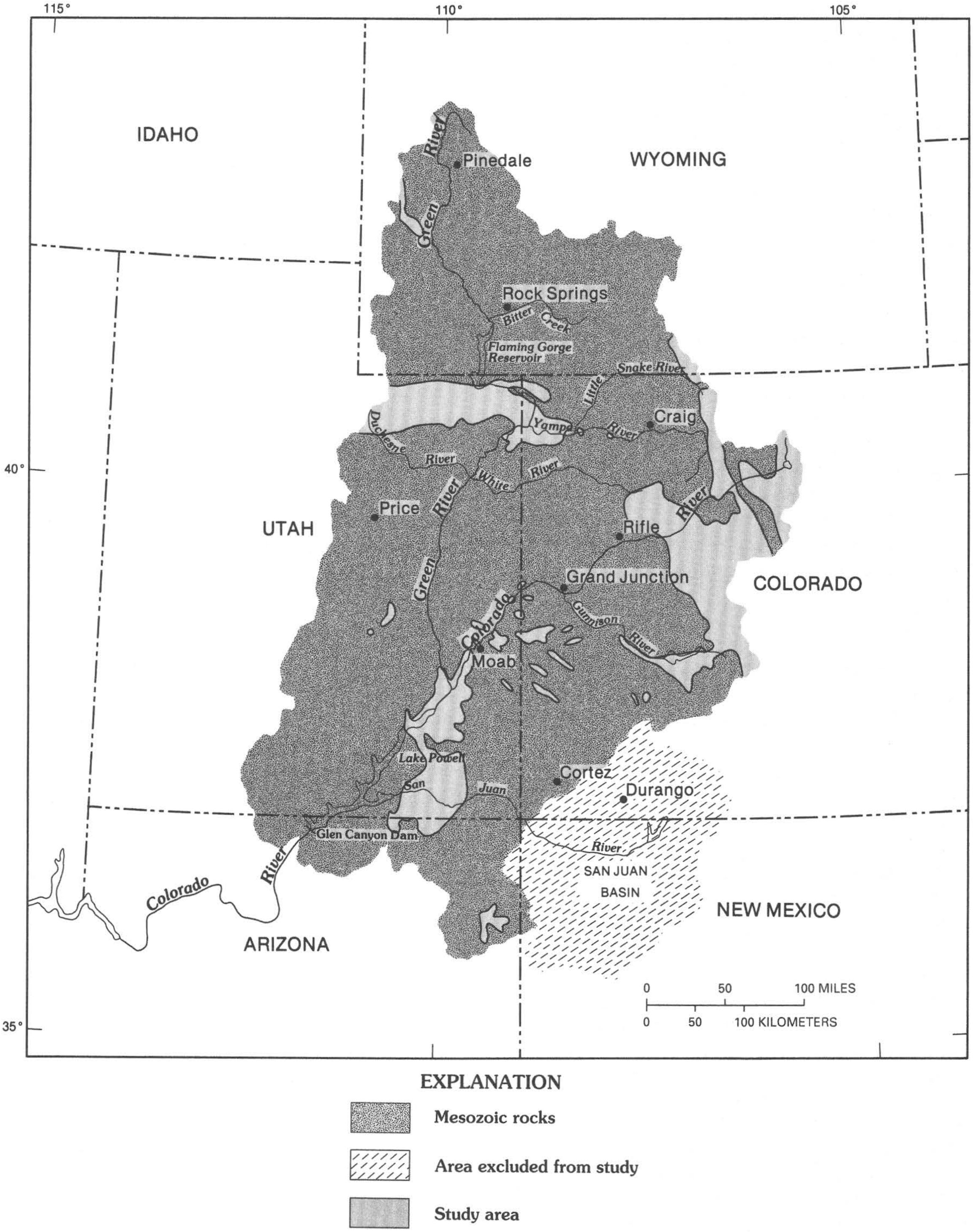


Figure 59. Areal extent of Mesozoic rocks in the Upper Colorado River Basin (modified from King and Beikman, 1974).

and the central and eastern Blue Ridge physiographic province form the other subarea, which consists mostly of metamorphic and igneous crystalline rocks. Large rift basins, extending from New Jersey to South Carolina within the Piedmont crystalline rocks, are filled with sedimentary rocks of early Mesozoic age.

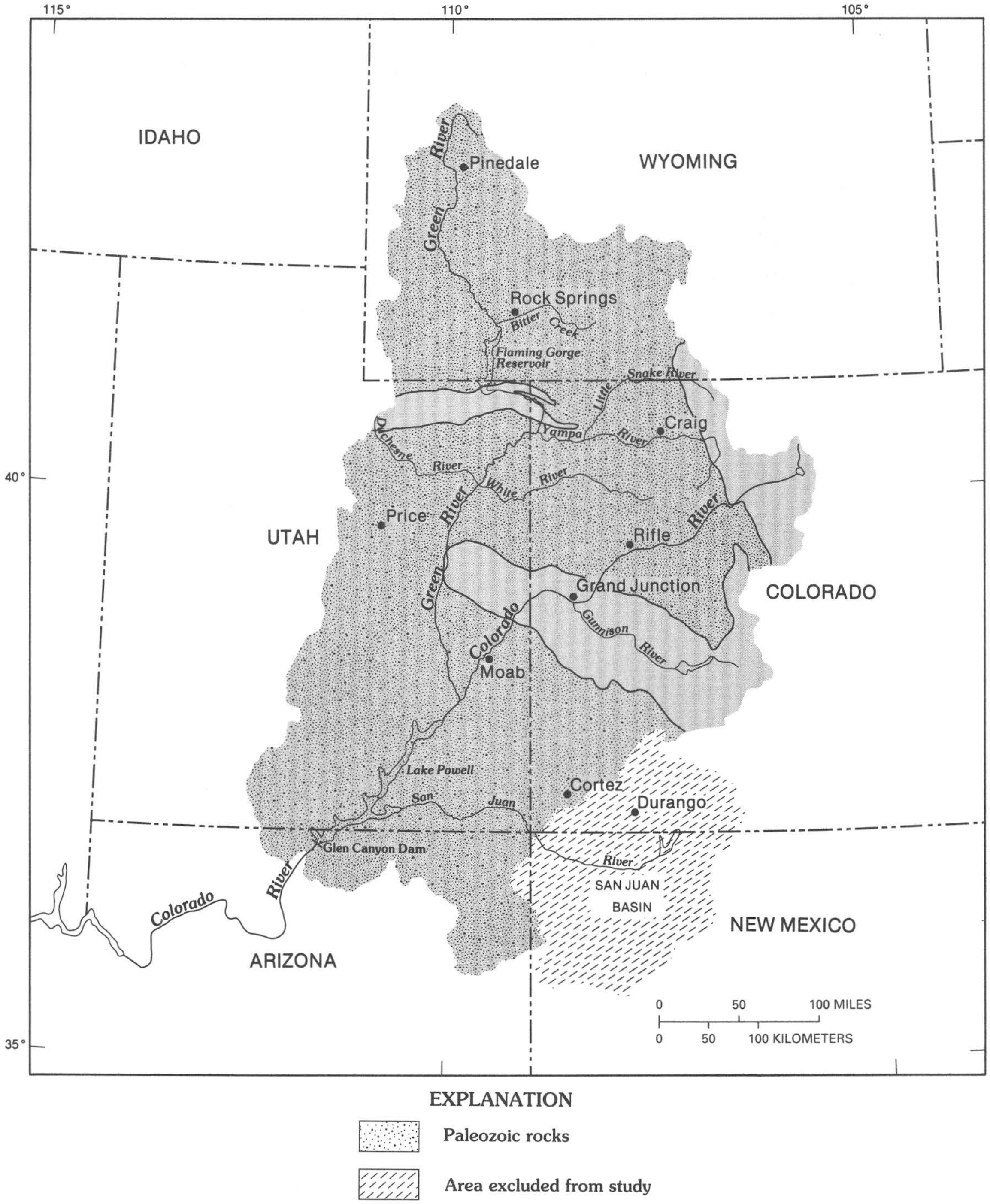


Figure 60. Areal extent of Paleozoic rocks in the Upper Colorado River Basin (modified from King and Beikman, 1974).

Regolith that consists of soil, alluvium, and weathered rock overlies most of the rocks throughout the entire study area. In places, regolith includes materials that were transported and deposited as glacial drift, colluvium, and alluvium. In other places, regolith may consist only of weathered parent rock, called residuum or saprolite. Thickness of regolith varies greatly, ranging from 0 ft to more than 150 ft. Regolith generally is divided into three zones: the soil zone, saprolite, and a transition zone separating the saprolite from unweathered rocks. Hydrologically, regolith acts as a storage reservoir that receives infiltrating precipitation. Water in regolith then slowly recharges the underlying rock aquifers.

Aquifers in the study area vary greatly in their hydrogeologic characteristics. For example, in the Valley and Ridge physiographic province, karst features such as sinkholes, solution cavities, and large springs occur where there are carbonate rocks. Large ground-water supplies can

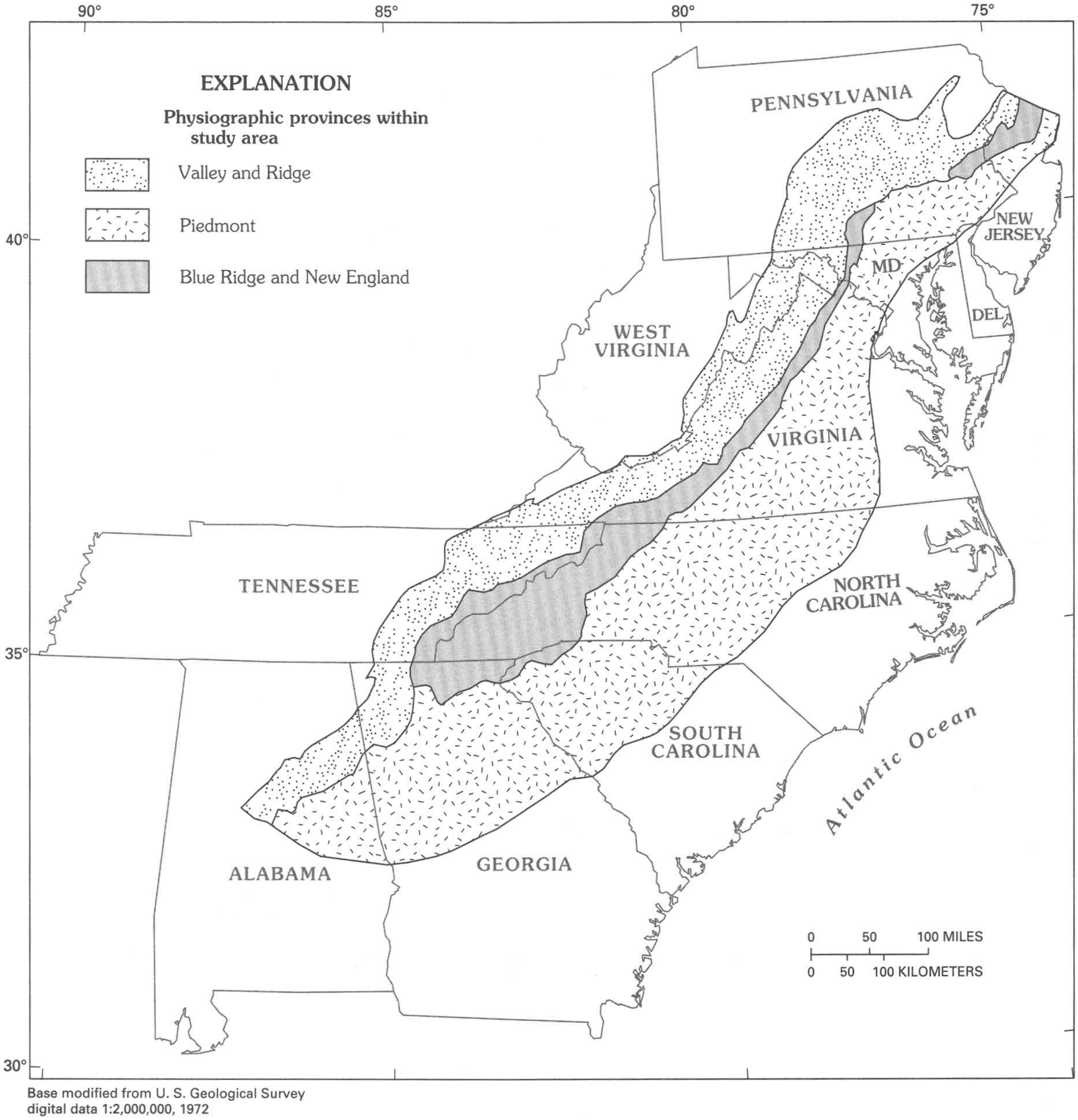


Figure 61. Study area of the Appalachian Valleys and Piedmont regional aquifer-system analysis and location of physiographic provinces (from Swain and others, 1991).

be obtained from the carbonate rocks, especially where associated with a thick regolith (50 ft or more). Reported well yields from a single well in carbonate rocks exceed 8,000 gal/min. Ground-water movement in the Valley and Ridge physiographic province generally is restricted by parallel rock ridges, which act as hydrologic boundaries and cause water to discharge to local streams. Well yields in the Piedmont and Blue Ridge physiographic provinces, which mainly consist of metamorphic and igneous crystalline rocks, vary greatly depending on the thickness of the regolith. Yields as great as 1,800 and 2,200 gal/min have been reported, respectively, from crystalline and sedimentary rocks of the Piedmont. Once water in the regolith is drained, well yield from crystalline rocks may decrease significantly. Several hydrogeologic terranes and conceptual flow systems have been identified for the study area, as summarized in table 2. These terranes and flow systems are described in further detail in Swain and others (1991).

In 1985, about 1,700 Mgal/d of water was pumped, of which 986 Mgal/d (about 58 percent of the total) was from aquifers in the Piedmont physiographic province, 567 Mgal/d (about 33 percent of the total) was from aquifers in the Valley and Ridge physiographic province, and the remaining 9 percent (about 163 Mgal/d) was from aquifers in the Blue Ridge physiographic province. Major problems with ground-water development in the study area are extremely variable well yields, sinkhole collapses during drilling in carbonate rock terranes, reduction in streamflow due to pumping from wells, difficulty in estimating sustainable yield of aquifers, and water-quality problems resulting from both natural geochemical processes and contamination from human activities.

One objective of the RASA study is to find possible solutions to these development problems. However, the principal objective of the study is to develop an understanding of ground-water flow systems in the various hydrogeologic terranes of the Appalachian Valleys and Piedmont. The study was started in 1988. As of early 1993, 20 reports had been completed, of which 18 are published.

EDWARDS-TRINITY REGIONAL AQUIFER SYSTEM, TEXAS, OKLAHOMA, AND ARKANSAS

The study area of the Edwards-Trinity regional aquifer-system analysis includes about 95,000 mi^2 in parts of central Texas, southeastern Oklahoma, and southwestern Arkansas (fig. 62). The aquifer system includes three major aquifers in rocks of Early Cretaceous age. The major aquifers, named the Edwards, the Trinity, and the Edwards-Trinity, together comprise about 80,000 mi^2. The Edwards aquifer is composed mostly of fractured and dissolutioned limestone that yields large quantities of water to wells and springs. The Trinity aquifer is composed primarily of dolomitic limestone, with interbedded sand, shale, and clay; the Edwards-Trinity aquifer generally is composed of limestone and dolomite in its upper part and quartz-rich sand in its lower part. These aquifers are laterally adjacent except in the southeastern part of the system, where part of the Trinity aquifer is overlain by the Edwards aquifer.

From Arkansas counterclockwise to the Rio Grande (fig. 62), the boundary of the aquifer system is the limit beyond which the lower Cretaceous rocks no longer exist or do not compose the principal water-yielding unit. Cretaceous rocks extend south into Mexico, but water-level data indicate that the Rio Grande is a regional discharge boundary of the aquifer system, and in any case, the hydrology of Mexico is beyond the scope of the study. Thus, a segment of the Rio Grande serves as part of the boundary of the aquifer system. Continuing counterclockwise from the Rio Grande into Arkansas, the boundary of the system is the updip limit of a freshwater/saline-water transition zone.

In the southern half of the study area (the area south and west of the Colorado River), much of the aquifer system is near the surface and unconfined. However, the southeastern fringe of the system is buried and confined. In the northern half of the study area, the aquifer system crops out in a band along its western and northern boundary and becomes buried and confined in its eastern part.

During the late 1980's an estimated 1.2 million acre-ft/yr of water was withdrawn from the study area for all uses. More than 80 percent of the withdrawals (1 million acre-ft/yr) occurred in the southern half of the study area, the area south and west of the Colorado River. Within that area, the major withdrawals are from the highly productive Edwards aquifer, which underlies an area of approximately 3,000 mi^2. An estimated 547,000 acre-ft of water was withdrawn from the Edwards in 1989, primarily to supply municipal and industrial water to the San Antonio metropolitan area and irrigation water to farms west of San Antonio. Thus, nearly one-half of the ground-water supplies are withdrawn from about 3 percent of the study area.

Among water issues affecting the aquifer system, one issue overshadows all others. That is the long-term capability of the Edwards aquifer to continue to supply all of the water needs of the greater San Antonio area. Large transmissivity values (200,000 to 2,000,000 ft^2/d; Maclay and Small, 1986), together with the capacity to accept plentiful recharge during wet periods, have thus far kept the Edwards from experiencing a long-term loss of water from storage. However, the aquifer has become more susceptible to drought in recent years. Increasingly large withdrawals have caused short-term water-level declines to increase in the San Antonio area.

The Edwards-Trinity regional aquifer-system analysis was started in 1986 and is scheduled for completion in 1994. Initially, the study area was divided into two parts separated by the Colorado River. The southern study area, consisting of the Edwards-Trinity aquifer system and contiguous hydraulically connected units in west-central

Table 2. Hydrologic characteristics of hydrogeologic terranes and conceptual flow systems in the Appalachian Valleys and Piedmont (from Swain and others, 1991).

	Hydrogeologic terranes	Hydrologic characteristics								
		Relief	Recharge	Discharge	Type of porosity or permeability	Type of flow	Depth of flow, in feet	Confined or unconfined	Regolith storage	Well yield
Valley and Ridge	Carbonate rocks, thick regolith	Low (residual regolith) High (transported regolith)	Mostly precipitation on topographic highs and streamflow	To streams and large springs at edge of ground-water basin	Intergranular in regolith; dissolution openings in rock	Diffuse and conduit	Shallow to intermediate, ≤ 600	Mostly unconfined	Large	Variable; can be as much as 1,000 gallons per minute
Valley and Ridge	Carbonate rocks and sandstone, thin regolith	Low (carbonate) Low to high (sandstone)	Precipitation on topographic highs and valley floors. Some streamflow loss[a]	To springs (carbonate) and as seepage to streams (sandstone)	Dissolution openings and fractures	Conduit and fracture	Shallow, ≤ 300	Mostly unconfined	Small	Carbonate, variable; sandstone, less variable than carbonate
Valley and Ridge	Clay-rich rocks	Low (valleys) High (mountain slopes)	Precipitation on topographic highs and valley floors. No streamflow loss	To streams by uniform seepage. No large springs	Large porosity at shallow depth; little or no permeability	Diffuse through clay-filled fractures	Very shallow, ≤ 150	Unconfined	Small to large	Very small, less variable than carbonate
Piedmont and Blue Ridge	Massive or foliated crystalline rocks, thick regolith	Low to high	Precipitation on topographic highs	To streams	Fracture	Fracture	Shallow (mostly) to intermediate, ≤ 500	Unconfined	Small	Proportional to regolith thickness
Piedmont and Blue Ridge	Massive or foliated crystalline rocks, thin regolith	Low to high	Precipitation on topographic highs	To streams	Fracture	Fracture	Shallow (mostly) to intermediate, ≤ 500	Unconfined	Small	Low
Piedmont and Blue Ridge	Metamorphosed carbonate rocks	Low to moderate	Precipitation on topographic highs	To streams	Dissolution openings, some fractures	Conduit fracture	Shallow	Unconfined	Small to moderate	Variable, some very high
Piedmont and Blue Ridge	Mesozoic sedimentary basins	Low to moderate	Precipitation on topographic highs	To streams	Intergranular, some fractures	Diffuse, fracture	(Mostly) shallow to intermediate, ≤ 800	Mostly unconfined, some confined	Small	Variable, decreasing from north to south

Valley and Ridge	Deep confined flow, sandstone	Low to moderate	Precipitation on topographic highs	To thermal springs or diffused into shallow-flow discharge	Intergranular porosity and secondary porosity from cement removal	Mostly diffuse	Shallow to deep, ≤ 5,000	Mostly confined	Smaller to moderate	Moderate; less variable than carbonate
	Deep confined flow, limestone	Low to moderate	Precipitation on topographic highs	To thermal springs or diffused into shallow-flow discharge	Paleokarst dissolution openings	Conduit	Shallow to deep, ≤ 3,000	Mostly unconfined	Moderate	Variable, tending to small or very small
	Spring basin	Low to high	Precipitation on topographic highs, valley floors	Mostly to large springs; some to streams	Intergranular in regolith; dissolution openings in rock	Diffuse and conduit	Shallow to intermediate, ≤ 600	Mostly unconfined	Large	Variable; can be as much as 1,000 gallons per minute

[a] Point recharge through sinkholes is possible in some areas.

Texas, was to be studied first because most water use and water issues are there; the northern study area, consisting of the Edwards-Trinity aquifer system in north-central Texas, southeastern Oklahoma, and southwestern Arkansas, was to be studied second. As of 1992, most work has been in the southern study area. Accordingly, the scope of work in the northern study area was reduced so that the project can finish on time.

The aquifer system in the southern study area (fig. 63) is divided into four geographic subareas: the Trans-Pecos, Edwards Plateau, Hill Country, and the Balcones fault zone south of the Colorado River (hereafter referred to as the Balcones fault zone). The Trans-Pecos and the Edwards Plateau together are coincident with the area of the Edwards-Trinity aquifer (figs. 62 and 63). The Hill Country coincides with the area where the Trinity is the principal aquifer. The Balcones fault zone is coincident with the area where the Edwards is the principal aquifer and the Trinity is a secondary aquifer.

Definition of a regional hydrogeologic framework in the southern study area is complete. The foundation of the framework definition is a series of seven hydrogeologic sections constructed primarily from geophysical logs, and a regional stratigraphic correlation chart synthesized from numerous sources.

