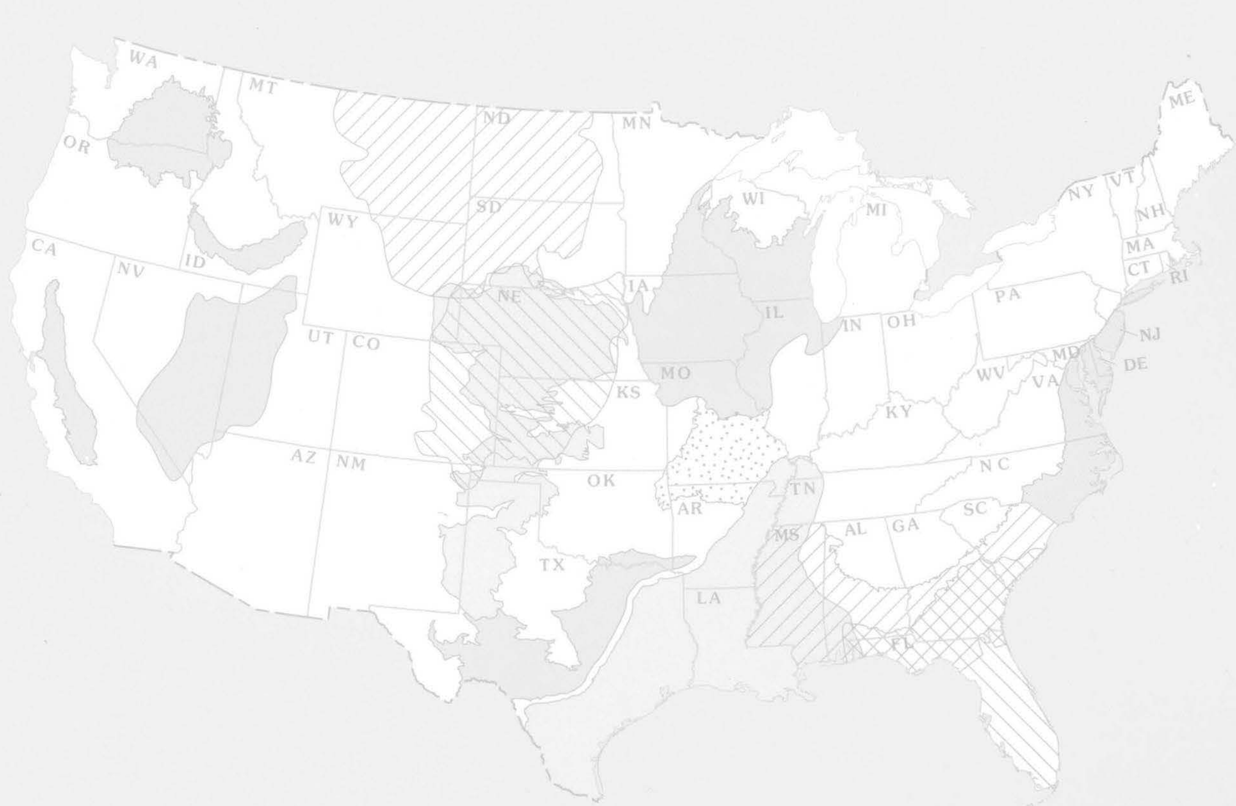
HYDROLOGIC BUDGETS OF REGIONAL AQUIFER SYSTEMS OF THE UNITED STATES FOR PREDEVELOPMENT AND DEVELOPMENT CONDITIONS

REGIONAL AQUIFER-SYSTEM ANALYSIS



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Hydrologic Budgets of Regional Aquifer Systems of the United States for Predevelopment and Development Conditions

By RICHARD H. JOHNSTON

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1425

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information; to analyze and develop an understanding of the system; and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Charles G. Groat
Director

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Multiply	*By*	*To obtain*
	Length	
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
acre-foot (acre-ft)	1,233	cubic meter
	Flow	
billion gallons per day (Ggal/d)	43.81	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
cubic feet per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
inch per year (in/yr)	25.4	millimeter per year
acre-foot per year (acre-ft/yr)	0.00123	cubic hectometer per year