Computer modeling was used extensively to quantify major components of the regional flow system and to develop areal distributions of recharge, discharge, and transmissivity in the southern study area. The regional flow system in the Edwards aquifer is controlled by a series of faults (the Balcones fault zone) that divert flow along the strike of the faults (fig. 64). Because of the complex aquifer geometry, a finite-element model was used rather than a finite-difference model common to most other RASA studies (Kuniansky, 1990). The finite-element mesh design has more flexibility to simulate the anisotropic transmissivity associated with faults and the locations of streams and springs than the finite-difference mesh design. A steady-state, single-layer model of the southern study area has been satisfactorily calibrated. Because the Edwards aquifer in the Balcones fault zone is characterized by rapid and dramatic changes in water levels in response to short-term stresses, and because the water-yielding zones are stacked vertically in the Trinity aquifer in the adjacent Hill Country, simulation of those parts of the system with a steady-state, single-layer model probably is unrealistic. A transient, multilayer finite-element model of the Edwards and the Trinity aquifers in the Balcones fault zone and the Hill Country, an area of about 10,000 mi^2, is nearing completion.

The geochemistry of the aquifer system in the southern study area is being studied to provide independent information on the nature of the flow system. A data base of "best available" existing water analyses has been constructed. From this data base, regional maps of hydrochemical facies and concentrations of dissolved solids, sulfate, chloride, and fluoride have been made. Recent work involved sampling of wells in the updip and downdip parts of the Trinity aquifer in the Hill Country to obtain major constituents and isotope data, primarily carbon-13 and carbon-14. These data are being used in mass-transfer modeling to derive chemical reactions that simulate observed water chemistry.

As of 1992, work in the northern study area consisted of preparation of a series of hydrogeologic sections based on geophysical logs that will be used to define the hydrogeologic framework there. No computer modeling is planned for the northern study area.

The Edwards-Trinity aquifer system in the southern study area also includes two mappable confining units (fig. 64). The Hammett confining unit occurs within the Trinity aquifer in the Hill Country and southeastern parts of the Edwards-Trinity aquifer in the Edwards Plateau. The Navarro–Del Rio confining unit directly overlies subcropping parts of the Edwards aquifer in the Balcones fault zone. The subdivision of the Cretaceous strata into aquifers and

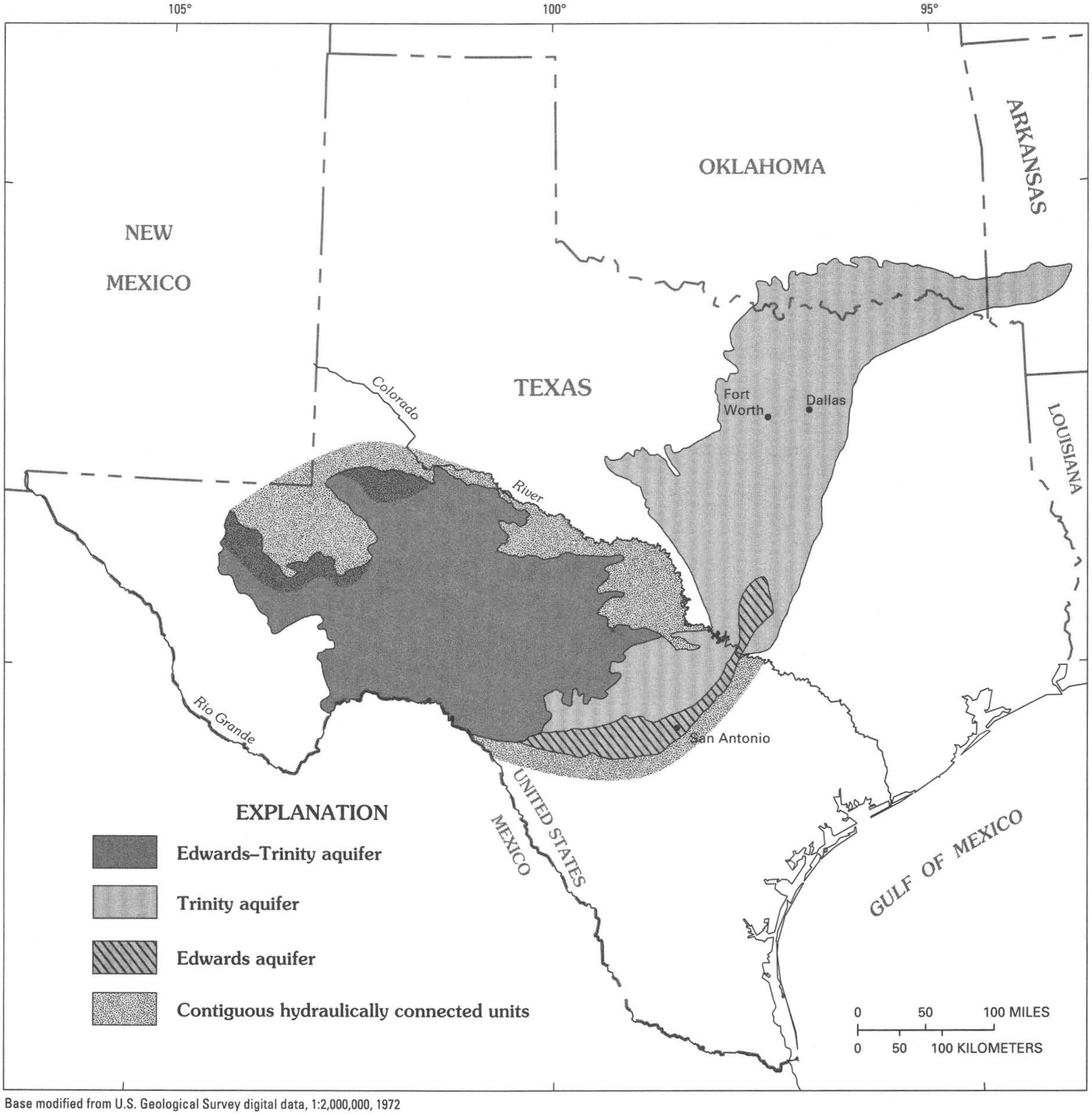


Figure 62. Study area of the Edwards-Trinity regional aquifer-system analysis and location of contiguous hydraulically connected units in central Texas, southeastern Oklahoma, and southwestern Arkansas.

confining units is based primarily on the relative capacity of the rocks to transmit water. This information was derived from well-yield and aquifer-test data and was extrapolated regionally on the basis of stratigraphy.

The principal units contiguous to and hydraulically connected to the aquifer system are the High Plains aquifer and the Cenozoic Pecos alluvium aquifer along the Pecos River (fig. 64). Ogallala sediments of the High Plains aquifer are essentially indistinguishable from underlying Lower Cretaceous sediments in the northwestern part of the study area (Mount and others, 1967, p. 45). Due to the dissolution of Permian salt beds and the subsequent collapse and erosion of the overlying Cretaceous section, a large volume of Edwards and Trinity strata is missing along the Pecos River near the northwestern margin of the study area. Following the removal of Edwards-Trinity rocks, alluvium of Tertiary and Quaternary age filled the structural trough to a thickness of as much as 1,500 ft. The

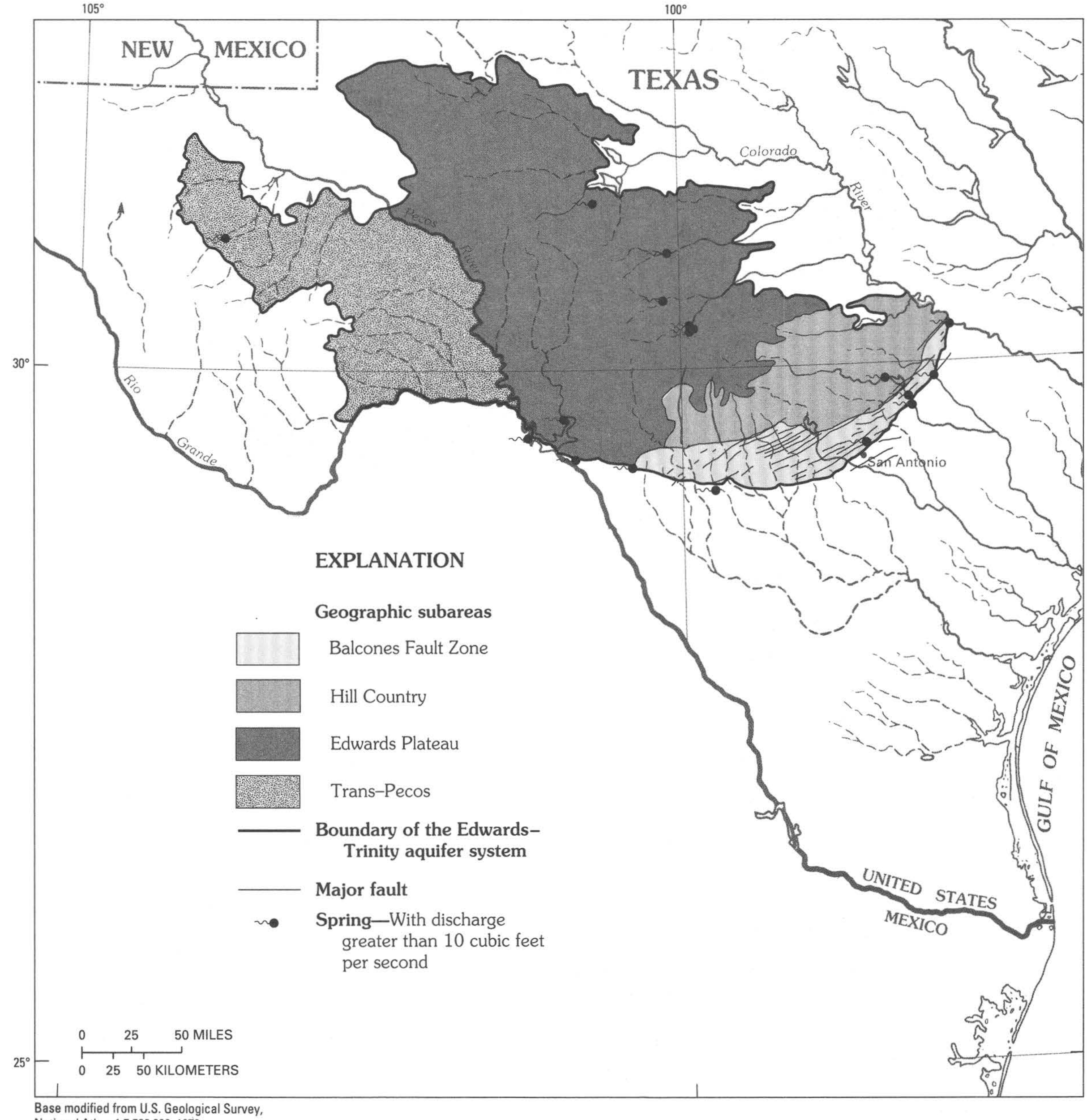


Figure 63. Geographic subareas of the Edwards-Trinity regional aquifer system in west-central Texas.

Cenozoic Pecos alluvium aquifer is a relatively permeable mixture of unconsolidated to semiconsolidated gravel, sand, silt, clay, and caliche that is hydraulically continuous with Edwards-Trinity rocks in the area.

Several minor aquifers in rocks of pre- and post-Cretaceous age are between the aquifer system and the Colorado River. Around the northeastern margin of the study area just south of the Colorado River, erosion of the basal rocks has formed a subtle topographic basin, within which a local ground-water regime merges with flow from the Edwards-Trinity aquifer.

The unique hydrogeology of the Balcones fault zone is a direct result of large-scale normal faulting during late Oligocene through early Miocene time that profoundly disrupted rocks in that area (Weeks, 1945). The resulting structure and subsequent dissolution of soluble carbonate constituents are primarily responsible for the marked contrast between the dynamic, vigorous flow regime that oc-

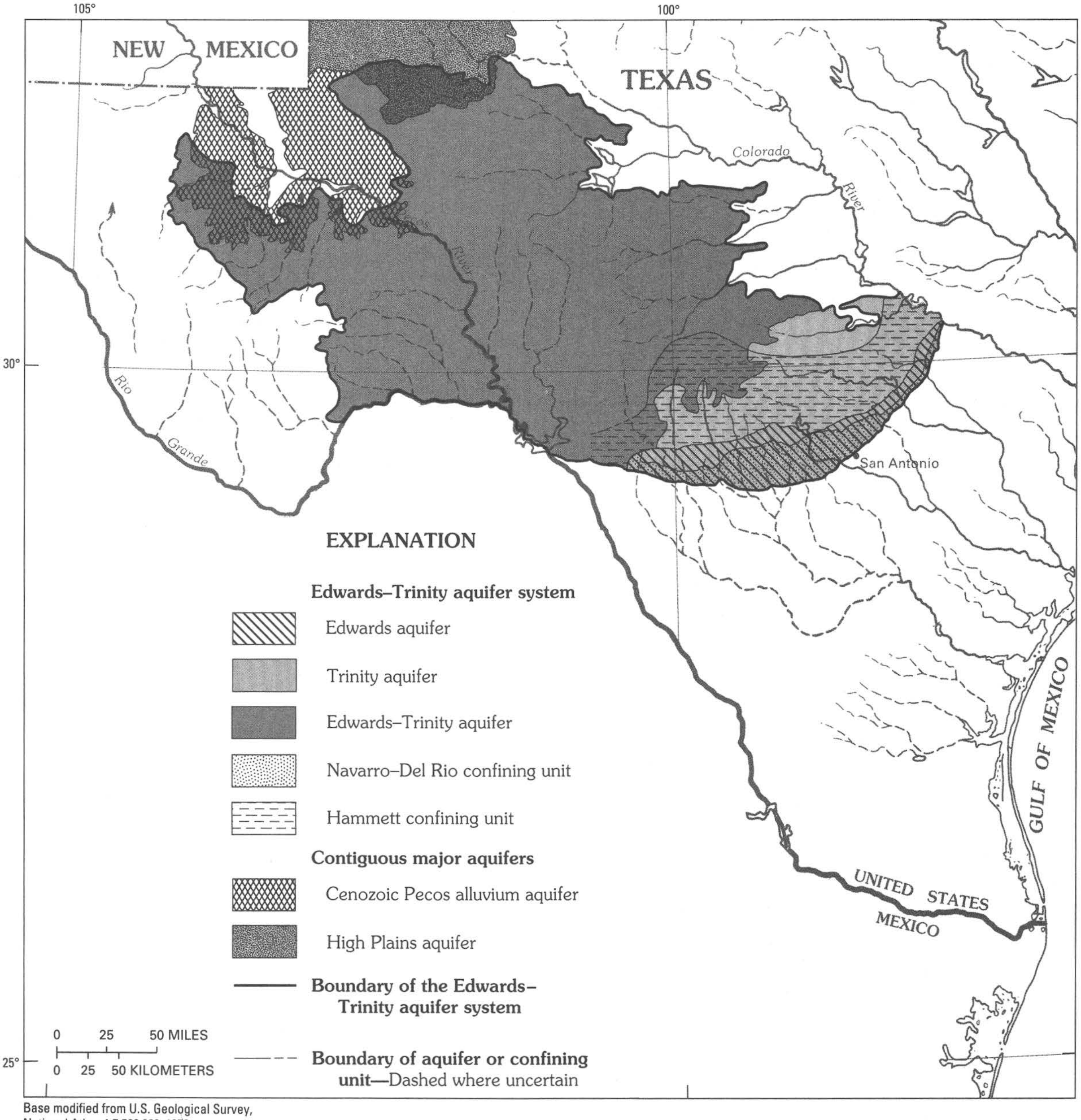


Figure 64. Aquifers and confining units in the Edwards-Trinity regional aquifer system and contiguous major aquifers in west-central Texas.

curs in shallow parts of the fault zone and the more sluggish flow regime that is typical elsewhere in the study area. The faulting created avenues for water to enter, flow through, and dissolve the carbonate rocks, which greatly enhanced the permeability of the Edwards aquifer (Abbott, 1975). Compaction and cementation resulting from burial and slow-moving ground water have combined to limit the permeability in the Trinity and Edwards-Trinity aquifers.

The striking contrast between the flow regime in the Edwards and that in other aquifers and contiguous hydraulically connected units in the southern study area is reflected in the regional distribution of estimated transmissivity. Based on the results of aquifer tests, geologic observation, and simulation, the transmissivity of the Edwards aquifer averages about 750,000 ft^2/d, whereas transmissivity of the Trinity aquifer in the Hill Country and of the Edwards-Trinity aquifer in the Edwards Plateau and the Trans-Pecos probably averages less than 10,000 ft^2/d.

Comparison of simulated components of the winter 1974–75 flow system to those of the predevelopment flow system gives some insight into how ground-water withdrawals may have affected the natural flow system (fig. 65). Results of simulations of development and predevelopment conditions indicate that the source of most of the water supplied to wells is diverted natural discharge to streams and springs, rather than induced recharge. Simulated total recharge to the aquifer system and contiguous hydraulically connected units increased about 5 percent, from 2.8 to 3 million acre-ft/yr, as the result of ground-water development. This result is compatible with hydrologic conditions—that is, no large source of water exists from which additional recharge might be induced. Streambed leakage in the southern part of the Hill Country and the northern part of the Balcones fault zone provides the largest concentrated volume of recharge to the flow system. The outcropping Edwards rocks are very permeable;

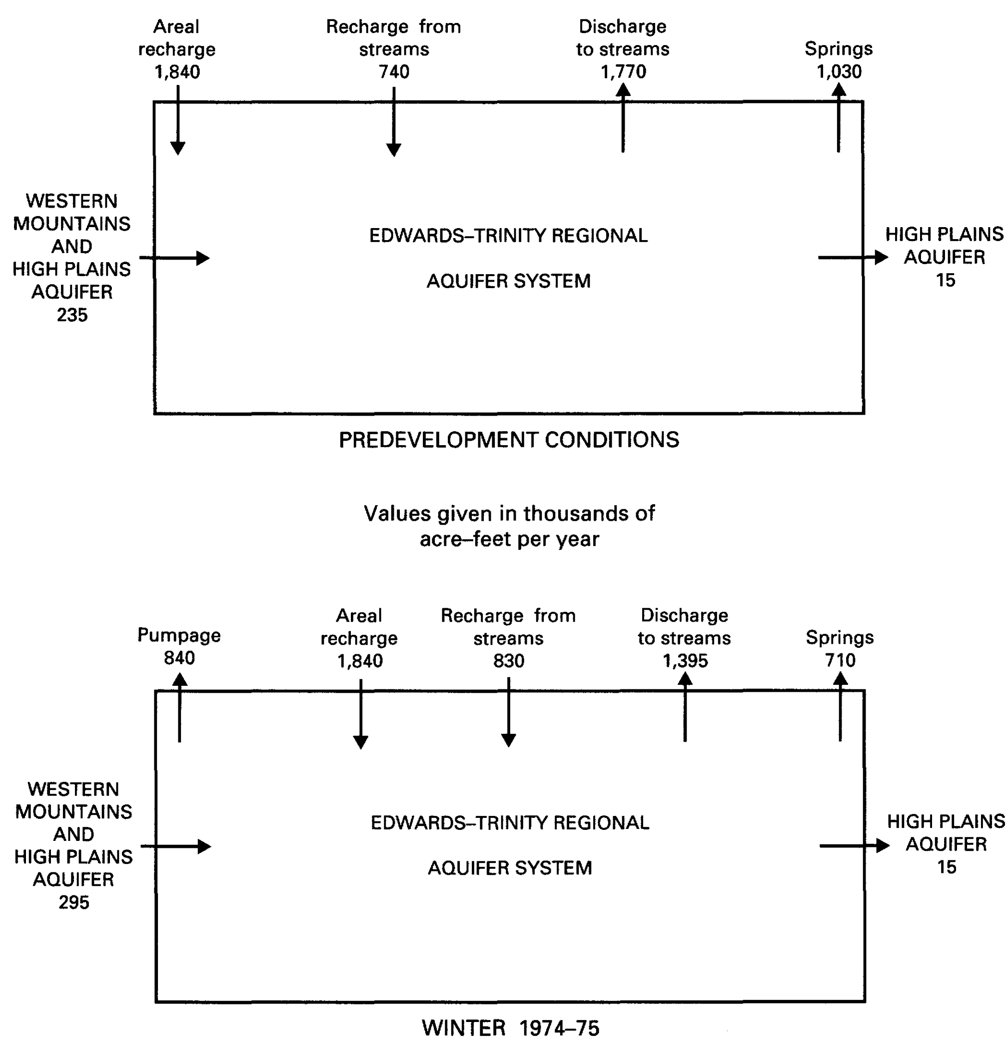


Figure 65. Simulated flow components to and from the Edwards-Trinity regional aquifer system in west-central Texas, predevelopment conditions and winter 1974–75.

thus, the small water-level changes in the Edwards aquifer resulting from well discharge have little effect on the rates of streambed leakage. Simulated withdrawals in the study area of 840,000 acre-ft/yr reduced simulated discharge to streams and springs from 2.8 to 2.1 million acre-ft/yr, a reduction of about 25 percent. Discharges of several major springs in the Edwards and in the Edwards-Trinity aquifers have been reduced or eliminated altogether by ground-water development.

The major part of the Edwards-Trinity aquifer system contains freshwater (dissolved-solids concentration less than 500 mg/L), but sizable parts contain marginally fresh water (dissolved-solids concentration 500 to 1,000 mg/L) or slightly saline water (dissolved-solids concentration 1,000 to 3,000 mg/L). The predominant water type is calcium bicarbonate; however, one of seven other water types characterizes the aquifer system in places.

The median concentration of dissolved solids among water analyses from the Edwards aquifer in the Balcones fault zone is 297 mg/L. Water in the Edwards aquifer is almost exclusively calcium bicarbonate type. The median dissolved-solids concentration among analyses from the Trinity aquifer in the Hill Country is 537 mg/L. Four bicarbonate and sulfate water types, spread vertically throughout the saturated section, characterize most of the Hill Country analyses; calcium bicarbonate predominates. The median concentration of dissolved solids in the Edwards-Trinity aquifer in the Edwards Plateau is 379 mg/L. Freshwater is nearly everywhere in the southern and northeastern parts of the aquifer; mostly slightly saline water is in the northwestern part. Water types are distributed in a similar pattern, with bicarbonate water nearly everywhere in the southern and northeastern parts of the aquifer. Sulfate and chloride water types characterize the northwestern part of the Plateau. The median concentration of dissolved solids among analyses from the Edwards-Trinity aquifer in the Trans-Pecos is 929 mg/L. Fresh, calcium bicarbonate water predominates in the southern part, and more mineralized mixed and sulfate water types are the most common in the northwestern part.

As of August 1992, nine reports have been completed.

MICHIGAN BASIN

The Michigan Basin regional aquifer-system analysis includes about 29,000 mi^2 of the Lower Peninsula of Michigan (fig. 66). The aquifer system consists of Mississippian and younger consolidated and unconsolidated sediments. The Marshall Sandstone (Mississippian), sandstones within the Grand River and Saginaw Formations (Pennsylvanian), and glacial deposits (Pleistocene) are major sources of ground water for supply in the Michigan basin. The contact between the Coldwater Shale (Mississippian) and the overlying Marshall Sandstone forms the outer boundary of the study area.

Saline water is present in the aquifer system at depths from 50 to 1,000 ft below land surface (Westjohn, 1989), and encroachment of saline water toward pumping centers is a significant problem related to ground-water supply in the State. In the center of the basin, the Marshall Sandstone and lower parts of the Saginaw Formation contain saline water or brine. In the Saginaw Lowland, saline water is present in glacial deposits. In the Lansing area, a cone of depression that extends over 100 mi^2 has developed in the Grand River–Saginaw aquifer. Water levels near the center of the cone have been as much as 160 ft below the predevelopment level. Saline water has periodically encroached into municipal supply wells in Lansing, Flint, Saginaw, Midland, and Mount Pleasant (fig. 66).

Increased demand for ground water in Michigan is anticipated. To manage and protect ground-water resources of the Michigan Basin, it is necessary to understand the distribution and relations between saline water and freshwater and to determine relations between saline water and past and present ground-water flow conditions. The major objectives of the Michigan Basin regional aquifer-system analysis study are to (1) describe the geology of Mississippian and younger geological units, (2) characterize the geochemistry of ground water, (3) delineate the interface between freshwater and saline water, and (4) quantitatively describe past and present ground-water flow conditions.

The aquifer system consists of a glacial-drift aquifer and three bedrock aquifers separated by confining units (fig. 67). Bedrock aquifers, in ascending order, are the Marshall, Parma-Bayport, and Grand River–Saginaw aquifers. The Coldwater Shale, which ranges from 500 to 1,100 ft in thickness, forms the base of the aquifer system.

The Marshall aquifer is the basal aquifer in the study area. It consists of sandstones that overlie the Coldwater confining unit as well as sandstones that form the lower part of the Michigan Formation (fig. 67). The Marshall aquifer consists of two or more permeable sandstones in the central part of the basin, but where the aquifer subcrops the glacial deposits, it consists of one permeable sandstone. Where more than one sandstone is present, intercalated carbonate, shale, siltstone, and (or) evaporite separate permeable sandstones. The composite thickness of permeable sandstone is from 75 to 225 ft.

The Michigan confining unit is an intercalated sequence of thin-bedded limestone, dolomite, shale, gypsum, anhydrite, and lenses of sandstone. The unit varies in thickness from 100 ft near the fringes of the subcrop area to about 400 ft in the central part of the study area.

The Bayport Limestone overlies the Michigan confining unit in some areas but is thin or absent in the central part of the basin (fig. 67). In areas where the Bayport is absent, the Parma Sandstone is present and overlies the

Michigan confining unit. Geophysical logs show that the Bayport Limestone consists predominantly of permeable limestone and sandstone. The Parma Sandstone Member and Bayport Limestone combine to form the Parma-Bayport aquifer, a hydraulically connected and stratigraphically continuous permeable unit over most of the basin. The Parma-Bayport aquifer is from 75 to 150 ft thick.

The Grand River-Saginaw aquifer, in most parts of the basin, consists of lenticular sandstones whose composite thickness is from 50 to 400 ft. The Grand River-Saginaw and Parma-Bayport aquifers are separated by the Saginaw confining unit, which consists of shale, siltstone, and thin-bedded sandstone intercalated with shale. Locally, this confining unit may yield water to wells; regionally, it acts as a confining unit.

Red beds of Late Jurassic age overlie the Grand River and Saginaw Formations in the west-central part of the study area. The red beds consist of mudstone and poorly consolidated red shale, gypsum, and minor amounts of sandstone. The red beds, glacial till, and lacustrine clay

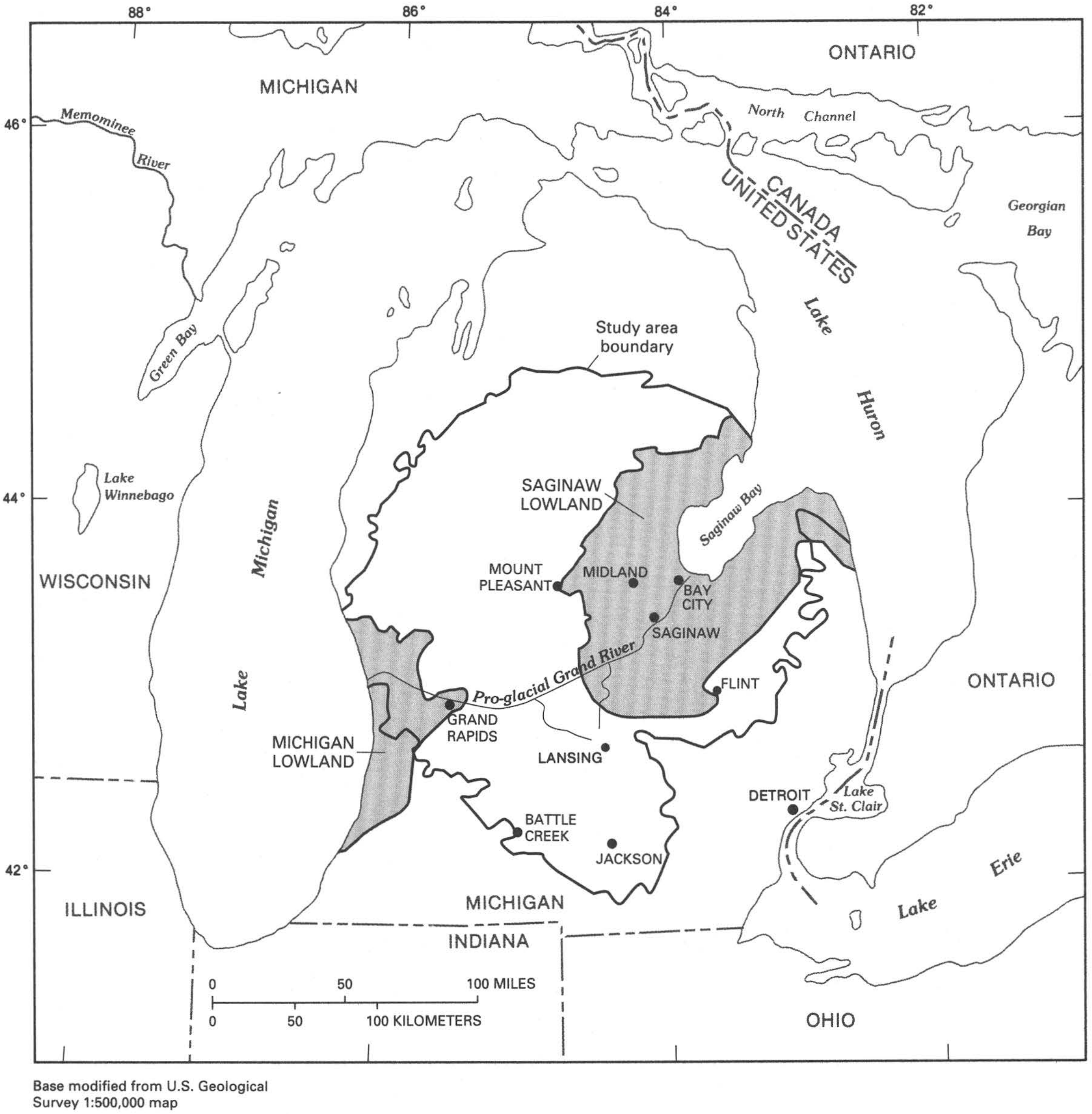


Figure 66. Study area of the Michigan Basin regional aquifer-system analysis.

form the glacial till–red beds confining unit that locally separates the glacial drift aquifer from the underlying Grand River–Saginaw aquifer.

Glacial deposits mantle nearly all of the study area. They are from 10 to 200 ft, 200 to 400 ft, and 400 to 1,000 ft thick in the southern, central, and northern parts, respectively. Coarse-grained glacial deposits are grouped to form the glacial drift aquifer.

Ground water in glacial drift generally has dissolved-solids concentrations less than 1,000 mg/L. However, dissolved-solids concentrations in water in glacial deposits in the Saginaw Lowland commonly exceed 1,000 mg/L. Water in the Grand River–Saginaw, Parma-Bayport, and Marshall aquifers is more saline at the center of the basin than at or near subcrops. Dissolved-solids concentrations in water from the Parma-Bayport and Marshall aquifers in the central part of the basin exceed 200,000 and 300,000 mg/L, respectively.

Electrical resistivity logs from oil exploration holes, chemical analyses of water samples, and surface geophysical data were used to construct a map of the altitude of the base of freshwater (fig. 68). Freshwater is defined as water having concentrations of dissolved solids less than 1,000 mg/L. Thickness of freshwater varies from about 1,000 ft in the northwest to less than 100 ft in the Saginaw Lowland.

In places where the Marshall aquifer is fractured and in hydraulic connection with glaciofluvial deposits, transmissivity is from 130 to 27,000 ft^2/d. Estimated hydraulic conductivities are from 10 to 550 ft/d. Analyses of tests of selected intervals in test holes indicate that hydraulic conductivity of the confined Marshall aquifer is from about 0.17 to 0.69 ft/d away from the subcrop area. Laboratory analyses of Marshall Sandstone cores indicate that intrinsic permeability is from 0.01 to 4 ft/d. These data show that the permeability of the Marshall aquifer decreases markedly from the subcrop area toward the center of the basin.

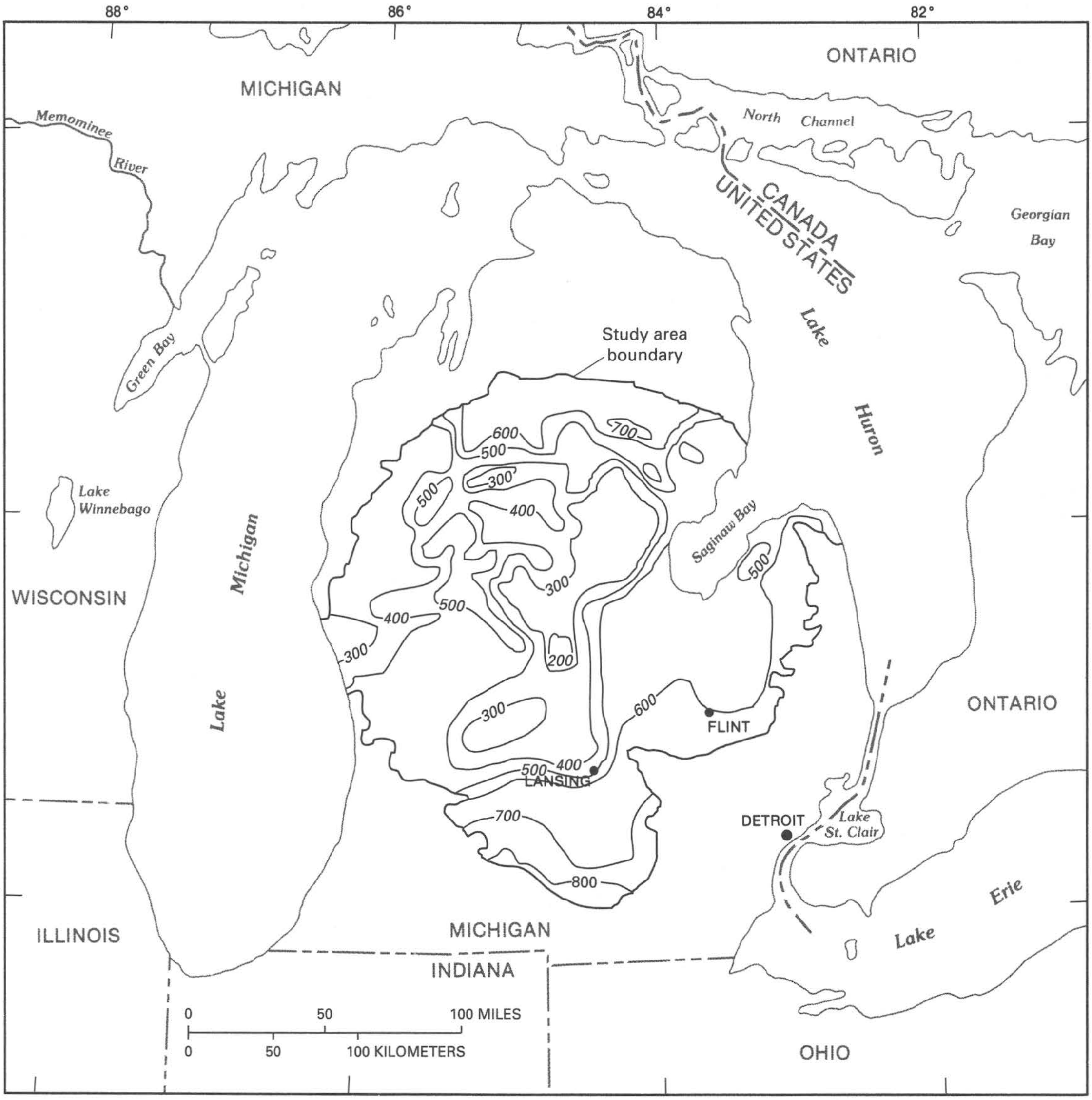
The Grand River–Saginaw aquifer is productive where lenticular sandstones are thickest, as in the south-central part of the State near Lansing. Transmissivity val-

Era	Period	Epoch	Glaciation	Stratigraphic unit		Hydrogeologic unit
Cenozoic	Quaternary	Holocene				Glacial drift aquifer
		Pleistocene	Wisconsin Illinoian Pre-Illinoian			
Mesozoic	Jurassic	Late		Unnamed red beds		Glacial till–red beds confining unit
Paleozoic	Pennsylvanian	Middle		Grand River Formation		Grand River–Saginaw aquifer
		Early		Saginaw Formation		Saginaw confining unit
					Parma Sandstone Member	Parma–Bayport aquifer
	Mississippian	Late		Grand Rapids Group: Bayport Limestone		
				Grand Rapids Group: Michigan Formation		Michigan confining unit
					Stray Sandstone Member	Marshall aquifer
		Early		Marshall Sandstone	Napoleon Sandstone Member	
				Coldwater Shale		Coldwater confining unit

Figure 67. Relation between stratigraphic and hydrogeologic units in the Michigan Basin (modified from Mandle and Westjohn, 1989).

ues from aquifer tests range from 300 to 13,500 ft^2/d. Estimated hydraulic conductivity is from 1 to 100 ft/d. Transmissivity values from aquifer tests conducted in wells completed in glacial deposits are from 650 to 82,000 ft^2/d. Estimated hydraulic conductivity is from less than 50 to more than 500 ft/d.

A generalized water-table map of Michigan's Lower Peninsula shows the presence of two areas of relatively high water-table altitude, which reflect the higher land-surface altitude of the northern and southern uplands (fig. 69). In the northern uplands, maximum altitude of the water table is between 1,200 and 1,300 ft; in the southern uplands, maximum altitude is about 1,000 ft. The water table slopes away from these areas either toward the Great Lakes or toward an elongated northeast-southwest-trending depression in the water table. This depression is in the pro-glacial Grand River valley, the site of the present-day Grand, Maple, and Saginaw Rivers.



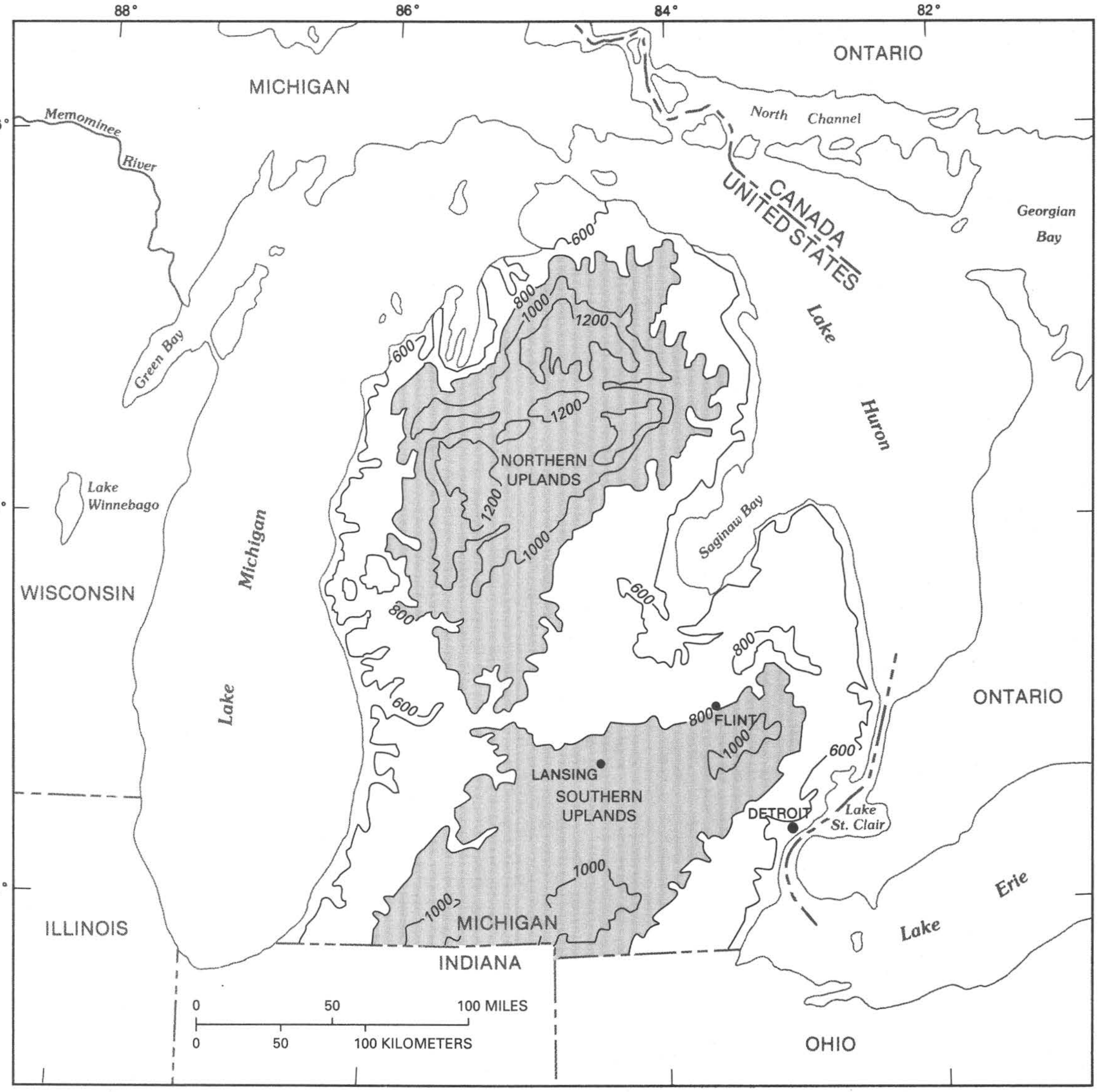
Base modified from U.S. Geological Survey 1:500,000 map

EXPLANATION

—500— **Base of freshwater contour**—Shows altitude of base of freshwater. Contour interval 100 feet. Datum is sea level

Figure 68. Altitude of base of freshwater in the Michigan Basin (from Westjohn, 1989).

The distribution of equivalent freshwater head in the Grand River–Saginaw aquifer (fig. 70) is similar to the distribution of head shown on the water-table map (fig. 69). However, head values for the Grand River–Saginaw aquifer are lower in the uplands and higher in the lowlands than heads in the glacial drift aquifer. This suggests that freshwater recharges the Grand River–Saginaw aquifer in the uplands, then flows toward the lowlands where it discharges upward into the glacial drift aquifer. Preliminary evaluation of data indicates that heads in the Marshall aquifer are greater than those in the Grand River–Saginaw and glacial drift aquifers in much of the area. It is not likely that the Marshall aquifer is recharged by freshwater in the northern uplands area. At and near the southern subcrop, local flow systems control groundwater flow.