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

REGIONAL AQUIFER-SYSTEM ANALYSIS

HYDROLOGIC BUDGETS OF REGIONAL AQUIFER SYSTEMS OF THE UNITED STATES FOR PREDEVELOPMENT AND DEVELOPMENT CONDITIONS

By Richard H. Johnston

ABSTRACT

Ground-water budgets are presented in this report for 14 regionally extensive aquifer systems; pumpage from 11 of these systems provided from 40 to 50 percent of the ground water withdrawn in the United States during the 1970's and 1980's. The budgets are based on simulation results from computer-based models developed as part of the Regional Aquifer-System Analysis Program of the U.S. Geological Survey. Most of the models cover large areas (30,000–300,000 square miles) and generally are constructed with coarse-mesh finite-difference grids designed to simulate regional ground-water flow. The ground-water budgets derived from these models generally do not include local flow that enters and exits regional aquifers after traveling only a few miles or flow in overlying surficial aquifers. Budgets are presented for predevelopment and recent pumping conditions for most of the aquifer systems.

Before development, many of the regional aquifer systems in humid areas were brim full; that is, most of the potential recharge was rejected from areas of outcrop. Climate, topography, and hydrogeologic setting (especially the occurrence of confined and unconfined conditions and the hydraulic properties of aquifers and confining units) were the major controls on rates of recharge and discharge. Predevelopment regional flow tended to be sluggish in the deep confined parts of the aquifer systems. The inability of clastic aquifers in the extensive Gulf Coastal Plain aquifer systems (underlying 290,000 square miles) to transmit water away from recharge areas limited predevelopment regional recharge to 4,500 cubic feet per second. In contrast, the Floridan aquifer system (underlying 100,000 square miles), which occurs in a similar humid climate but is characterized by a different hydrogeologic setting (very permeable carbonate rocks that occur at shallow depth throughout a large area), had a predevelopment recharge rate of 21,500 cubic feet per second. In the drier parts of the Central and the Western United States, recharge to and flow through most regional aquifer systems were small before development. For example, predevelopment recharge to the southern part of the unconfined High Plains aquifer (underlying 29,000 square miles in Texas and New Mexico) was only 270 cubic feet per second. Predevelopment recharge to the Great Plains aquifer system (the Dakota Sandstone and associated units), which is deeply buried throughout most of its areal extent of 170,000 square miles in the central Great Plains, was about 340 cubic feet per second.

The effect of ground-water withdrawals on water budgets is evident for the 11 regional aquifer systems with significant pumpage. A major consequence of development is a large increase in regional flow through the deeper parts of the systems. In nine of the aquifer systems, more than 50 percent of the ground water pumped is supplied by increased recharge that occurs by means of one or more of the following mechanisms: an increase in the percolation rate from outcrop and (or) subcrop recharge areas into the deeper and generally confined parts of aquifer systems, induced leakage from overlying or underlying aquifers, and return flow of excess irrigation water that is supplied by imported surface water or pumped ground water. The largest increases in regional recharge have occurred in the three most heavily pumped aquifer systems—the Gulf Coast, the High Plains, and the California Central Valley. Return flow from irrigation has been the principal source of increased inflow to the High Plains and the California Central Valley aquifer systems; increased downward percolation and induced leakage have been the principal sources of inflow to the Gulf Coastal Plain aquifer systems. Pumpage from two aquifer systems—the Edwards–Trinity of Texas and the Southeastern Coastal Plain—is supplied mostly by interception of ground water that otherwise would discharge either to streams and springs or as diffuse upward leakage.

Ground-water withdrawals have caused moderate to large losses of storage in three regional aquifer systems. A large decrease in confined aquifer storage owing to inelastic compaction of fine-grained sediments accompanied by extensive land subsidence has occurred in the southern part of the California Central Valley aquifer system (the San Joaquin Valley) and, to a much lesser extent, in two localities of the Gulf Coastal Plain aquifer systems. Long-term water-table declines with significant decreases in saturated aquifer thickness have occurred in a large area of the southern High Plains aquifer and, to a lesser degree, in the Mississippi River Valley alluvial aquifer, which is a major unit of the Gulf Coastal Plain aquifer systems.