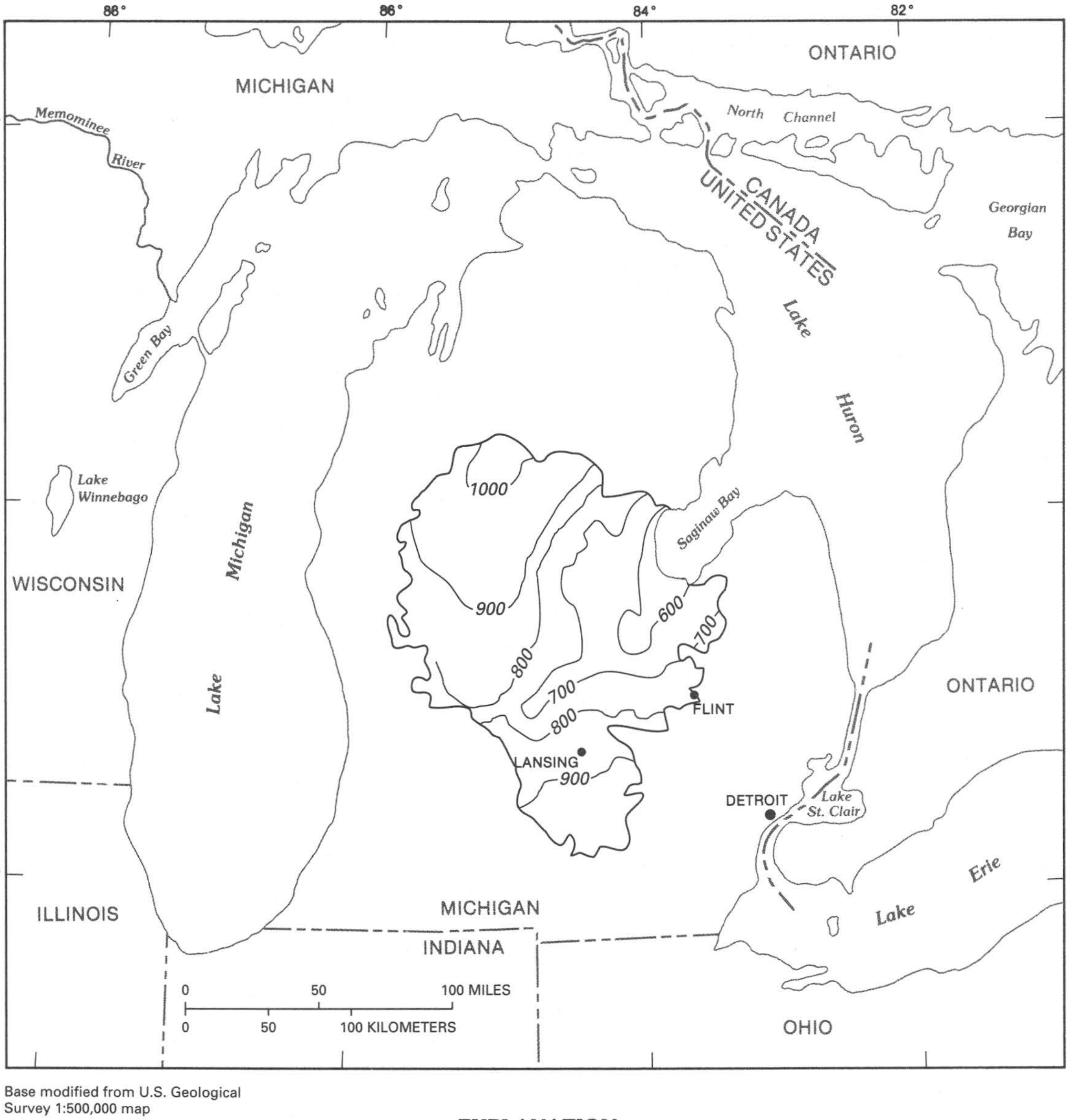
Base modified from U.S. Geological Survey 1:500,000 map

EXPLANATION

—*800*— **Water-table contour**—Shows altitude of water table. Contour interval 200 feet. Datum is sea level

Figure 69. Generalized water table in the glacial drift aquifer of the Lower Peninsula of Michigan (from Mandle and Westjohn, 1989).

A finite-difference computer program (McDonald and Harbaugh, 1988) was used to simulate three-dimensional ground-water flow. Modifications to the program were made to allow simulation of variable-density flow. The modifications and computer program are similar to those developed by Kontis and Mandle (1988). The aquifer system was discretized into five layers with four intervening confining layers. The Marshall, Parma-Bayport, Grand River–Saginaw, and glacial drift aquifers were each represented by one layer in the model. The intervening glacial till–red beds, Saginaw, Michigan, and Coldwater confining units also were simulated. The modeled area



EXPLANATION

—*900*— **Line of equal hydraulic head corrected to freshwater density** (1.94 slugs per cubic foot at 60°F). Interval 100 feet

——— **Line of contact between Saginaw Formation and Bayport Limestone**

Figure 70. Generalized equivalent freshwater head in the Grand River–Saginaw aquifer of the Michigan Basin (from Mandle and Westjohn, 1989).

was extended to incorporate the adjacent Great Lakes as lateral-flow boundaries. The Traverse aquifer, a bottom layer representing the Devonian Traverse Limestone and underlying older carbonate rocks, was added to simulate the perimeter and lower boundary. This addition allowed simulation of ground-water flow across the Coldwater confining unit. The upper boundary for the flow model was the water table, which was represented by a constant-head boundary for these simulations.

Preliminary computer simulation produced freshwater head distributions for the Grand River–Saginaw aquifer that were similar to predevelopment heads. Simulation indicates that a downward component of flow exists in upland areas and an upward component of flow exists in the pro-glacial Grand River valley and in the Saginaw and Michigan Lowlands (Mandle and Westjohn, 1989). These simulated flow patterns suggest that the presence of saline ground water in the Saginaw and Michigan Lowlands may be the result of upwelling of deeper saline water that is part of the regional-flow system.

This on-going study was started in 1985. As of July 1992, 11 reports had been completed.

MIDWESTERN BASINS AND ARCHES GLACIAL AND CARBONATE REGIONAL AQUIFER SYSTEM

The Midwestern Basins and Arches glacial and carbonate regional aquifer-system analysis was called "The Ohio-Indiana carbonate-bedrock and glacial-aquifer-system analysis" in previous reports. This new name was selected because it generally reflects the geological province recognized by many geologists and hydrologists and is in accordance with the nomenclature described by the Committee on Stratigraphic Units of North America of the American Association of the Petroleum Geologists (AAPG COSUNA). The study area also extends beyond the previously delineated areas to include parts of Illinois and Michigan and the entire ground-water flow system (fig. 71).

The study area lies between the Appalachian Plateaus physiographic province to the east, the Illinois structural basin to the west, the Michigan structural basin and Lake Erie to the north, and the Ohio River to the south (fig. 71). The study area is mostly within the Central Lowland physiographic province, east of the Mississippi River, and includes about 43,000 mi^2.

The regional aquifer system consists of a single massive Silurian and Devonian carbonate rock aquifer and overlying hydraulically connected aquifers in unconsolidated Quaternary glacial deposits. Throughout most of the study area, the carbonate rock aquifer subcrops beneath glacial deposits (figs. 71 and 72). The lower boundary of the aquifer system is in Upper Ordovician rocks that include undifferentiated Cincinnatian rocks in northwestern and west-central Ohio and the Maquoketa Group in Indiana. These rocks are mostly shale, cherty and argillaceous limestone, and fine-grained clastic rocks. They are characterized by low permeability and considered to be the base of the aquifer system. The aquifer system extends laterally and downdip from the northern, eastern, and western margins of carbonate rock subcrop areas. In central Ohio within a relatively short distance downdip from the Silurian-Devonian subcrop area, water in the carbonate rocks has a dissolved-solids concentration of more than 10,000 mg/L (fig. 73). The interface between fresher ground water and the ground water having concentrations of dissolved solids of 10,000 mg/L or more is sharp. This abrupt transition occurs because the thickness of an overlying Devonian shale increases substantially within a relatively short distance from the rock subcrop, and the vertical recharge of freshwater from glacial deposits to the carbonate rocks decreases. However, on the western side of the study area, the transition zone from freshwater to water having dissolved-solids concentration of 10,000 mg/L is wider and extends farther from the Silurian-Devonian subcrop limit into the Illinois structural basin than does the transition zone on the eastern side of the area (fig. 73). In this area (western side) the Devonian shale is not as thick as on the eastern side. Along the northern side of the study area, the 10,000 mg/L dissolved-solids boundary is intermediate in distance from the Silurian-Devonian subcrop area compared with the eastern and western sides. The southern hydrologic boundary is the Ohio River. The upper boundary of the regional aquifer system is the water table in glacial deposits.

Silurian rocks of the aquifer system are predominantly limestone and dolomite, interbedded with thin beds of shale and gypsum. The carbonates are typically massive, crystalline dolomite and grade locally into reef structures. Brecciated dolomites, shaly dolomites, fossiliferous and cavernous limestones and dolomites also are present as a result of variations in depositional environments and postdepositional erosion and weathering. Devonian rocks are predominantly limestone that display karst features in some places. A unit of thick shale in the Upper Devonian rocks marks the upper hydrogeologic boundary of the Silurian-Devonian rock aquifer.

In western Ohio and eastern Indiana, the Silurian-Devonian rock aquifer receives recharge from glacial deposits in subcrop areas. Elsewhere, water in glacial deposits discharges locally to streams, except for a small amount of water that infiltrates to the underlying rock aquifer through confining units. Water in rock aquifers is mostly under confined conditions, except where the rocks are close to or exposed at land surface. Water in the rock aquifer generally flows toward major rivers, to Lake Erie, and to subcrop areas along the Scioto Valley and the Illinois structural basin.

Lateral discontinuity of glacial deposits and variations in secondary permeability of the rocks are major

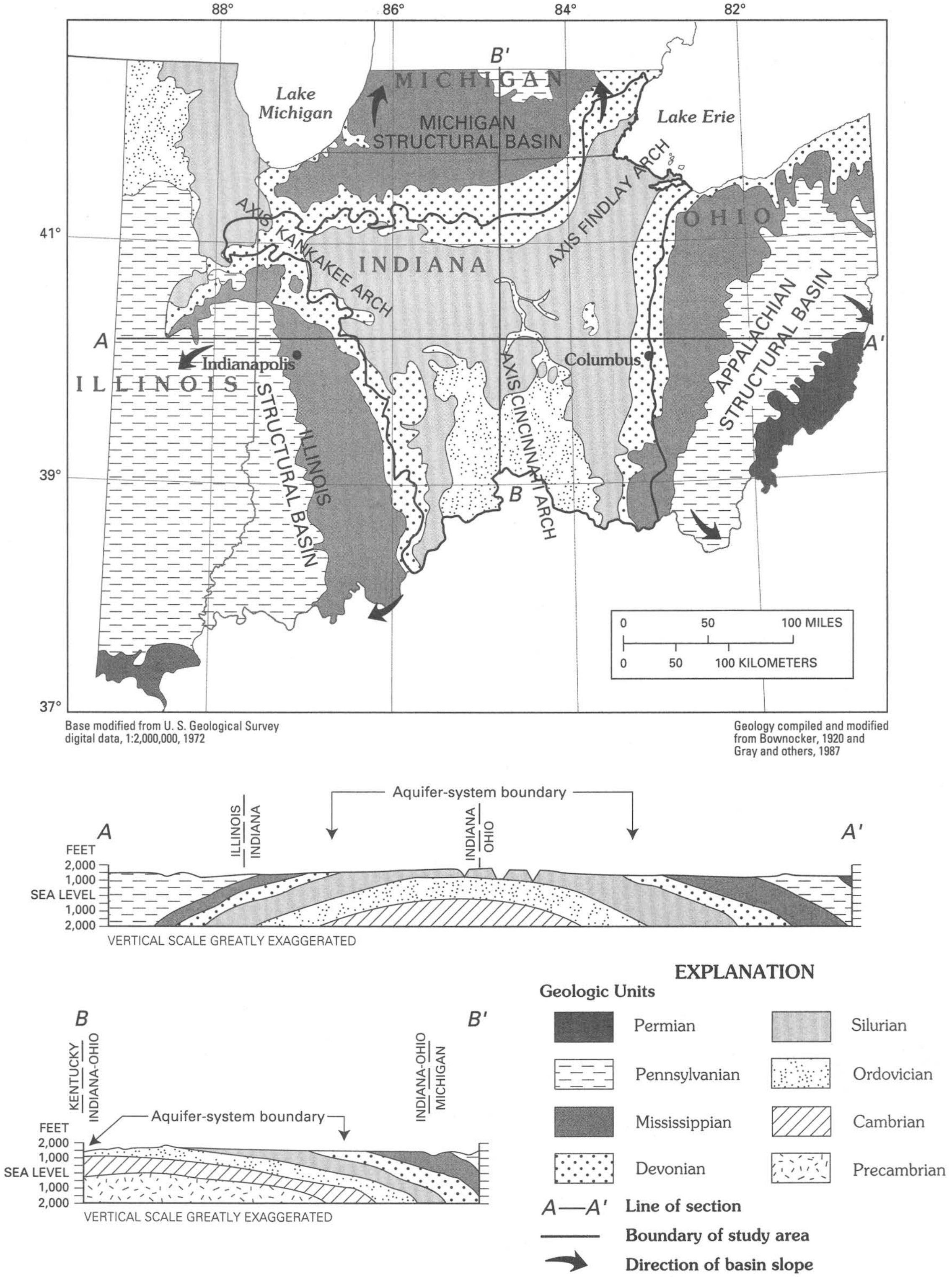


Figure 71. Study area and generalized geology of the Midwestern Basins and Arches glacial and carbonate regional aquifer-system analysis.

concerns in planning the development of ground water in the study area. Reported transmissivity of the rocks is from 70 to 28,000 ft^2/d in Ohio and from 300 to 52,000 ft^2/d in Indiana. Glacial deposits in the study area have a wide range of hydraulic conductivity, depending on their texture and lithology. Differences in hydraulic conductivi-

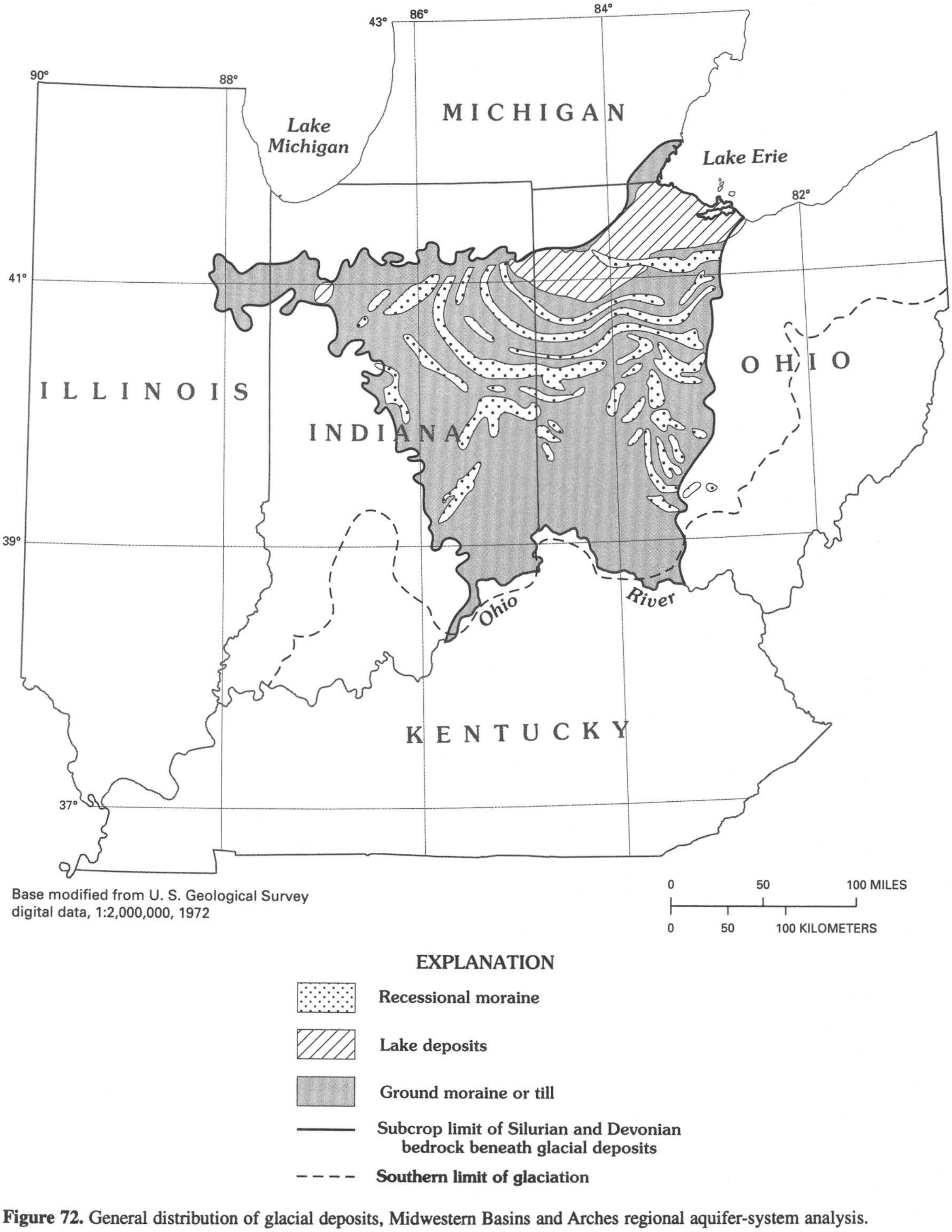


Figure 72. General distribution of glacial deposits, Midwestern Basins and Arches regional aquifer-system analysis.

ty cause differences in rates of ground-water movement and in the amount of recharge to underlying rocks. Locally, the hydraulic conductivity of glacial deposits can differ by several orders of magnitude, even within the same type of deposits. Generally, transmissivity of outwash is from 300 to 70,000 ft^2/d in Indiana and from 1,300 to 60,000 ft^2/d in Ohio. The vertical hydraulic conductivity of clay-rich till is from 3.7×10^{-1} to 3.0×10^{-3} ft/d in Indiana

Figure 73. General distribution of dissolved-solids concentration in water from the Silurian-Devonian carbonate rock aquifer.

(Fleming, 1989) and from 1.17×10^{-3} (Strobel, 1990) to 4×10^{-3} (Norris, 1959) in northwestern Ohio. These values are one to five times greater than model-generated hydraulic conductivity values normally reported from other parts of the study area.

Quality of water in the carbonate rock aquifer varies spatially and with depth depending on the lithology and occurrence of evaporitic deposits, such as gypsum, especially in the northeastern part of the study area. Generally, the quality of water in glacial deposits is good. The concentration of dissolved solids in water in the Silurian-Devonian rock aquifer normally is less than 1,000 mg/L in the western and central part of the study area and ranges from 1,000 to 3,000 mg/L in the northeastern part of the area (fig. 73).

In 1980, more than 280 Mgal/d of ground water was pumped to supply industry, agriculture, and a population of more than 6.3 million people. Most of the water was withdrawn from glacial deposits. The carbonate rock aquifer has not been affected by pumpage from wells, except in northwestern Indiana, where irrigation causes seasonal water-level declines.

The study was started in 1988. As of mid-1992, six reports were published and five reports were undergoing technical review.

NORTHERN ROCKY MOUNTAINS INTERMONTANE BASINS, MONTANA, AND IDAHO

The Northern Rocky Mountains Intermontane Basins RASA is an investigation of hydrogeologic conditions of intermontane basin-fill aquifers in western Montana and central and northern Idaho. Geographically, these basins exist separately; hydrogeologically, they share many characteristics because of their common structural and depositional histories and physiographic settings. The study area is about 80,000 mi^2 and extends westward from the Northern Great Plains in Montana to the Columbia Plateau in western Idaho, and northward from the Snake River Plain in Idaho to the United States–Canada border (fig. 74).

On the basis of stratigraphy and geologic structure, about 70 basins were delineated in the study area (fig. 75). Basins range in size from 10 to 400 mi^2 and are filled with as much as several thousand feet of unconsolidated to poorly consolidated Tertiary and Quaternary continental sediments.

The Continental Divide (fig. 74) separates the study area into two major drainage systems: the Missouri River drainage to the east and the Columbia River drainage to the west. Major streams in the Missouri River drainage include the Big Hole, Jefferson, Madison, and Gallatin Rivers. Major streams in the Columbia River drainage include the Snake, Salmon, Clearwater, Spokane, Clark Fork/Pend Oreille, Blackfoot, Bitterroot, Flathead, and Kootenai Rivers (fig. 74). Annual precipitation on the study area ranges from about 8 in. in basins in east-central Idaho to about 100 in. in some mountainous parts of Montana. Most valleys receive about 10 to 30 in. of precipitation per year; more than 50 percent of the annual precipitation falls during November to April as snow.

Most of the intermontane basins of the northern Rocky Mountains were formed by Basin and Range tectonics during the Miocene Epoch, creating an area of broadly distributed crustal extension characterized by hundreds of normal faults. As the crust extended, downthrown fault blocks became basins, while upthrown fault blocks became the intervening mountains (Eaton, 1979). In general, most of the basins trend northerly to northwesterly, roughly parallel to basin-margin normal faults and perpendicular to the regional extension.

The intermontane basins subsided intermittently throughout the Tertiary Period, resulting in continental deposits as much as 16,000 ft thick. In southwestern Montana, these deposits are assigned to the Bozeman Group, composed of the Renova Formation and the overlying Sixmile Creek Formation. Names for the Tertiary deposits vary within the study area; however, the stratigraphy is generally correlative on a regional basis. Historically, the lower predominantly fine-grained deposits have been named the Renova Formation, whereas the overlying predominantly coarse-grained deposits have been named the Sixmile Creek Formation. However, recent work on the stratigraphy of the Tertiary deposits indicates that fine- and coarse-grained deposits occur in both formations (Hanneman and Wideman, 1991). Both the Renova and Sixmile Creek Formations consist of lacustrine and fluvial sediments that exhibit abrupt lateral and vertical facies changes. The Renova Formation is generally considered to be too deep and not sufficiently permeable to be a viable aquifer. In contrast, the uppermost gravels of the Sixmile Creek Formation form the most productive deep aquifer in the basins with transmissivities of about 1,000 ft^2/d.

Quaternary fluvial and glacial deposits overlie some Tertiary deposits. Quaternary deposits are primarily alluvium along streams and colluvial and alluvial-fan deposits near mountain flanks. However, in the north, the basins were subjected to repeated glacial advances, inundation by glacial lakes, and, lastly, alluvial deposition. Glacial deposits are from a few feet to hundreds of feet thick.

Unconsolidated Holocene alluvial deposits overlie glacial deposits in the north and Tertiary deposits in the south. The most significant water-yielding deposits are streambed alluvium having thicknesses of 10 to 200 ft and, to a lesser degree, alluvial fans along the basin margins having thicknesses of as much as 500 ft. Alluvial aquifers have typical transmissivities of about 10,000 to 100,000 ft^2/d.

Flow systems in basin-fill aquifers in many intermontane basins are largely isolated with little or no known hydraulic connection between unconsolidated deposits of adjacent basins (Clark and Kendy, 1992b). However, through-flowing streams provide a significant hydraulic connection between basins. Ground water in one basin discharges to a stream, which flows to the next basin where the water may recharge the underlying aquifers. Ground water may flow between some basins through locally permeable bedrock or along faults having zones of increased permeability.

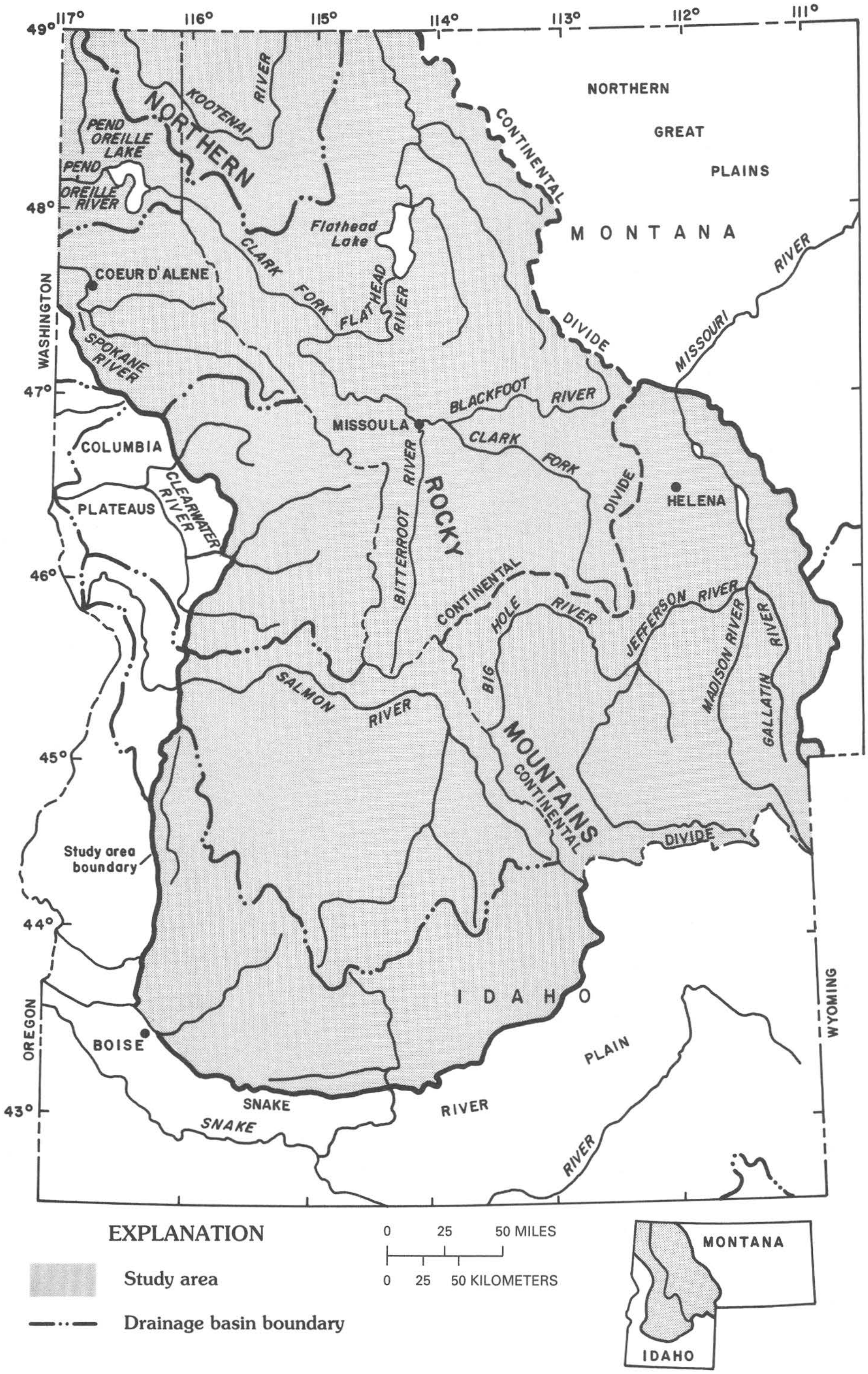


Figure 74. Study area of the Northern Rocky Mountains Intermontane Basins regional aquifer-system analysis.

Basin-fill aquifers are primarily recharged by stream infiltration and subsurface inflow from surrounding bedrock along the mountain fronts, and to a minor extent by direct infiltration of precipitation. Infiltration of applied irrigation water and seepage from irrigation canals also provide recharge in some basins.

The direction of flow in the alluvial aquifers generally follows the topography, with flow components being

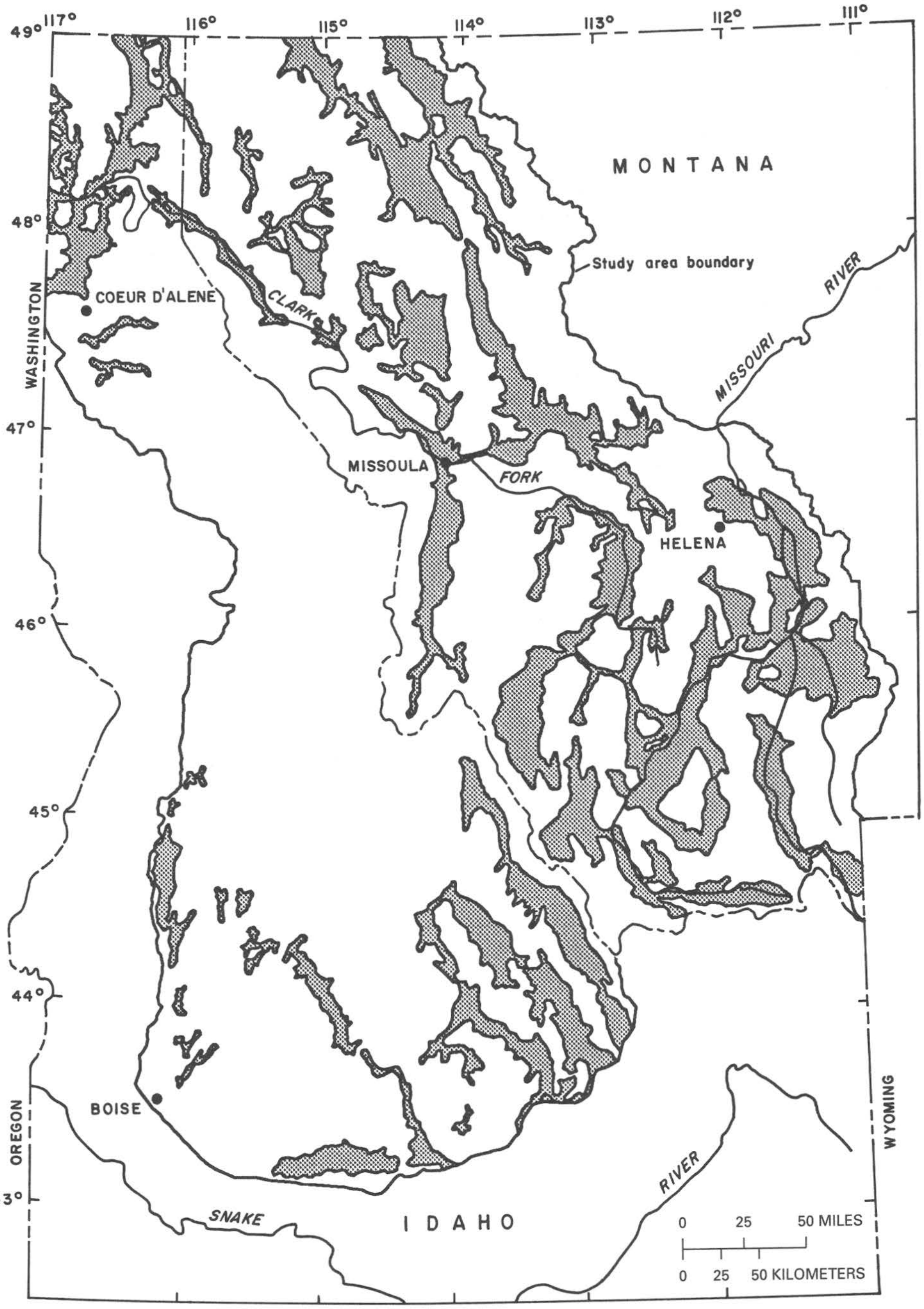


Figure 75. Intermontane basins in the northern Rocky Mountains (shaded).

toward major streams and downvalley. The direction of lateral flow in deep aquifers may be different than in the shallow aquifers in response to confining strata, faulting, or other deep structural controls. Depth to water ranges from land surface to hundreds of feet below land surface in topographically high areas near basin margins.

The Northern Rocky Mountains Intermontane Basins RASA study was started in 1990. As of early 1993, three reports have been published. The study will provide hydrogeologic information on the intermontane basin-fill aquifers in western Montana and central and northern Idaho. An important element of the study is to develop a geographically indexed data base of hydrogeology and related information including geology, land and water use, soil types, climatic data, physical features, water levels, water quality, aquifer boundaries, and hydraulic characteristics of aquifers (Clark and Kendy, 1992a). The other important elements are to develop methods of evaluating water resources particular to the intermontane basins of the northern Rocky Mountains. The common geologic history shared by the basins is the key to their related hydrogeology and to this study.

PUGET-WILLAMETTE LOWLAND, WASHINGTON, OREGON, AND CANADA

The Puget-Willamette Lowland (PWL) aquifer system is in western Washington, western Oregon, and a small part of southwestern British Columbia, Canada (fig. 76). The study area extends from near the Fraser River, British Columbia, Canada, to just south of Cottage Grove, Oregon. The PWL is composed of two distinct areas, the Puget Sound Lowland (PSL) and the Willamette Lowland (WL). The PSL study includes about 17,600 mi^2; the WL study includes about 5,680 mi^2. About 2,500 mi^2 of the PSL study area is covered by seawater. The two study areas include Puget Sound and the Willamette River, which drain parts of the Cascade Range, the Coast Range, and the Olympic Mountains. The extent of the aquifer system to be studied in the PSL is defined by the area underlain by Quaternary sediments (7,200 mi^2); in the WL, it is the area underlain by Quaternary sediments and upper Tertiary sediments and volcanics (4,100 mi^2). Both of the aquifer systems include several structural ground-water basins.

A complex geologic history has resulted in highly variable aquifer lithology. Alluvium, glacial, and interglacial sediments compose the aquifer system in the PSL and have been named the Puget Sound aquifer system. These deposits consist principally of recent alluvium, recessional and advance outwash, till, and other glaciofluvial and interglacial sediments. In the WL, alluvium basin-fill sediments and basalt materials compose the aquifer system and have been named the Willamette Lowland aquifer system. Older Tertiary and pre-Cenozoic sedimentary, volcaniclastic, volcanic, and metamorphic rock units define both the lateral and the basal boundaries of the aquifer systems in both areas and have been named the basement confining unit.

About 70 percent of the population of Washington and Oregon reside in the study areas, mainly in the metropolitan areas of Bellingham, Everett, Seattle and vicinity, Tacoma, and Olympia in the PSL; and Vancouver, Portland and vicinity, Salem, and Eugene in the WL. The burgeoning population is increasing the demand for available water. In some areas, available water supplies are already fully appropriated. Some supplies are limited due to contamination from anthropogenic sources and to saltwater intrusion from Puget Sound in the PSL and by older brackish ground water in the WL.

The PWL is a structural basin that extends from the Coast Mountains just north of the Fraser River in British Columbia to about Cottage Grove in central-western Oregon (fig. 76). The PWL is bordered by the Cascade Range on the east and the Coast Range and Olympic Mountains on the west. North of the Olympic Mountains, the western boundary is defined by the Canadian-Washington border located in the waters south and east of Vancouver Island, British Columbia. The southern boundary of the PSL is approximately defined by the extent of Pleistocene glaciation, which is characterized by a series of low hills near the divide between the Puget Sound drainage and the Chehalis River basin. The northern boundary of the WL is in Cowlitz County, Washington, and is defined by an outcrop of the Columbia River Basalt Group that extends northward along the Columbia River from the north end of the Portland basin. The southern boundary of the WL is a line of foothills where the Coast and Cascade ranges merge.

Altitudes of the valley floors or lowlands are from sea level to about 500 ft. The foothills or uplands have altitudes from 500 to about 1,500 ft. The altitude of the crest of the Cascade Range averages about 7,500 ft on the north to about 4,500 ft on the south; a series of stratovolcanoes in the Cascade Range rise from 8,000 to 14,000 ft above sea level. Altitude of the Olympic Mountains in the northwestern part of the PWL averages about 3,000 ft.

In the PSL, lowlands typically are alluvial river valleys with glacial outwash and till plains. These lowlands are separated from the bordering mountains by uplands with rolling hills and terraces. The transition from uplands to mountains generally is abrupt, except near the southern boundary. WL topography is interrupted in places by narrow, north- and northwest-trending, continuous basaltic ridges, which divide the north-central part of the valley into unequal-sized east and west segments. The topography in southwest Portland and northern Clackamas County also is interrupted by numerous irregular-shaped, low volcanic hills. Geologic structures in the WL divide the valley into four structural and topographic basins.

The PWL has a mid-latitude humid, Pacific Coast marine climate due to eastward-moving Pacific Ocean derived air masses. The adjacent mountains provide protection from southward moving Canadian cold-air masses and from Pacific Ocean winter storms. As a result, both summer and winter temperatures are moderated, there is a distinct winter precipitation season and summer dry season, and altitude and location have a large influence on the distribution of precipitation and temperature.

On lowlands of the PSL, precipitation varies from about 15 in/yr in the "rain shadow" of the Olympic Mountains to about 60 in/yr near the Olympic foothills. On lowlands of the WL, precipitation varies from about 37 in/yr near Portland, Oregon, to about 55 in/yr near the Cascade foothills. Precipitation on mountains bordering each area is from 50 to 200 in/yr. Most precipitation falls during the winter and is generally rain at altitudes of about 1,000 to 1,500 ft, rain and snow at altitudes up to about 2,500 ft, and snow at higher altitudes.

In the PSL, annual surface-water runoff from an area of about 13,700 mi^2 averages about 46,000 ft^3/s (45 in/yr).

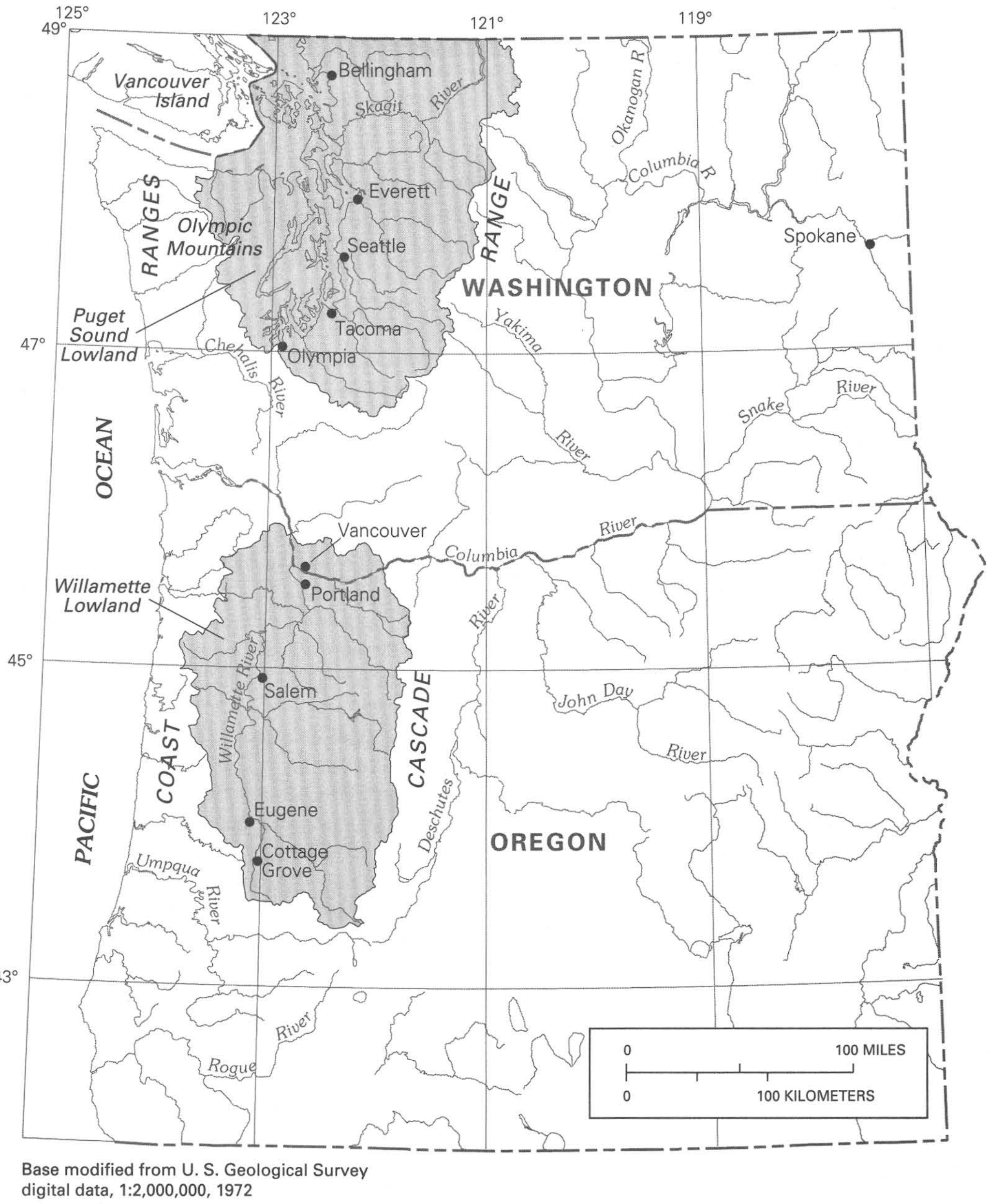


Figure 76. Study areas of the Puget-Willamette Lowland regional aquifer-system analysis.

Runoff from islands in northern Puget Sound, which represents less than 3 percent of the total PSL land area, averages about 10 in/yr. Runoff from the Willamette River drainage averages about 33,000 ft^3/s (40 in/yr) from an area of about 11,100 mi^2. Runoff within selected basins in both study areas ranges from about 35 to 80 in/yr.

The Puget Sound aquifer system is composed of unconsolidated deposits as much as 3,300 ft thick and consists of materials deposited by (1) advancing and retreating continental glaciers, (2) numerous alpine glaciers emanating from the adjacent Cascade Range and Olympic Mountains, and (3) rivers and relatively quiet water of lakes and bays during interglacial episodes, when much of the lowland consisted of saltwater embayments and freshwater lakes. Each of these depositional regimes resulted in complex lithostratigraphic patterns and corresponding geologic units that are difficult to correlate on a regional scale. The complexity within each depositional sequence was compounded by the erosive action of continental glaciers.

In a regional context, three types of deposits are associated with continental glaciers—advance outwash, till, and recessional outwash. The lateral and vertical extent of each type of deposits is best known for Vashon Drift deposited during Fraser Glaciation. Vashon Drift is relatively undisturbed and close to land surface.

The oldest rocks in the Willamette Lowland are early Tertiary marine sediments and subordinate marine volcanics, which crop out chiefly in foothills of the Coast Range along the western margin of the valley. These rocks dip gradually eastward beneath the younger basin-fill sediments and, in part, grade eastward into the Tertiary volcaniclastic and volcanic rocks of the Western Cascades. Collectively, marine rocks of the Coast Range and volcanic and volcaniclastic rocks of the Western Cascades generally have low permeability and are poor aquifers (McFarland, 1983). These rocks are thousands of feet thick beneath the valley and form the base to the overlying Willamette Lowland aquifer system.

In the central part of the WL, basement rocks are overlain by Miocene volcanic rocks of the Columbia River Basalt Group. Basaltic lava was erupted from linear vent systems in northeastern Oregon, southeastern Washington, and western Idaho. The lava was deposited as a series of areally extensive thin sheets. Each flow followed topographic or structural lows and topped many intervening low hills. As a consequence, some flows in eastern and western Oregon are thickest in paleovalleys and thin across hills. The basalt underlies younger formations and is as much as 1,000 ft thick.

Overlying the basalt in the northern part of the WL is a sequence of Quaternary and Tertiary basin-fill fluvial sediments. In the remainder of the lowland, where the basalt is absent, the Quaternary-Tertiary sequence lies directly on basement rock. The lower part of the basin-fill sediments consists of fine-grained clay and silt to mudstone and siltstone, which grade upward into sandy and gravelly units. Sediments become finer grained in a westerly and northwesterly direction, away from the eastern valley margins. These sediments appear to have been deposited as a series of low, broad coalescing alluvial fans issuing primarily from the Cascade Range on the eastern side of the valley, with lesser fans issuing from the Coast Range on the western side of the valley. The combined thickness of these sediments is greatest in the northern part of the WL, where geologic structures have greater amplitude.

Valley lowlands below an altitude of about 400 ft were inundated during the Pleistocene by floods caused by periodic breaching of an ice dam in Idaho (Bretz, 1923; Waitt, 1985). Breaching of the ice dam released enormous volumes of glacial meltwaters stored in glacial Lake Missoula, an ice marginal lake in Montana (Pardee, 1910). The waters flooded large areas adjacent to the present Columbia River, Willamette Valley, and the Columbia River valley downstream from present-day Portland. These floods spread across the Portland basin, where they scoured older deposits, deposited new sheets and deltas, and formed backwater lakes. In the Portland basin, sand and gravel deltas formed in lakes where currents were sufficiently swift, whereas fine-grained deposits (fine-grained sands and silts) were deposited in slack-water areas and in the remainder of the area inundated by lakes.

Youngest deposits in the WL are the shallow alluvial deposits along principal streams. Along the flood plain of the Columbia River, these deposits may be as much as 300 ft thick and consist chiefly of sand, with some sand and gravel, as well as finer grained overbank deposits consisting of silts and fine sands. Along most of the Willamette River flood plain, the alluvial deposits consist chiefly of sand and gravel as much as 70 ft thick and averaging about 50 ft; in places, they are covered by thin, fine-grained overbank deposits.

In the PSL, ground water generally moves from glaciated uplands fronting the Olympic Mountains and Cascade Range to streams and seawater bodies. Movement is predominantly lateral in aquifers and vertically downward toward deeper units in high-altitude areas. The gradient is upward from deeper aquifers in low-altitude areas and near streams and seawater bodies.

In the upper aquifers in the PSL, lateral hydraulic gradient generally is from 30 to 60 ft/mi; however, in deeper units it is from 5 to 10 ft/mi. Hydraulic conductivity of glacial aquifers generally is from 30 to 100 ft/d, but hydraulic conductivity of coarse-grained alluvial aquifers is from 100 to 200 ft/d.