INTRODUCTION

The hydrologic budgets of the regional aquifer systems described in this report were developed during the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey (USGS). The RASA Program has provided quantitative appraisals of the major ground-water systems of the United States. A summary of the RASA Program, which includes brief descriptions of the hydrology of the 25 regional aquifer systems investigated, is presented in Sun and Johnston (1994).

The final reports of each RASA study are a series of USGS Professional Papers numbered from 1400 to 1424. Generally, one chapter in each numbered professional paper is devoted to a quantitative description of the regional ground-water flow system. Many of these flow-system descriptions provide for the first time ground-water budgets for predevelopment and recent pumping conditions. These budgets are based on computer simulations of predevelopment and development conditions and use the regional hydrologic data bases, information on boundary conditions, and pumpage data compiled during the RASA studies. The publications that give detailed descriptions of the ground-water budgets and characteristics of the regional ground-water flow systems can be found in the "References" section at the end of this report.

The purposes of this report are to provide summary descriptions of the ground-water budgets of 14 regional aquifer systems, which provided nearly one-half of the ground water pumped in the United States during the 1970's and 1980's; to describe the hydraulic and geologic factors that control flow through regional aquifer systems under natural conditions; and to describe the sources of water withdrawn from the regional aquifer systems on the basis of differences between predevelopment and development ground-water budgets.

REGIONAL AQUIFER SYSTEMS

Aquifer systems investigated under the RASA program were classified by Sun (1986) as being of two general types—an aquifer system that comprises an extensive set of associated aquifers and confining units that may be discontinuous locally but which act hydrologically as a single aquifer system on a regional scale, or a system that consists of a set of independent aquifers that share many common hydrologic characteristics.

Aquifer systems of the first type may contain several geologic formations and chronostratigraphic units, as well as several regional aquifers and confining units. Examples include the California Central Valley aquifer system, which contains numerous beds of gravel, sand, silt, and clay, and the Floridan aquifer system, which consists of several carbonate-rock formations that underlie Florida and parts of three other States. Hydraulic continuity exists to the extent that a flow system can be defined for the entire aquifer system. Given sufficient water-level data, potentiometric surfaces can be mapped for the aquifer system or its component aquifers. The 14 aquifer systems for which ground-water budgets are presented in this report are of the first general type. Locations of these aquifer systems are shown on figure 1.

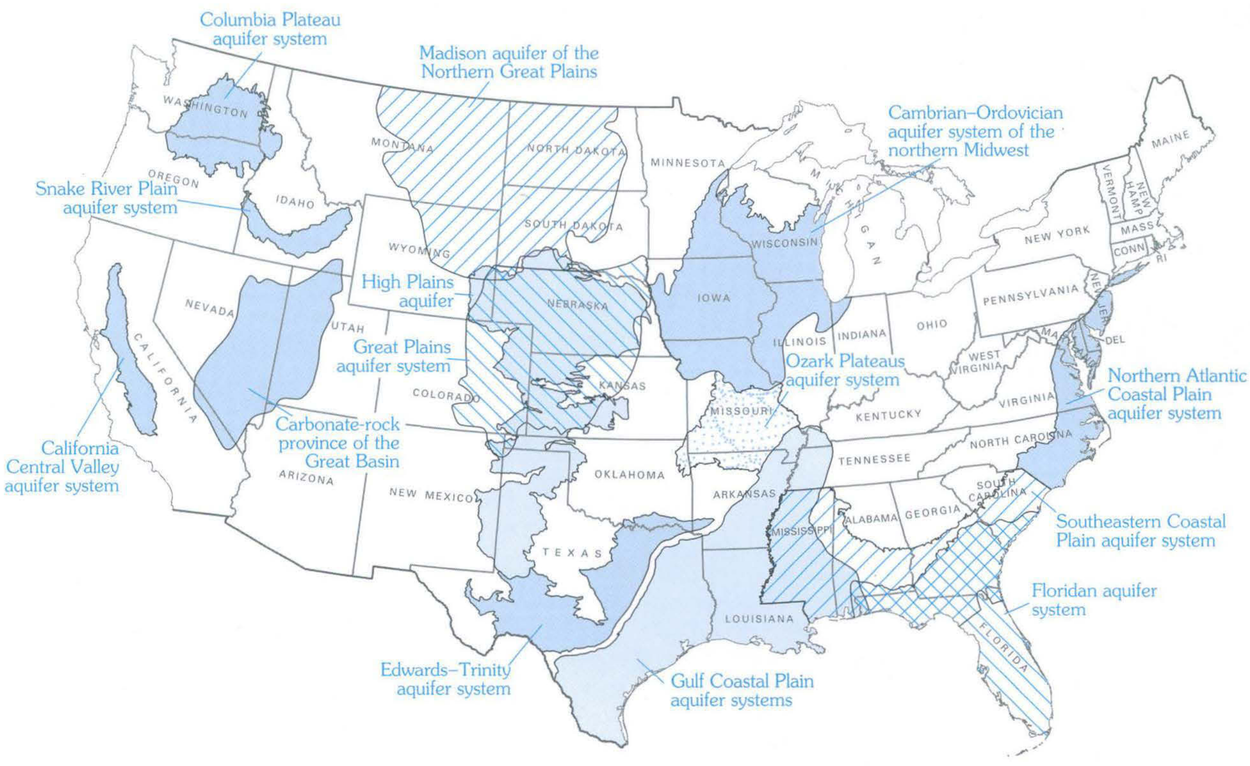


FIGURE 1.—Location of regional aquifers and aquifer systems with hydrologic budgets described in this report.

Examples of the second type of aquifer system include those found in the alluvial basins of Arizona and New Mexico and in the glacial outwash valleys of the Northeastern United States. These aquifer systems contain numerous isolated flow systems and cannot be simulated as a single hydrologic unit. Hydrologic changes in one aquifer have virtually no effect on other aquifers. The RASA approach was to investigate a few of these isolated aquifers to establish common principles and hydrogeologic characteristics that control the occurrence, movement, and quality of ground water.

SIMULATION OF FLOW IN REGIONAL AQUIFER SYSTEMS

REGIONAL, INTERMEDIATE, AND LOCAL GROUND-WATER FLOW REGIMES

Natural ground-water flow can be subdivided into local, intermediate, and regional flow regimes, as described by Toth (1963). Local flow generally is controlled by topography. Recharge to local flow regimes occurs in topographically high areas, and discharge occurs in nearby low areas, such as stream valleys. Local flow paths are characteristically short and occur at relatively shallow depth, as shown in figure 2*A*. Intermediate flow paths are longer and deeper than local flow paths and underlie several local flow regimes. Regional flow regimes extend from regional recharge areas to distant discharge areas, such as major rivers or other surface-water bodies, or at the downgradient terminus of an aquifer system. In general, regional flow moves slowly through deep, confined parts of an aquifer system and constitutes a small percentage of the total flow through the aquifer system. However, under development conditions that involve large ground-water withdrawals from deep confined aquifers, significant quantities of local and intermediate flow can be diverted into the regional flow regime.

Toth's (1963) concept of three ground-water flow regimes assumed that aquifers are homogenous and isotropic. Consequently, any geologic feature or condition that introduces heterogeneity on a moderately large scale can distort or modify this concept. Some examples of geologic conditions that cause aquifer heterogeneity and anisotropy are as follows:

- Karstic features in carbonate rocks, such as large cavernous openings, can distort short local flow paths and concentrate flow along highly preferential, longer (intermediate to regional) flow paths.
- Major faults, if sealed along fault planes, can restrict flow or, if open, can enhance flow in preferred directions.
- Abrupt facies changes from fine- to coarse-grained sediments can disrupt ground-water flow and create preferential flow paths along highly permeable, coarse-grained beds.

The effects of geology (specifically heterogeneity and anisotropy) on ground-water flow patterns were demonstrated by Freeze and Witherspoon (1967) by using numerically simulated flow nets. These investigations illustrate the influence of permeability variations in combination with topography on flow patterns. Despite the wide variety of flow patterns that result from differences in geology and topography, Toth's (1963) concept is very useful for describing flow in the regional aquifer systems described in this report. Figure 2 shows Toth's three flow regimes in two regional aquifer systems for which ground-water budgets are discussed in this report.