Quality of ground water in the PSL is suitable for most uses. The dominant water types are calcium bicarbonate and magnesium bicarbonate in upper aquifers. Deeper aquifers contain water of a sodium bicarbonate and sodium chloride type. The sodium chloride water is associated with mixing of seawater.

In the WL, most regional ground-water flow occurs in the basin-fill sediments and overlying Quaternary deposits; significant amount of flow also occurs in the Columbia River Basalt Group. Most water in the basalt occurs in the interflow zones between successive basalt flows. Interflow zones consist of very porous, highly fractured basalt and flow-top breccias and, sometimes, interbedded coarse-grained sediments. The basalt has high lateral permeability in interflow zones and low permeability across flow interiors. Basalt can yield moderate to large amounts of water to wells. Increased withdrawal of ground water from the basalt has occurred in recent years; however, the basalt is still largely undeveloped in many places because it is more economical to construct wells in the overlying basin-fill sediments.

Generally, basin-fill sediments are the most important aquifers in the Willamette Lowland aquifer system. However, except for the Portland basin, no regional hydrologic information on the characteristics of these basin-fill sediments is available.

The Puget-Willamette Lowland regional aquifer-system analysis was started in 1989. As of mid-1992, three reports had been completed.

SOUTHERN CALIFORNIA BASINS

The regional aquifer-system analysis study of the southern California basins covers an area of 75,000 mi^2 (fig. 77). The study area includes 89 hydrologic units as defined by the California Department of Water Resources (1969) (fig. 77) and referred to in this report as drainage basins. These basins can be grouped according to common characteristics and relations into coastal and desert basins.

The objective of the Southern California Basins RASA study is to analyze the major problems and issues that affect the use of ground water in southern California including (1) ground-water overdraft, (2) ground-water contamination, (3) seawater intrusion, (4) quantity and distribution of recharge, (5) interaquifer flow, and (6) conjunctive use of ground water and surface water. Because of the large size of the study area and the large number of basins involved, it is impractical to study these problems and issues in each basin. Therefore, selected basins will be studied to determine the major geohydrologic processes and human activities that control or influence these problems or issues. At least one coastal and one desert basin will be intensively studied.

The studies involve assembling available geohydrologic data into a geographic information system (GIS), defining the regional geohydrology and geochemistry, and developing ground-water flow and solute-transport models to help understand the ground-water flow systems. Information obtained from these intensive studies should aid in the effective management of the ground-water resources of these and other basins in southern California.

The region has a varied climate, ranging from very wet to very dry; however, the entire region shares the characteristic of dry summers. Precipitation varies markedly from year to year, and the region is subject to relatively long periods of time in which precipitation and runoff are significantly above or below the long-term mean. Because of the variability of precipitation and runoff, ground water is an extensively used resource throughout the region.

The drainage basins include an assemblage of water-bearing and non-water-bearing materials. In coastal basins the non-water-bearing materials consist predominantly of folded and faulted sedimentary and metamorphic rocks. Water-bearing materials are in structural lowlands or valleys and consist of unconsolidated to poorly consolidated deposits of gravel, sand, silt, and clay. These deposits are from less than 100 ft to more than several thousand feet thick and form the major coastal ground-water basins. Ground-water movement between adjacent basins is limited because non-water-bearing sedimentary and metamorphic rocks surround and underlie the basins.

Desert basins include the Mojave Desert, the Colorado Desert, and valleys and ranges of the Great Basin. The ground-water basins are filled with unconsolidated to partly consolidated alluvial and basin-fill deposits. Non-water-bearing igneous and metamorphic rocks form the hills and mountains that surround the ground-water basins. Significant ground-water movement between basins occurs only where the non-water-bearing rocks do not extend above the water table.

The coastal basin selected for intensive study is the Santa Clara–Calleguas basin; the desert basin selected is the Mojave basin (fig. 77). These basins are affected by most of the major problems and issues that have been identified for study. Both basins have existing geohydrologic data bases—an essential factor in determining the major geohydrologic processes and human activities that control or influence these problems or issues. In addition, water-management agencies in both basins have ongoing cooperative programs with the U.S. Geological Survey. These cooperative programs will fund the collection and analysis of some of the detailed geohydrologic data needed to successfully answer the study objectives.

The Santa Clara–Calleguas basin extends from the Pacific Ocean on the west to the Mojave Desert on the east and covers about 2,000 mi^2. The topography consists of alternating synclinal valleys and anticlinal hills. The valleys and hills merge to the west with the Oxnard Plain. Almost 90 percent of the drainage-basin surface has rugged topography. This study will concentrate on the water-bearing deposits in that part of the Santa Clara–Calleguas basin in Ventura County (fig. 78).

Agricultural and petroleum production are the chief economic activities. As in all of the coastal basins, urbanization since the late 1940's has resulted in the transfer of agricultural lands to residential and commercial uses, especially on the Oxnard Plain. The climate of the drainage basin varies from a moist Mediterranean type near the Pacific Ocean to a near-desert type at the extreme eastern boundary.

Of the 2,000 mi^2 drainage basin, only about 310 mi^2 in Ventura County is underlain by water-bearing deposits. These deposits are the main source of water for agricultural and municipal supplies in the basin. They consist of unconsolidated alluvial deposits of Holocene age, unconsolidated alluvial and marine deposits of late Pleistocene age, and unconsolidated to partly consolidated marine and continental deposits of late Pliocene to mid-Pleistocene age. Orogenesis

Figure 77. Study area of the Southern California Basins regional aquifer-system analysis and location of drainage basins.

during the mid-Pleistocene produced intense folding, faulting, and uplift. An erosional unconformity separates the folded older deposits from the overlying undisturbed or gently folded younger deposits. Beneath the Oxnard Plain, this unconformity surface has been used to divide the water-bearing deposits into upper and lower aquifer systems.

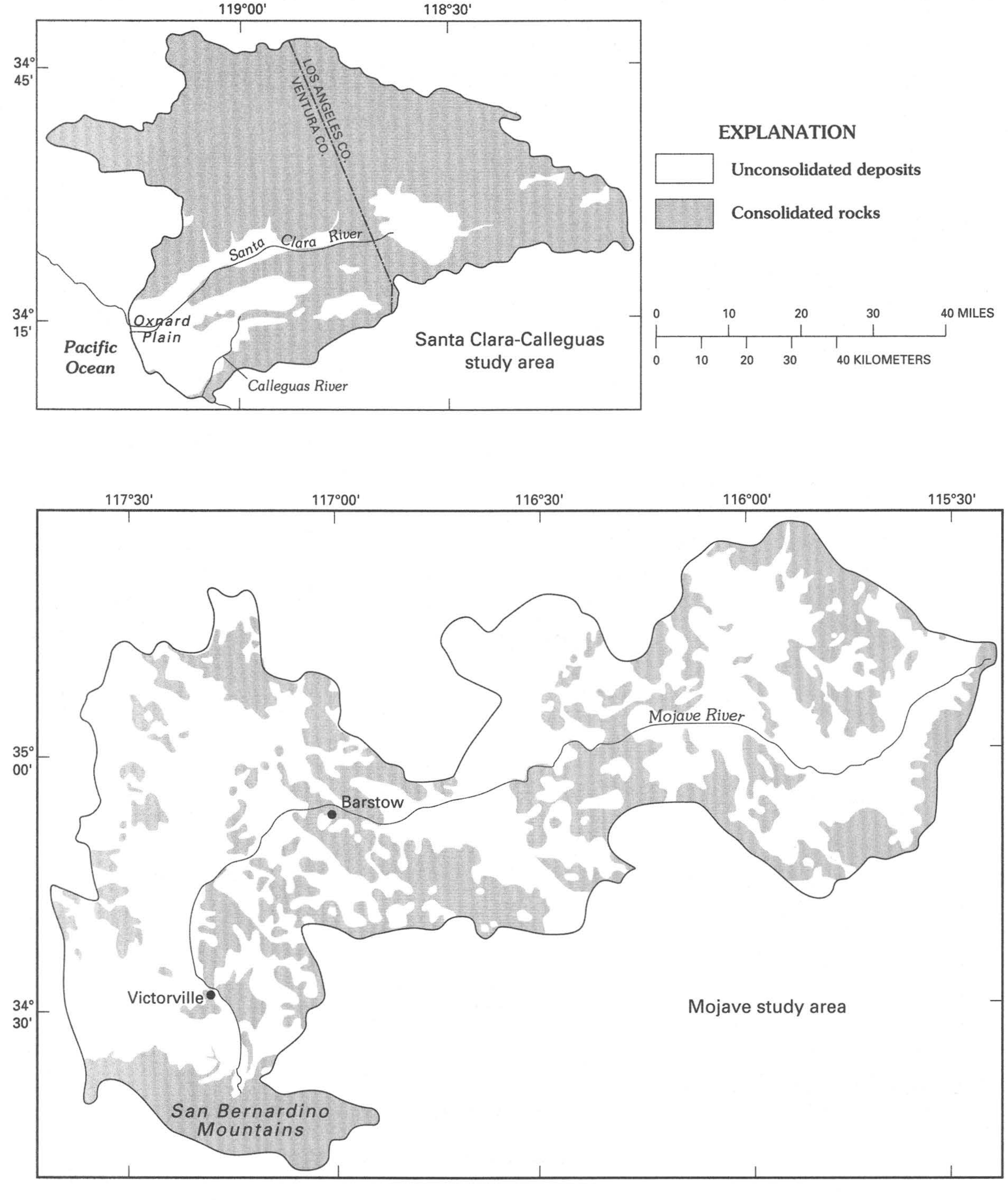


Figure 78. Santa Clara–Calleguas and Mojave basin study areas.

Under predevelopment conditions, ground-water movement in both the upper and lower aquifer system was from recharge areas along the Santa Clara River to discharge areas near the coast. Ground water discharged as underflow through offshore outcrops, to streams near the coast, and by evapotranspiration in lowlands along the coast. Ground-water pumping near the coast has caused water levels to decline below sea level in parts of the upper and lower aquifer systems. These water-level declines have resulted in seawater intrusion through outcrop areas in submarine canyons near the coast. Seawater intrusion was first suspected in the early 1930's and became a serious problem in the 1950's. The most serious seawater intrusion occurred in the upper aquifer system. On the basis of chloride data collected from monitor wells, the County of Ventura Public Works Agency (1990) estimated that in 1989 more than 23 mi^2 of the Oxnard aquifer (principal water-bearing unit of the upper aquifer system) was intruded by seawater (fig. 79).

To control seawater intrusion, local agencies have adopted a management plan to (1) decrease pumping from the upper aquifer system, (2) increase pumping from the

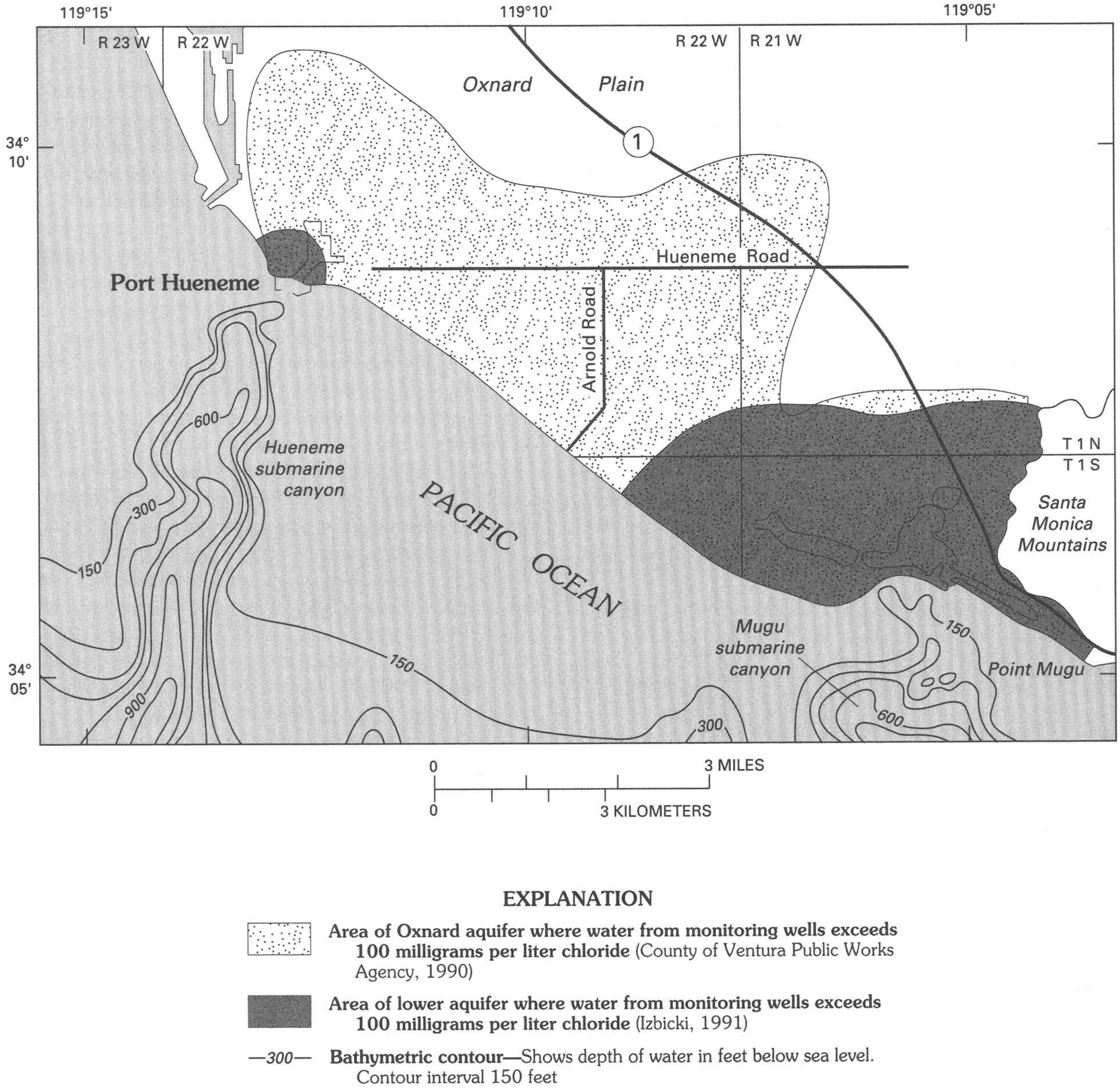


Figure 79. Chloride concentrations in water from wells on the Oxnard Plain, 1989 (modified from Izbicki, 1991).

lower aquifer system, (3) increase recharge of surface water, and (4) reduce ground-water pumping by 25 percent. Most of the Santa Clara–Calleguas study will involve analyzing the effectiveness of this management plan.

The Mojave basin is in the Mojave Desert region of southern California and covers about 5,100 mi^2 (fig. 77). The area of interest for this study includes about 3,340 mi^2 of the basin west of Afton Canyon (fig. 78).

The Mojave basin is an alluvial plain that slopes gently northward and eastward. The plain consists of valleys and closed basins, separated by hills and low mountains. Climate of the basin is characterized by low precipitation, low humidity, and high summer temperatures. The proximity of the basin to the highly urban Los Angeles area has stimulated recent population growth in excess of 5 percent per year. Water supplies in the basin are almost entirely from ground water.

The Mojave River is the principal stream traversing the study area and is the main source of recharge to underlying aquifers. Alluvial material beneath the flood plain of the Mojave River constitutes the most productive aquifer in the basin and yields much of the ground water pumped from the basin. The alluvial deposits generally are from ¼ to 1 ½ mi in width and are as much as 200 ft thick. The deposits consist of boulders, gravel, sand, and silt. Except where igneous and metamorphic rocks crop out, older alluvium and fan deposits underlie most of the basin. The older alluvium and fan deposits are as much as 1,000 ft thick, and contain most of the ground water in storage. Partly consolidated to consolidated sedimentary rocks of Tertiary age underlie the older alluvium and fan deposits in most of the basin. The Tertiary sedimentary rocks include some water-bearing units; however, the water they contain is mostly of poor quality and yields from wells generally are low.

About 80 percent of the total ground-water recharge in the basin is believed to be from leakage of floodflows in the Mojave River along its 100-mi reach between the San Bernardino Mountains and Afton Canyon. Some recharge from minor tributary streams occurs along the San Bernardino Mountain front. As residential development has increased, septic systems have become a source of recharge. Recharge from direct infiltration of precipitation is insignificant.

Ground-water pumping historically has been from wells along the Mojave River. Development in recent years has moved some of the pumping away from the river. An imbalance between the quantity and distribution of pumpage and recharge has created serious overdraft conditions in many areas. Local management agencies would like to supplement natural flow to the Mojave River to help alleviate the overdraft conditions. A thorough understanding of ground-water and surface-water relations is needed to evaluate the effectiveness of this management option. This study will concentrate on investigating the exchange of water between the river and the underlying and surrounding deposits.

The Santa Clara–Calleguas basin was the initial basin selected for intensive study. Work on this basin began in October 1989 and is scheduled for completion in September 1993. Work on the Mojave basin began in October 1991. This report discusses only the progress and results of the Santa Clara–Calleguas basin study because work has only recently begun in the Mojave basin.

Most of the geohydrologic data available are from wells that are open only to the upper aquifer or are open to several aquifers. Data from these wells are inadequate to characterize the three-dimensional hydraulic and water-quality properties of the study area. Since the start of the project, the U.S. Geological Survey has constructed multiple monitoring wells at 20 sites in the Santa Clara–Calleguas basin. These monitoring wells make it possible to collect aquifer- and depth-dependent data such as hydraulic head, water quality, and hydraulic properties.

Seawater intrusion is probably the main problem affecting the utilization of ground water in the Santa Clara–Calleguas basin. Agencies responsible for management of seawater intrusion presently use 100 mg/L chloride as the criterion to determine the position of the seawater front. On the basis of this criterion, it was estimated that in 1989 more than 23 mi^2 of the Oxnard aquifer of the upper aquifer system was intruded by seawater (County of Ventura Public Works Agency, 1990). Many of the wells used to determine the seawater front are abandoned irrigation supply wells or old steel-casing monitor wells.

Water-quality data from more than 40 wells installed as part of this study and results of direct-current resistivity soundings completed for this study show that the area affected by seawater intrusion is less than originally believed. Trace-element data used in conjunction with stable-isotope data revealed that the source of elevated chloride concentrations, in at least some wells, is leakage of seawater from the overlying perched aquifer through failed casings or sanitary seals (Izbicki, 1991). In other wells, irrigation return may be the cause of the elevated chloride concentrations.

Prior to this RASA study, seawater intrusion into the lower aquifer system was not considered a serious threat, and ground-water pumping was shifted from the upper to the lower aquifer system. Previous investigators believed that there was a 200-yr supply of freshwater stored in the lower aquifer system offshore. Data from one of the monitoring sites installed at Port Hueneme near the mouth of a submarine canyon (fig. 79) indicate that seawater already has intruded the lower aquifer system through outcrops in the submarine canyon. The lower aquifer system outcrops in the submarine canyon less than 2 mi offshore.

Ground-water pumping from the lower aquifer near Point Mugu (fig. 79) also has resulted in elevated chloride concentrations in samples from wells. Plots of the ratios of chloride to iodide as a function of chloride indicate that seawater is not the source of elevated chloride concentrations in this part of the basin (Izbicki, 1991). Data obtained from a monitoring site installed as part of this study indicate that high-chloride brines from the underlying Tertiary rocks are the source of the elevated chlorides.

Surface spreading of water from the Santa Clara River has been used to recharge the aquifers in the Santa Clara–Calleguas basin for about 65 yr near Saticoy, about 8 mi from the coast (fig. 78). Previous studies reported that the surface spreading recharged the upper and lower aquifer systems. In this part of the basin, lenticular clay beds that are present in the aquifer system beneath most of the Oxnard Plain were thought to be absent or less extensive, thus allowing recharge water to readily move through the aquifer system.

Tritium data collected for this study indicate that surface spreading does recharge the upper aquifer system, but water recharged since the early 1950's has not yet reached the coast. Water from most wells in the lower aquifer system does not contain tritium, and it must have been recharged prior to the early 1950's. Carbon-14 ages, estimated for water from wells in the lower aquifer system more than 1 mi downgradient of the recharge site, are from 900 to about 25,000 yr before present. These data indicate that the lower aquifer system is not effectively recharged by surface spreading.

The Southern California Basins RASA study was started in 1984; however, it was suspended immediately to redirect the resources to the Central Valley RASA. The study was restarted in 1990. As of mid-1992, nine reports had been completed, of which six are published.

GROUND WATER ATLAS OF THE UNITED STATES

As discussed in the section "Application of Regional Aquifer-System Analysis Program Information," a key product of the RASA Program is compilation of an atlas describing the ground-water resources of the United States. The atlas, which is designed in a graphical format that is supported by descriptive discussions, will be composed of 14 chapters. An introductory chapter will present an overview of the Nation's ground-water conditions, describe effects of development such as saltwater encroachment and land subsidence, and include two maps showing the distribution of major aquifers on a nationwide scale. This introductory chapter will be compiled following completion of 13 descriptive chapters, each of which describes ground-water conditions in a particular region (fig. 2). The 13 chapters (or segments) collectively cover the 50 States, Puerto Rico, and the U.S. Virgin Islands, and describe geologic and hydrologic conditions for the major aquifers in each region. The scale of the atlas does not allow portrayal of local features of the geology and hydrology, nor does it include discussion of minor aquifers in a region. However, extensive lists of references are included at the end of each chapter for readers who seek detailed, local information on specific aquifers. The descriptive atlas chapters will be published in the U.S. Geological Survey's Hydrologic Investigations Atlas HA–730 series, with a letter A–N assigned to each segment (fig. 2).

As of mid-1993, two segments had been published: segment 6 describing ground-water conditions in Alabama, Florida, Georgia, and South Carolina (Miller, 1990), and segment 9 describing ground-water conditions in Iowa, Michigan, Minnesota, and Wisconsin (Olcott, 1992). As of mid-1993, six segments (segments 1, 2, 4, 7, 10, and 12) were in preparation for printing. Five other segments (segments 3, 5, 8, 11, and 13) were either in review or being written. The entire atlas is scheduled to be completed in 1995; however, printing of all segments will require additional time. For additional information, readers may contact J.A. Miller, Project Chief, U.S. Geological Survey Regional Office, Norcross, Georgia.