In the Columbia Plateau (basaltic-rock) aquifer system of the Pacific Northwest, Hansen and others (1994) defined local flow systems with flow paths that extend up to about 10 mi in length, intermediate flow systems with flow paths from about 10 to 30 mi in length, and regional flow paths of more than 30 mi in length. Most local flow occurs in upland areas with water that moves along the short flow paths to discharge at small streams or seeps and springs along canyon walls (fig. 2*A*). Much of the water that moves along the longer intermediate flow paths also occurs in the uplands, and some of it mixes with local flow to become part of the local flow-system discharge (Hansen and others, 1994). Some of the intermediate flow also merges with the regional flow paths that ultimately terminate in the regional discharge area located in the lowest part of the Columbia Plateau along major streams, such as the Columbia and the Snake Rivers. Simulated discharge to major streams from the combined intermediate and regional flow systems accounts for more than one-third of the total simulated flow through the aquifer system.

Ground-water flow in the Floridan aquifer system that underlies the karstic springs area of north-central and northwestern peninsular Florida differs markedly from that in the basaltic rock aquifer system just described. Small streams are almost nonexistent in the karst area, and ground-water discharge occurs at large springs or major streams that are incised into the upper part of the Floridan aquifer system (fig. 2*B*). The local ground-water flow system of Toth (1963) generally does not exist; flow paths are longer, and intermediate flow systems are dominant. Deep regional flow in the lower part of the Floridan aquifer system comprises only a small percentage of the total ground water that is recharged and discharged within the karstic springs area. The dominance of intermediate flow in the karst area is indicated by flow simulations (Bush and Johnston, 1988, p. 44) and ground-water chemistry (Faulkner, 1973, p. 75). However, in the hilly outcrop

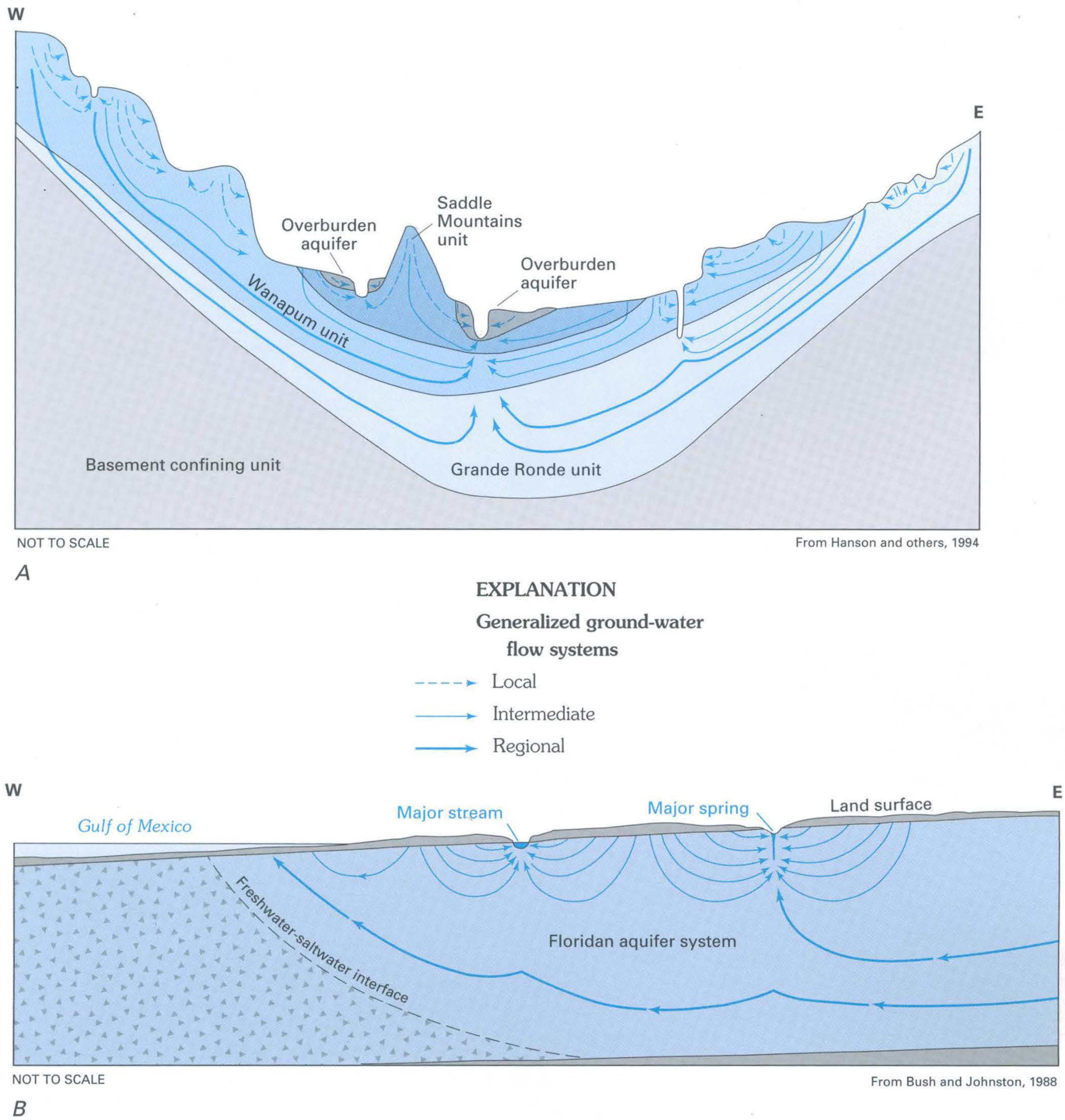


FIGURE 2.—Flow systems in: *A*, Basalt aquifer units of the Columbia Plateau aquifer system; *B*, The Floridan aquifer system in the north-central Florida Springs area.

area of the Floridan aquifer system in Georgia, surface drainage is better developed, and local flow probably accounts for most of the total ground-water flow. According to Bush and Johnston (1988), flow patterns in other unconfined and semiconfined areas of the Floridan aquifer system "are some combination of these extremes" but are more like those of the karstic springs area than the Georgia outcrop area.

SIMULATED REGIONAL GROUND-WATER BUDGETS FROM COARSE-MESH MODELS—THE SCALE PROBLEM

Most of the regional flow models developed during the RASA Program were used to simulate predevelopment and recent pumping conditions. 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 the Gulf Coastal Plains, the High Plains, the Great Plains, the central and northern Midwest, and the California Central Valley), the discretization of most of the systems is relatively coarse. The grid spacing and other features of the regional models discussed in this report are summarized in table 1. Note that the area of the grid blocks in 12 of the 14 coarse-mesh models ranges from 16 to 256 mi^2. However, in two of the models (those used for simulation of the Columbia Plateau aquifer system and the Edwards–Trinity aquifer system), finer meshes were used.

In most terranes where a modeled system includes near-surface aquifers, the fraction of the total ground-water flow that the model simulates becomes smaller as the size of model grid cells becomes larger. 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 (fig. 2*A*), much of the recharge travels as local flow only short distances before it discharges to the streams. Consequently, local flow is not simulated by many coarse-grid regional models, as indicated in figure 3. In contrast, in areas of little topographic relief and few streams, such as the karst areas of the Floridan aquifer system (fig. 2*B*), 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 that control the fraction of total ground-water flow simulated by a regional model that includes near-surface units are topography and drainage density. These characteristics are typically variable across large regional aquifer systems. Accordingly, the fraction of total ground-water flow that is simulated by a coarse-grid model varies spatially, thus making the differentiation of flow regimes difficult to quantify for the model as a whole. Although most RASA modelers have confronted this problem by describing the effect of these variations on their simulations, rigorous quantitative analysis of the effect is lacking.