PART III. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The RASA Program was a successful effort to evaluate the major ground-water systems of the United States. During the 15-yr program (1978–92), 25 regional aquifer systems, including the most heavily pumped aquifers in the Nation, were intensively studied. As of mid-1992, 18 of the regional aquifer studies are essentially completed; 7 of the studies and the National Ground Water Atlas project are ongoing.

All RASA projects involved the assembly of existing geologic, hydrologic, and geochemical information for the purpose of analyzing and understanding a major ground-water system. In addition, most projects had to fill data voids to provide a complete description of the ground-water system. These efforts in data-deficient areas included exploratory drilling and testing, conducting mass measurements of ground-water levels, collection and chemical analysis of water samples, and application of new techniques for determination of water use from heavily pumped aquifers. Computer simulation was used extensively to analyze regional ground-water systems under natural conditions, to analyze the hydrologic responses of regional aquifers to development, and to examine changes in water chemistry throughout regional aquifers. Results of these studies are contained in nearly 900 published reports. These publications range from compilations of basic geologic and hydrologic data to interpretive reports that explain the functioning of complex aquifer systems under natural conditions and under development conditions involving large ground-water withdrawals. A series of U.S. Geological Survey Professional Papers, consisting of several chapters, has been or is being prepared for each regional aquifer system. Individual chapters describe various aspects of the geology, hydrology, and geochemistry of the regional aquifer system or address the hydrology and water problems of subareas within the system in greater detail.

Results of the RASA Program were used as a major, but not exclusive, source of information for compilation of a Ground Water Atlas of the United States. The atlas includes 14 chapters, an introductory chapter and 13 chapters (segments), each of which describes the hydrogeology and hydrologic conditions for important aquifers in an area of several States. Collectively, the completed atlas will cover the 50 States, Puerto Rico, and the U.S. Virgin Islands.

The three major contributions of the RASA Program are (1) assembly of data from numerous local studies and long-term data-collection programs into systematic regional data bases; (2) comprehensive descriptions of the geologic, hydrologic, and geochemical characteristics of regional aquifer systems; and (3) an understanding of how regional ground-water-flow systems function under natural (predevelopment) and current (developed) conditions. To achieve these results, a variety of new and traditional investigative approaches were tried, and new concepts of regional ground-water systems were tested. A sampling of some of the new concepts that were developed and approaches that were successfully used during the RASA Program are as follows:

New concept of an aquifer system in the California Central Valley. Williamson and others (1989) proposed that the continental deposits of the Central Valley constitute a single aquifer system with varying vertical leakance and confinement rather than a water-table aquifer in the northern part and a two-aquifer system separated by a regional confining unit in the southern part, as described by previous workers. The new conceptual model was suggested by analysis of water levels and sediment textures and by simulated flow conditions.

New concept of regional ground-water flow in the Great Basin of Nevada and Utah and adjacent States. Ground-water flow in the Great Basin was conceptualized as relatively shallow flow through basin-fill deposits and adjacent mountain ranges, superimposed over deep flow in Paleozoic carbonate rocks, by Prudic and others (in press). Based on model-derived flows, the deep flow system was divided into 5 regions; the overlying shallow flow system was divided into 17 regions that approximately coincide with flow systems delineated from topography, ground-water levels, discharge areas, and water budgets. The delineation of these flow regions differs in part from those of previous investigators.

Hydrologic analysis of the Floridan aquifer system led to discovery of two large springs. The existence of a depression in the potentiometric surface of the Upper Floridan aquifer at Little Lake George in central Florida indicated a probable area of ground-water discharge. Calibration of a ground-water flow model during the RASA investigation indicated the probable existence of considerable ground-water discharge in the same area. During 1981, USGS divers entered "Croaker hole" in the bottom of the lake (which penetrated into limestone of the upper Floridan aquifer) and measured a spring discharge of 80 ft^3/s (Tibbals, 1990). In similar manner, another submerged spring was discovered in central Florida and discharge of 6 ft^3/s was measured.

Simulation of pumping from multiaquifer wells in the Cambrian-Ordovician aquifer system in the Northern Midwest. Simulation of pumping from the Cambrian-Ordovician aquifer system used a special computer code (based on work by Bennett and others, 1982) to calculate the approximate withdrawal rates from each aquifer tapped by a multiaquifer well. This method allows the direct use of reported pumpage from such wells, eliminating the need to estimate the withdrawal from individual aquifers (Young and others, 1989a). Another advantage of this procedure is that it allows comparison of simulated composite heads with water-level measurements in wells.

Estimating ground-water pumpage from the High Plains aquifer. The large areal extent of the High Plains aquifer (174,000 mi^2) precluded direct measurement of ground-water pumpage for irrigation. An indirect method of estimating pumpage was used in which irrigated acreage was first estimated by digital analysis of Landsat data (Thelin and Heimes, 1987). The amount of applied irrigation water was measured at several hundred field sites during the 1980 growing season. The volume of ground-water pumped from the High Plains aquifer in eight States was calculated by combining the field measurements with the mapped irrigated acreage information.

Source of recharge to the Cambrian-Ordovician aquifer system in the Northern Midwest based on geochemistry. The direction of increase of total dissolved solids in water in the Cambrian-Ordovician aquifer system in central Iowa suggests that water moves southwestward, approximately perpendicular to the flow direction indicated from the potentiometric surface. The ground water is isotopically depleted in the heavy isotopes oxygen-18 and deuterium. Isotope depletion and the dissolved-solids distribution suggests that this ground water originated as recharge during Pleistocene time, probably from subglacial meltwater under very high hydraulic gradients (Siegel, 1989).

Identification of the seaward extent of freshwater in the Floridan aquifer system based on hydrologic testing in an offshore oil well. Prior to RASA, it was known that freshwater extended at least 25 mi offshore in the Floridan aquifer system. Hydrologic testing was conducted in an offshore oil well (located 55 mi east of the northeast Florida coast) during the Floridan aquifer system RASA. Head and salinity data obtained from the Upper Floridan aquifer indicated that the tested interval is in the transition zone between freshwater and seawater in the Upper Floridan aquifer (Johnston and others, 1982).

RECOMMENDATIONS

The RASA Program focused on 25 regional aquifer systems that provide much of the ground water used for irrigation, industrial purposes, and large public water supplies in the United States. These regional ground-water systems consist mostly of deep, confined aquifers. In general, the analyses of these deep systems did not include detailed investigations of overlying shallow aquifers. For the most part, the RASA studies simply treated the shallow aquifers as local sources of recharge to the deep aquifers and sinks for upward discharge from them. However, many shallow aquifers are important sources of domestic and agricultural water supplies in rural areas and for public water supplies in small cities and towns.

A logical follow-up to the RASA Program is a more detailed analysis of the important shallow, unconfined aquifers conducted on a regional basis. Some of the shallow aquifers have been the subject of intensive hydrologic investigations under the U.S. Geological Survey Federal-State Cooperative Program. Generally, these investigations have been concerned with local water quality and quantity problems.

Several shallow, unconfined aquifers are sufficiently extensive to be major sources of ground water. For example, the Biscayne aquifer, a shallow, highly permeable limestone and sandstone aquifer is the principal source of water in southernmost Florida. The Biscayne aquifer provides the public water supply of Miami and other cities in south Florida because the underlying regional aquifer system (Floridan) contains saline water.

The major justification for beginning a program of shallow aquifer studies is that most contamination of ground water has occurred in or has affected shallow, unconfined aquifers and not the deep regional aquifer systems. Shallow, highly permeable aquifers such as those consisting of sand and gravel or limestone are highly vulnerable to contamination from land surface or near-surface sources (such as herbicides, insecticides, fertilizers, septic systems, leaking landfills, and leaking buried storage tanks). Most contaminants dissolved in water are moved by advective transport—that is, with the ground-water flow. Therefore, the ground-water flow system must be defined in order to provide information on the flow paths and times of travel of the contaminants.

It is obviously impractical to investigate all shallow, local aquifers in the United States. However, if it can be determined that a group of many shallow aquifers in a region share common geologic and hydrologic characteristics, then detailed investigations of a few representative aquifers may be sufficient. This approach was successfully used during the RASA Program in the investigation of alluvial basins in Arizona and New Mexico. The major objectives of each detailed shallow aquifer study would be (1) to define the hydrogeologic framework of the shallow aquifer with emphasis on defining aquifer heterogeneity, (2) to define the ground-water budgets, and (3) to describe the chemical and physical processes that produced the present ground-water quality. As in the RASA Program, these studies would utilize computer simulation extensively to analyze the shallow flow systems.

The shallow aquifer studies would benefit from the findings of the RASA Program, especially from water budgets developed for regional confined aquifers. These budget studies quantified rates of downward leakage from shallow aquifers into confined aquifers and upward leakage from the confined aquifers. Without the budget studies from the RASA Program, it would be difficult to determine these leakage rates.

A second recommended followup to the RASA Program is a long-term program of periodically preparing potentiometric surface maps for the major multistate aquifers based on synoptic water-level measurements. As noted earlier in this report, an important contribution of the RASA Program was preparation of some of the first potentiometric surface maps providing full coverage of multistate aquifers. Such maps were essential for describing and analyzing the flow systems in these regional aquifers. In particular, the maps were used to calibrate computer models of flow in such aquifers.

Since completion of RASA projects, continued preparation of potentiometric surface maps for multistate aquifers has varied depending upon local interest and availability of funding. For some aquifers, maps have been prepared in one State but not in an adjoining State. As part of the long-term basic data collection program of the U.S. Geological Survey, we recommend that synoptic potentiometric surface maps be prepared for the Nation's major aquifers at intervals of about 5 yr.

The need for an ongoing program of potentiometric surface mapping of the Nation's aquifers is indicated by a congressional directive to the U.S. Geological Survey to monitor water levels in the High Plains aquifer. Section 306, Title III of Public Law 98-242 (as amended) authorizes and directs the U.S. Geological Survey in cooperation with States in the High Plains region to monitor water levels in the High Plains aquifer and report annually to Congress. In general, the magnitude of water-level declines observed in the High Plains aquifer are not occurring in other regional aquifers. Therefore, a 5-yr interval of synoptic water-level measurements should provide adequate definition of changes for most major aquifers.

REFERENCES CITED

Abbott, P.L., 1975, On the hydrology of the Edwards Limestone, south-central Texas: Journal of Hydrology, v. 24, p. 251–269.

Ackerman, D.I., 1990, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States: U.S. Geological Survey Open-File Report 90-358, 11 p.

Anderson, T.W., Freethey, G.W., and Tucci, Patrick, 1992, Geohydrology and water resources of alluvial basins in south-central Arizona and parts of adjacent States: U.S. Geological Survey Professional Paper 1406–B, 67 p.

Anna, L.O., 1986, Geologic framework of the ground-water system in Jurassic and Cretaceous rocks in the northern Great Basins in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–B, 36 p.

Back, William, 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498–A, 42 p.

Back, William, Rosenshein, J.S., and Seaber, P.R., eds., 1988, Hydrogeology: Geological Society of America, The Geology of North America, Boulder, Colorado, v. O–2, 524 p.

Barker, R.A., and Pernik, Maribeth, in press, Regional hydrology and simulation of deep ground-water flow in the Southeastern Coastal Plain aquifer system in Mississippi, Alabama, Georgia, and South Carolina: U.S. Geological Survey Professional Paper 1410–C.

Beck, B.F., and Sinclair, W.C., 1986, Sinkholes in Florida—An introduction: Florida Sinkhole Research Institute Report 85-86-4, 16 p.

Beckman, J.D., and Williamson, A.K., 1990, Salt-dome locations in the Gulf Coastal Plain, south-central United States: U.S. Geological Survey Water Resources Investigations Report 90-4060, 44 p.

Bennett, G.D., Kontis, A.L., and Larson, S.P., 1982, Representation of multiaquifer well effects in three-dimensional ground-water flow simulation: Ground Water, v. 20, no. 3, p. 334–341.

Bertoldi, G.L., Johnston, R.H., and Evenson, K.D., 1991, Ground water in the Central Valley, California—A summary report: U.S. Geological Survey Professional Paper 1401–A, 44 p.

Bownocker, J.A., Completed 1920 (1981), Geologic map of Ohio: Ohio Geological Survey, scale 1:500,000.

Bredehoeft, J.D., and Hanshaw, B.B., 1968, On the maintenance of anomalous fluid pressures—I. Thick sedimentary sequences: Geological Society of America Bulletin, v. 79, p. 1097–1105.

Bretz, J.H., 1923, The channeled scablands of the Columbia Plateau: Journal of Geology, v. 31, p. 617–649.

Brown, D.L., Blankennagel, R.K., MacCary, L.M., and Peterson, J.A., 1984, Correlation of paleostructure and sediment deposition in the Madison Limestone and associated rocks in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–B, 24 p.

Busby, J.F., Kimball, B.A., Downey, J.S., and Peter, K.D., in press, Geochemistry of ground water in aquifers and confining units of the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–F.

Busby, J.F., Plummer, L.N., Lee, R.W., and Hanshaw, B.B., 1991, Geochemical evolution of water in the Madison aquifer in parts of Montana, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–F, 89 p.

Bush, P.W., 1988, Simulation of saltwater movement in the Floridan aquifer system, Hilton Head Island, South Carolina: U.S. Geological Survey Water-Supply Paper 2331, 19 p.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–C, 80 p.

California Department of Water Resources, 1969, Names and area code numbers of hydrologic areas in the Southern District: California Department of Water Resources Office Report, 57 p.

Carman, R.L., in press, Measurement of evapotranspiration in phreatophyte areas, Smith Creek Valley and Carson Desert, west-central Nevada, 1983: U.S. Geological Survey Water-Resources Investigations Report 89-4118.

Carpenter, M.C., 1991, Earth-fissure movements associated with fluctuations in ground-water levels near the Picacho Mountains, south-central Arizona, 1980–84: U.S. Geological Survey Open-File Report 90-561, 64 p.

Chamberlin, T.C., 1885, Requisite and qualifying conditions of artesian wells: U.S. Geological Survey 5th Annual Report to the Secretary of the Interior, 1883–84, p. 131–173.

Chapelle, F.H., and Knobel, L.L., 1985, Stable carbon isotopes of bicarbonate in the Aquia aquifer, Maryland—Evidence of an isotopically heavy source of carbon dioxide: Ground Water, v. 23, no. 5, p. 592–599.

Chapelle, F.H., and McMahon, P.B., 1991, Geochemistry of dissolved inorganic carbon in a coastal plain aquifer—1. Sulfate from confining beds as an oxidant in microbial CO_2 production: Journal of Hydrology, 127, p. 85–108.

Clark, D.W., and Kendy, Eloise, 1992a, Plan of study for the regional aquifer-system analysis of the Northern Rocky Mountains Intermontane Basins, Montana and Idaho: U.S. Geological Survey Water-Resources Investigations Report 92-4116, 16 p.

———1992b, Regional analysis of the Northern Rocky Mountains Intermontane Basins, Montana and Idaho, *in* Prince, K.R., and Johnson, A.I., eds., Aquifers of the Far West: American Water Resources Association Monograph series no. 16, p. 55–64.

Cooley, R.L., Konikow, L.F., and Naff, R.L., 1986, Nonlinear-regression ground-water flow modeling of a deep regional aquifer system: Water Resources Research, v. 22, no. 13, p. 1759–1778.

County of Ventura Public Works Agency, 1990, Oxnard Plain of Ventura County, 1989 seawater intrusion study, 5 p.

Craigg, S.D., in press, Geologic framework of the San Juan structural basin of New Mexico, Colorado, Arizona, and Utah, with emphasis on Triassic through Tertiary rocks: U.S. Geological Survey Professional Paper 1420–B.

Darton, N.H., 1896, Preliminary report of artesian waters of a portion of the Dakotas: U.S. Geological Survey 17th Annual Report to the Secretary of the Interior, 1895–96, pt. 2, p. 609–694.

———1905, Geology and underground water resources of the central Great Plains: U.S. Geological Survey Professional Paper 32, 433 p.

Davis, M.E., Sparkes, A.K., and Peacock, B.S., 1983, Results of a test well in the Nanafalia Formation near Melvin, Choctaw County, Alabama: U.S. Geological Survey Water-Resources Investigations Report 82-4108, 17 p.

Dettinger, M.D., 1989, Reconnaissance estimates of natural recharge to desert basins in Nevada, U.S.A., by using chloride-balance calculations: Journal of Hydrology, v. 106, no. 1–2, p. 55–78.

Downey, J.S., 1982, Machine-readable data files from the Madison Limestone and Northern Great Plains regional aquifer-system analysis project, Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 82-4107, 26 p.

———1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–G, 47 p.

———1986, Geohydrology of bedrock aquifers in the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–E, 87 p.

———1988, Regional bedrock aquifers of the Northern Great Plains, north-central United States, *in* McLean, J.S., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the western mountain area: American Water Resources Association Monograph series no. 14, p. 5–13.

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402–A, 64 p.

Drost, B.W., and Whiteman, K.J., 1986, Surficial geology, structure and thickness of selected geohydrologic units in the Columbia Plateau, Washington: U.S. Geological Survey Water-Resources Investigations Report 86-4236, 10 sheets.

Dugan, J.T., Schild, D.E., and Kastner, W.M., 1990, Water-level changes in the High Plains aquifer underlying parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas—Predevelopment through nonirrigation season 1988–89: U.S. Geological Survey Water-Resources Investigations Report 90-4153, 29 p.

Dysart, J.E., 1988, Use of oxygen-18 and deuterium mass-balance analysis to evaluate induced recharge to stratified-drift aquifers *in* Randall, A.D., and Johnson, A.I., eds., Regional aquifer systems of the United States, The Northeast Glacial Aquifers: American Water Resources Association Monograph series no. 11, p. 133–154.

Eaton, G.P., 1979, Regional geophysics, Cenozoic tectonics, and geologic resources of the Basin and Range provinces and adjoining regions, *in* Newman, G.W., and Good, H.D., eds., 1979 Basin and Range Symposium: Rocky Mountain Association of Geologists and Utah Geological Association, p. 11–39.

Ewart, C.J., 1986, Oahu Island regional aquifer-system study, *in* Sun, R.J., ed., Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 195–204.

Fleming, T.H., 1989, Description and results of the pumping test at the Juiletta Landfill [Originally compiled by the Indiana Geological Survey, unpublished data on file in Indianapolis office of the Indiana Department of Natural Resources, Division of Water, 11 p.]

Garabedian, S.P., 1986, Application of a parameter-estimation technique to modeling the regional aquifer underlying the eastern Snake River Plain, Idaho: U.S. Geological Survey Water-Supply Paper 2278, 60 p.

———1993, Hydrology and digital simulation of the regional aquifer system, eastern Snake River Plain, Idaho: U.S. Geological Survey Professional Paper 1408–F, 102 p., 10 plates.

Geldon, A.L., 1988, Hydrostratigraphic characterization of Paleozoic formations in the Upper Colorado River Basin, Arizona, Colorado, New Mexico, Utah and Wyoming, *in* McLean, J.S., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the western mountain area: American Water Resources Association Monograph series no. 14, p. 135–159.

———in press, Hydrologic properties and ground-water flow systems of the Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin: U.S. Geological Survey Professional Paper 1411–E.

Gilliom, R.D., Belitz, Kenneth, Deverel, S.J., Dubrovsky, N.M., and Fujii, Roger, 1989, Preliminary assessment of sources, distribution, and mobility of selenium in the San Joaquin Valley, California: U.S. Geological Survey Water Resources Investigations Report 88-4186, 129 p.

Gomez-Gomez, Fernando, Quinones-Aponte, Vicente, and Johnson, A.I., eds., 1991, Regional aquifer systems of the United States, Aquifers of the Caribbean Islands: American Water Resources Association Monograph series no. 15, 113 p.

Goodell, S.A., 1988, Water use on the Snake River Plain, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408–E, 51 p.

Gray, H.H., Ault, C.H., and Keller, S.J., 1987, Bedrock geology map of Indiana: Indiana Geological Survey Miscellaneous Map 48, scale 1:500,000.

Grose, L.T., 1972, Tectonics, *in* Geologic atlas of the Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, p. 35–44.

Grubb, H.F., 1984, Planning report for the Gulf Coast Regional Aquifer-System Analysis in the Gulf of Mexico Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 84-4219, 30 p.

———1987, Overview of the Gulf Coast regional aquifer-system analysis, south-central United States, *in* Vecchioli, John, and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Monograph series no. 9, p. 101–118.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p.

Haeni, F.P., in press, Application of surface-geophysical methods to investigation of sand and gravel aquifers in the glaciated Northeastern United States: U.S. Geological Survey Professional Paper 1415–C.

Hanneman, D.L., and Wideman, C.J., 1991, Sequence stratigraphy of Cenozoic continental rocks, southwestern Montana: Geological Society of America Bulletin, v. 103, no. 10, p. 1335–1345.

Harrill, J.R., 1986, Great Basin regional aquifer-system study, *in* Sun, R.J., ed., Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 146–151.

Heath, R.C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78 p.

Helgesen, J.O., and Leonard, R.B., 1989, Geohydrology of the Great Plains aquifer system, *in* Swain, L.A., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph series no. 13, p. 179–190.

Helgesen, J.O., Leonard, R.B., and Wolf, R.J., 1993, Hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geological Survey Professional Paper 1414–E, 80 p., 10 plates.

Henderson, Thomas, 1985, Geochemistry of ground water in two sandstone aquifer systems in the Northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey Professional Paper 1402–C, 84 p.

High Plains Associates, 1982, Six-state High Plains–Ogallala aquifer regional resources study: Austin, Texas, 438 p.

High Plains Study Council, 1982, A summary of results of the Ogallala aquifer regional study, with recommendations to the Secretary of Commerce and Congress, 61 p.

Hosman, R.L., 1991, Regional stratigraphy and subsurface geology of Cenozoic deposits, Gulf Coastal Plain, south-central United States: U.S. Geological Survey Open-File Report 91-66, 43 p.

Hotchkiss, W.R., and Johnson, A.I., eds., 1992, Regional aquifer systems of the United States, Aquifers of the southern and eastern States: American Water Resources Association Monograph series no. 17, 115 p.

Hull, L.C., 1984, Geochemistry of ground water in the Sacramento Valley, California: U.S. Geological Survey Professional Paper 1401–B, 36 p.

Ireland, R.L., Poland, J.F., and Riley, F.S., 1984, Land subsidence in the San Joaquin Valley, California, as of 1980: U.S. Geological Survey Professional Paper 437–I, 183 p.

Izbicki, J.A., 1991, Sources of chloride in a coastal aquifer in California: American Society of Civil Engineers 1991 Symposium on Ground Water in the Pacific Rim, Honolulu, Hawaii, July 22–26, 1991, Proceedings, p. 71–77.

Johnston, R.H., 1989, The hydrologic responses to development in regional sedimentary aquifers: Ground Water, v. 27, no. 3, p. 316–322.

Johnston, R.H., and Bush, P.W., 1988, Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–A, 24 p.

Johnston, R.H., Bush, P.W., Krause, R.E., Miller, J.A., and Sprinkle, C.L., 1982, Summary of hydrologic testing in Tertiary limestone aquifer, Tenneco offshore exploratory well-Atlantic OCS, Lease-Block 427 (Jacksonville NH 17-5): U.S. Geological Survey Water-Supply Paper 2180, 15 p.

Jorgensen, D.G., 1988, Using geophysical logs to estimate porosity, water resistivity, and intrinsic permeability: U.S. Geological Survey Water Supply Paper 2321, 24 p.

Kernodle, J.M., and Craigg, S.D., 1992, Using a geographic information system to assist in a regional aquifer-system analysis: U.S. Geological Survey Yearbook, fiscal year 1991, p. 12–14.

King, P.B., and Beikman, H.M., 1974, Geologic map of the United States, exclusive of Alaska and Hawaii: U.S. Geological Survey, 3 sheets, scale 1:2,500,000.

Kjelstrom, L.C., 1986, Flow characteristics of the Snake River and water budget for the Snake River Plain, Idaho and eastern Oregon: U.S. Geological Survey Hydrologic Investigations Atlas HA-680, 2 sheets, scale 1:1,000,000.

———in press, Streamflow gains and losses in the Snake River and ground-water budgets for the Snake River Plain, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408–C.

Kohout, F.A., 1965, A hypothesis concerning cyclic flow of salt-water related to geothermal heating in the Floridan aquifer: New York Academy of Sciences Transactions, ser. 2, v. 28, no. 2, p. 249–271.

Konikow, L.F., and Bredehoeft, J.D., 1992, Ground-water models cannot be validated: Advances in Water Resources, v. 15, p. 75–83.

Kontis, A.L., and Mandle, R.J., 1980, Data-base systems for Northern Midwest regional aquifer-system analysis: U.S. Geological Survey Water-Resources Investigations Report 80-104, 23 p.

———1988, Modifications of the three-dimensional ground-water flow model to account for variable water density and effects of multiaquifer wells: U.S. Geological Survey Water-Resources Investigations Report 87-4265, 78 p.

Krause, R.E., and Randolph, R.B., 1989, Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina: U.S. Geological Survey Professional Paper 1403–D, 65 p.

Kuiper, L.K., 1983, A numerical procedure for the solution of the steady-state variable-density groundwater flow equation: Water Resources Research, v. 19, no. 1, p. 234–240.

———1985, Documentation of a numerical code for the simulation of variable density ground-water flow in three dimensions: U.S. Geological Survey Water-Resources Investigations Report 84-4032, 90 p.

Kuniansky, E.L., 1990, A two-dimensional finite-element flow model for confined aquifers in steady state: U.S. Geological Survey Open-File Report 90-187, 77 p.

Lane, R.C., 1988, Selected ground-water information for the Columbia Plateau regional aquifer system, Washington and Oregon, 1982–1985: v. 2. Water levels: U.S. Geological Survey Open-File Report 88-183, 136 p.

Laney, R.L., and Davidson, C.B., 1986, Aquifer nomenclature guidelines: U.S. Geological Survey Open-File Report 86-534, 46 p.

Lapham, W.W., 1989, Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity: U.S. Geological Survey Water-Supply Paper 2337, 35 p.

Larson, S.P., 1978, Direct solution algorithm for the two-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 79-202, 25 p.

Leahy, P.P., 1982, A three-dimensional ground-water flow model modified to reduce computer memory requirements and better simulate confining-bed and aquifer pinchouts: U.S. Geological Survey Water-Resources Investigations Report 82-4023, 60 p.

Leahy, P.P., and Martin, Mary, 1993, Geohydrology and simulation of ground-water flow in the Northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Professional Paper 1404–K, 80 p., 22 plates.

Leahy, P.P., Martin, Mary, and Meisler, Harold, 1987, Hydrologic definition of the Northern Atlantic Coastal Plain aquifer system based on regional simulation, *in* Vecchioli, John, and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph series no. 9, p. 7–24.

Leake, S.A., 1990, Interbed storage changes and compaction in models of regional ground-water flow: Water Resources Research, v. 26, no. 9, p. 1939–1950.

———1991, Simulation of vertical computation in models of regional ground-water flow, *in* Johnson, A.I., ed., Land Subsidence: International Symposium on Land Subsidence, 14th May 1991, Houston, Texas, International Association of Hydrological Sciences Publication 200, p. 565–574.

Lindholm, G.F., 1986, Snake River Plain regional aquifer-system study, *in* Sun, R.J., ed., Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 88–106.

———in press, Summary of the Snake River Plain aquifer-system analysis: U.S. Geological Survey Professional Paper 1408–A.

Lobmeyer, D.H., 1985, Freshwater heads and ground-water temperatures in aquifers of the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–D, 11 p.

Luckey, R.R., and Ferrigno, D.F., 1982, A data-management system for areal interpretive data for the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 82-4072, 112 p.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1986, Digital simulation of ground-water flow in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–D, 57 p.

———1988, Effects of future ground-water pumpage on the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–E, 44 p.

Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652, 2 sheets, scale 1:2,500,000.

MacCary, L.M., 1984, Apparent water resistivity, porosity, and water temperature of the Madison Limestone and underlying rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–D, 14 p.

MacCary, L.M., Cushing, E.M., and Brown, D.L., 1983, Potentially favorable areas for large-yield wells in the Red River Formation and Madison Limestone in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–E, 13 p.

Maclay, R.W., and Small, T.A., 1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: Texas Water Development Board Report 296, 90 p.

Mandle, R.J., and Kontis, A.L., 1992, Simulation of regional ground-water flow in the Cambrian-Ordovician aquifer system in the Northern Midwest, United States: U.S. Geological Survey Professional Paper 1405–C, 97 p.

Mandle, R.J., and Westjohn, D.B., 1989, Geohydrologic framework and ground-water flow in the Michigan Basin, *in* Swain, L.A., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph series no. 13, p. 83–109.

Martin, Angel, Jr., and Whiteman, C.D., 1991, Hydrology of the coastal lowlands aquifer system in parts of Alabama, Florida, Louisiana, and Mississippi: U.S. Geological Survey Open-File Report 91-72, 110 p.

Maslia, M.L., and Hayes, L.R., 1988, Hydrogeology and simulated effects of ground-water development of the Floridan aquifer system, southwest Georgia, northwest Florida, and southernmost Alabama: U.S. Geological Survey Professional Paper 1403–H, 71 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 578 p.

McFarland, W.D., 1983, A description of aquifer units in western Oregon: U.S. Geological Survey Open-File Report 82-165, 35 p.

McLean, J.S., and Johnson, A.I., eds., 1988, Regional aquifer systems of the United States, Aquifers of the western mountain area: American Water Resources Association Monograph series, no. 14, 229 p.

Meisler, Harold, 1980, Preliminary delineation of salty ground water in the Northern Atlantic Coastal Plain: U.S. Geological Survey Open-File Report 81-71, 37 p.

———1989, The occurrence and geochemistry of salty ground water in the Northern Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 1404–D, 51 p.

Meisler, Harold, Leahy, P.P., and Knobel, L.L., 1985, Effect of eustatic sea-level changes on saltwater-freshwater relations in the Northern Atlantic Coastal Plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.

Mesko, T.W., Williams, T.A., Ackerman, D.J., and Williamson, A.K., 1990, Ground-water pumpage from the Gulf Coast aquifer system, 1960–85, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 89-4180, 177 p.

Meyer, F.W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan aquifer system in southern Florida: U.S. Geological Survey Professional Paper 1403–G, 59 p.

Meyer, W.R., and Carr, J.E., 1979, A digital model for simulation of ground-water hydrology in the Houston area, Texas: Texas Department of Water Resources Report LP-103, 131 p.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–B, 91 p.

———1988, Geohydrologic data from the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Open-File Report 88-86, 678 p.

———1990, Ground water atlas of the United States, Segment 6—Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey Hydrologic Investigations Atlas HA–730–G, 28 p.

———1992, Summary of the hydrology of the Southeastern Coastal Plain aquifer system in Mississippi, Alabama, Georgia, and South Carolina: U.S. Geological Survey Professional Paper 1410–A, 38 p.

Miller, J.A., Barker, R.A., and Renken, R.A., 1987, Hydrogeology of the Southeastern Coastal Plain aquifer system—An overview, *in* Vecchioli, John, and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph series no. 9, p. 53–57.

Miller, J.A., and Renken, R.A., 1988, Nomenclature of regional hydrogeologic units of the Southeastern Coastal Plain aquifer system: U.S. Geological Survey Water-Resources Investigations Report 87-4202, 21 p.

Morrissey, D.J., Randall, A.D., and Williams, J.H., 1988, Upland runoff as a major source of recharge to stratified drift in the glaciated Northeast, *in* Randall, A.D., and Johnson, A.I., eds., Regional aquifer systems of the United States, The Northeast Glacial Aquifers: American Water Resources Association Monograph series no. 11, p. 17–36.

Mount, J.R., Rayner, F.A., Shamburger, V.M., Jr., Peckam, R.C., and Osborne, F.L., Jr., 1967, Reconnaissance investigation of the ground-water resources of the Colorado River Basin, Texas: Texas Water Development Board Report 51, 107 p.

Newton, G.D., 1991, Geohydrology of the regional aquifer system, western Snake River Plain, southwestern Idaho: U.S. Geological Survey Professional Paper 1408–G, 52 p.

Norris, S.P., 1959, Vertical leakage through till as a source of recharge to a buried-valley aquifer at Dayton, Ohio: Ohio Department of Natural Resources, Division of Water, Technical Report no. 2, 16 p.

Olcott, P.G., 1992, Ground Water Atlas of the United States, Segment 9—Iowa, Michigan, Minnesota, and Wisconsin: U.S. Geological Survey Hydrologic Investigations Atlas HA–730–J, 31 p.

Page, R.W., 1986, Geology of the fresh ground-water basin of the Central Valley, California, with texture maps and sections: U.S. Geological Survey Professional Paper 1401–C, 54 p.

Pardee, J.T., 1910, The glacial Lake Missoula: Journal of Geology, v. 18, no. 4, p. 376–386.

Peterson, J.A., 1984, Stratigraphy and sedimentary facies of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–A, 34 p.

Plummer, L.N., 1977, Defining reactions and mass transfer in part of the Floridan aquifer: Water Resources Research, v. 13, no. 5, p. 801–812.

Plummer, L.N., Busby, J.F., Lee, R.W., and Hanshaw, B.B., 1990, Geochemical modeling of the Madison aquifer in parts of Montana, Wyoming, and South Dakota: Water Resources Research, v. 26, no. 9, p. 1981–2014.

Prince, K.R., and Johnson, A.I., eds., 1992, Regional aquifer systems of the United States, Aquifers of the Far West: American Water Resources Association Monograph series no. 16, 127 p.

Prudic, D.E., Harrill, J.E., and Burbey, T.J., in press, Conceptual evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent States: U.S. Geological Survey Professional Paper 1409–D.

Quinones-Aponte, Vicente, 1991, Water-resources development and its influence on the water budget for the aquifer system in the Salinas to Patillas area, Puerto Rico, *in* Gomez-Gomez, Fernando, and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Caribbean Islands: American Water Resources Monograph series no. 15, p. 37–55.

Randall, A.D., and Johnson, A.I., eds., 1988, Regional aquifer systems of the United States, The Northeast Glacial Aquifers: American Water Resources Association Monograph series no. 11, 156 p.

Reid, M.S., Renken, R.A., Wait, R.L., Aucott, W.R., and Lee, R.W., 1986, Hydrologic and geologic analysis of two wells in Marion County, South Carolina: U.S. Geological Survey Water-Resources Investigations Report 86-4102, 20 p.

Renken, R.A., 1984, Hydrogeology of the Southeastern Coastal Plain aquifer system of the United States: U.S. Geological Survey Water-Resources Investigations Report 84-4243, 269 p.

———in press, Geology and hydrogeology of the Southeastern Coastal Plain aquifer system of Mississippi, Alabama, Georgia, and South Carolina and adjacent areas of North Carolina and Florida: U.S. Geological Survey Professional Paper 1410–B.

Renken, R.A., Gomez-Gomez, Fernando, Quinones-Aponte, Vicente, and Dacosta, Rafael, 1991, Structure and depositional patterns and their influence on the hydraulic conductivity of fan-deltas in southern Puerto Rico, *in* Gomez-Gomez, Fernando, and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Caribbean Islands: American Water Resources Monograph series no. 15, p. 25–36.

Robertson, F.N., 1991, Geochemistry of ground water in alluvial basins of Arizona and adjacent parts of Nevada, New Mexico, and California: U.S. Geological Survey Professional Paper 1406–C, 90 p.

Rodriquez-Martinez, Jesus, 1991, The hydrogeologic framework of the Northern Coastal Province aquifer system of Puerto Rico, *in* Gomez-Gomez, Fernando, and Johnson, A.I., Regional aquifer systems of the United States, Aquifers of Caribbean Islands: American Water Resources Association Monograph series no. 15, p. 5–16.

Ryder, P.D., 1985, Hydrology of the Floridan aquifer system in west-central Florida: U.S. Geological Survey Professional Paper 1403–F, 63 p.

Ryder, P.D., and Ardis, A.F., 1991, Hydrology of the Texas Gulf Coast aquifer systems: U.S. Geological Survey Open-File Report 91-64, 127 p.

Sasman, R.T., Ludwigs, R.S., Benson, C.R., and Kirk, J.R., 1986, Water-level trends and pumpage in the Cambrian and Ordovician aquifers in the Chicago region, 1980–1985: Illinois State Water Survey Circular 166, 47 p.

Siegel, D.I., 1989, Geochemistry of the Cambrian-Ordovician aquifer system in the Northern Midwest: U.S. Geological Survey Professional Paper 1405–D, 76 p.

———1991, Evidence for dilution of deep, confined ground water by vertical recharge of isotopically heavy Pleistocene water: Geology, v. 19, p. 433–436.

Signor, D.C., and Imes, J.L., 1989, Geohydrology of regional aquifer systems in Cretaceous and older rocks underlying the Central United States, *in* Swain, L.A., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph series no. 13, p. 149–163.

Sinclair, W.C., 1982, Sinkhole development resulting from ground-water withdrawal in the Tampa area, Florida: U.S. Geological Survey Water-Resources Investigations Report 81-50, 19 p.

Solley, W.B., Chase, E.B., and Mann, W.B., IV, 1983, Estimated use of water in the United States in 1980: U.S. Geological Survey Circular 1001, 56 p.

Solley, W.B., Merk, C.F., and Pierce, R.R., 1988, Estimated use of water in the United States in 1985: U.S. Geological Survey Circular 1004, 82 p.

Souza, W.R., and Voss, C.I., 1986, Modeling a regional aquifer containing a narrow transition between freshwater and saltwater using a solute transport simulation, Part II—Analysis of a coastal aquifer system: Delft University of Technology Salt Water Intrusion Meeting, 9th, Delft, The Netherlands, May 12–16, 1986, Proceedings, p. 457–473.

Sprinkle, C.L., 1989, Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–I, 105 p.

Strobel, M.L., 1990, Characteristics affecting the vertical flow of ground water through selected glacial deposits in Ohio: Columbus, Ohio State University, M.S. thesis, 185 p. [unpublished].

Sun, R.J., ed., 1986, Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, 264 p.

Sun R.J., and Weeks, J.B., 1991, Bibliography of Regional Aquifer-System Analysis Program of the U.S. Geological Survey, 1978–1991: U.S. Geological Survey Water-Resources Investigations Report 91-4122, 92 p.

Suter, Max, Bergstrom, R.E., Smith, H.F., Emrich, G.H., Walton, W.C., and Larson, T.E., 1959, Preliminary report on groundwater resources of the Chicago region, Illinois: Illinois State Water Survey and State Geological Survey Cooperative Groundwater Report 1, 89 p.

Swain, L.A., Hollyday, E.F., Daniel, C.C., III, and Zapecza, O.S., 1991, Plan of study for the regional aquifer-system analysis of the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces of the Eastern and Southeastern United States, with a description of the study-area geology and hydrology: U.S. Geological Survey Water-Resources Investigations Report 91-4066, 44 p.

Swain, L.A., and Johnson, A.I., eds., 1989, Regional aquifers of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph series no. 13, 238 p.

Swanson, D.A., and Wright, T.L., 1978, Bedrock geology of northern Columbia Plateau and adjacent areas in the Channeled Scablands, chap. 3, *in* Baker, V.R., and Nummedal, D., eds., Planetary Geology program: Washington, D.C., National Aeronautics and Space Administration, p. 37–57.

Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.P., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457–G, 59 p.

Takasaki, K.J., and Mink, J.F., 1985, Evaluation of major dike-impounded ground-water reservoirs, island of Oahu: U.S. Geological Survey Water-Supply Paper 2217, 77 p.

Thayer, P.A., 1984, Relationship of porosity and permeability to petrology of the Madison Limestone in rock cores from three test wells in Montana and Wyoming: U.S. Geological Survey Professional Paper 1273–C, 29 p.

Thelin, G.P., and Heimes, F.J., 1987, Mapping irrigated cropland from Landsat data for determination of water use from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–C, 38 p.

Tibbals, C.H., 1990, Hydrology of the Floridan aquifer system in east-central Florida: U.S. Geological Survey Professional Paper 1403–E, 98 p.

Torak, L.J., 1982, Modification and corrections to the finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Water-Resources Investigations Report 82-4025, 67 p.

Trapp, Henry, Jr., 1993, Hydrogeological framework of the Northern Atlantic Coastal Plain, in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York: U.S. Geological Survey Professional Paper 1404–G.

Trapp, Henry, Jr., Knobel, L.L., Meisler, Harold, and Leahy P.P., 1984, Test well DO-CE88 at Cambridge, Dorchester County, Maryland: U.S. Geological Survey Water-Supply Paper 2229, 48 p.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 104 p.

Trescott, P.C., and Larson, S.P., 1976, Supplement to Open-File Report 75-438, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76-591, 21 p.

U.S. Geological Survey, 1970, The National atlas of the United States: Washington, D.C., U.S. Geological Survey, 417 p.

U.S. House of Representatives, 1977, Report of Committee on Appropriations for the Department of the Interior and related agencies for fiscal year 1978: Washington, D.C., 95th Congress, First Session, House Report no. 95-392.

Vecchioli, John, and Johnson, A.I., eds., 1987, Regional aquifer systems of the United States, Aquifers of the Atlantic and Gulf Coastal Plain, American Water Resources Association Monograph series no. 9, 173 p.

Voss, C.I., 1984, A finite-element simulation model for saturated-unsaturated fluid-density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport: U.S. Geological Survey Water-Resources Investigations Report 84-4369, 409 p.

Voss, C.I., and Souza, W.R., 1986, Modeling a regional aquifer containing a narrow transition between freshwater and saltwater using a solute transport simulation, Part I—Theory and methods: Delft University of Technology Salt Water Intrusion Meeting, 9th, Delft, The Netherlands, May 12–16, 1986, Proceedings, p. 493–514.

Waitt, R.B., Jr., 1985, Case for periodic, colossal jokulhlaups from Pleistocene Glacial Lake Missoula: Geological Society of America Bulletin, v. 96, p. 1271–1286.

Wallace, R.H., Jr., Kraemor, T.F., Taylor, R.E., and Wesselman, J.B., 1979, Assessment of the geopressured-geothermal resources in the northern Gulf of Mexico basin, *in* Muffler, L.J.P., ed., Assessment of geothermal resources of the United States, 1978: U.S. Geological Survey Circular 790, p. 132–155.

Weeks, A.W., 1945, Balcones, Luling, and Mexia fault zones in Texas: American Association of Petroleum Geologists Bulletin, v. 29, no. 12, p. 1733–1737.

Weeks, J.B., Gutentag, E.D., Heimes, F.J., and Luckey, R.R., 1988, Summary of the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–A, 30 p.

Weiss, Emanuel, 1982, A model for the simulation of flow of variable density ground water in three-dimensions under steady-state conditions: U.S. Geological Survey Open-File Report 82-352, 66 p.

Westjohn, D.B., 1989, Application of geophysics in the delineation of the freshwater/saline-water interface in the Michigan Basin, *in* Swain, L.A., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph series no. 13, p. 111–134.

Whitehead, R.L., 1992, Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408–B, 32 p.

Wilkens, D.W., 1986, Southwest alluvial-basin regional aquifer-systems study in parts of Colorado, New Mexico, and Texas, *in* Sun, R.J., ed., Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 107–115.

Williamson, A.K., Grubb, H.F., and Weiss, J.S., 1990, Ground-water flow in the Gulf Coast aquifer system, south-central United States—A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 89-4071, 124 p.

Williamson, A.K., Prudic, D.E., and Swain, L.A., 1989, Ground-water flow in the Central Valley, California: U.S. Geological Survey Professional Paper 1401–D, 127 p.

Wood, W.W., and Low, W.H., 1988, Solute geochemistry of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408–D, 79 p.

Young, H.L., 1992a, Summary of ground-water hydrology of the Cambrian-Ordovician aquifer system in the Northern Midwest: U.S. Geological Survey Professional Paper 1405–A, 55 p.

———1992b, Hydrogeology of the Cambrian-Ordovician aquifer system in the Northern Midwest: U.S. Geological Survey Professional Paper 1405–B, 97 p.

Young, H.L., MacKenzie, A.J., and Mandle, R.J., 1989a, Simulation of ground-water flow in the Cambrian-Ordovician aquifer system in the Chicago-Milwaukee area of the Northern Midwest, *in* Swain, L.A., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph series no. 13, p. 39–72.

Young, H.L., Mandle, R.J., Kontis, A.L., and Siegel, D.I., 1989b, The Cambrian-Ordovician regional aquifer system in the Northern Midwest—A summary, *in* Swain, L.A., and Johnson, A.I., Regional aquifer systems of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph series no. 13, p. 5–37.

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