Simulation of development conditions that involves pumping from deep confined aquifers generally requires some diversion of local flow from shallow aquifers into the regional flow regime. A mechanism is thus required that permits vertical flow into the deep aquifers. Some RASA models used specified heads in model layers that represented shallow aquifers as a method of supplying vertical flow to deep aquifers. [See, for example, the discussion of boundary and initial conditions in the Cambrian–Ordovician aquifer system of the northern Midwest by Mandle and Kontis (1992, p. 31)]. This approach assumes that heads in the shallow aquifer are unaffected by pumping from the deep aquifer. A drawback of this method is that an unrealistically large volume of vertical flow into deep aquifers can be computed unless the volume is limited to a probable maximum amount. A different approach was used to simulate pumping conditions in the unconfined and confined aquifers of the Northern Atlantic Coastal Plain aquifer system. The coarse-grid 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, p. 21). 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 and allowed for variable rates of vertical flow from and to the confined aquifers.

Most of the ground-water budgets presented in this report are derived from coarse-grid computer models designed to simulate "regional flow." Such budgets generally 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 percentage of the total ground-water flow system represented by "regional flow" is partly dependent on the mesh size of the model. During predevelopment conditions, the amount of local flow was commonly much greater than regional flow, especially in humid areas. A common characteristic of humid and semiarid areas is that rates of regional flow are increased by development. In the humid East, especially, much "local" flow is diverted into the regional flow system as withdrawals from deep confined aquifers increase. For example, in the Cambrian–Ordovician aquifer system of the northern Midwest, simulated recharge to the regional flow system was small (570 ft^3/s) before development. However, simulated recharge to the regional flow system for recent pumping conditions (mostly induced vertical leakage) was about 1,400 ft^3/s (Mandle and Kontis, 1992, fig. 37).

Total recharge to a regional aquifer system does not necessarily increase under pumping conditions; only the part of the total recharge that percolates to zones of pumping within the intermediate or regional flow regimes increases. Where local flow systems do not

TABLE 1.—*Computer models used for simulation of predevelopment and development flow conditions in regional aquifer systems*
[mi, mile; ft, foot; 3–D, three dimensional; 2–D, two dimensional; RASA, Regional Aquifer-System Analysis]

Regional aquifer system	Problem	Characteristics of model used	Computer program references	RASA report references
California Central Valley aquifer system.	Simulation of flow in sand-silt-clay aquifer system that involves very large ground-water withdrawals, land subsidence, and recharge by imported surface water.	3–D finite-difference model; four active layers and 6-mile grid spacing.	Trescott (1975), Trescott and Larson (1976), Meyer and Carr (1979), Torak (1982).	Williamson and others (1989).
Cambrian–Ordovician aquifer system of the northern Midwest.	Simulation of flow in sandstone and carbonate-rock aquifers that involves pumping from multi-aquifer wells and variable density flow.	3–D finite difference model; five active layers and 16-mi grid spacing.	Trescott (1975), Kontis and Mandle (1988).	Mandle and Kontis (1992).
Carbonate-rock province of the Great Basin.	Simulation of shallow flow in basin-fill deposits super-imposed over deeper flow through fractured carbonate rocks.	3–D finite difference model; two active layers and 5- by 7.5-mile grid blocks.	McDonald and Harbaugh (1988).	Prudic and others (1995).
Columbia Plateau aquifer system.	Simulation of flow in basaltic and sedimentary aquifers that involve pumpage and recharge from applied irrigation water and canal leakage.	3–D finite-difference model; five active layers and 8,500- by 15,000-foot grid blocks.	McDonald and Harbaugh (1988).	Hansen and others (1994).
Edwards-Trinity aquifer system.	Simulation of flow in carbonate aquifers of complex geometry owing to fracturing and faulting.	2–D finite-element model; single layer and variable size elements.	Kuniansky (1990).	Kuniansky and Holligan (1994).
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; two active layers and 8-mi grid spacing.	Trescott (1975), Trescott and Larson (1976).	Bush and Johnston (1988).
Great Plains aquifer system.	Simulation of flow in Dakota Sandstone and associated units that involves withdrawal of ground water and petroleum.	3–D finite-difference model; four active layers and 14-mi grid spacing.	McDonald and Harbaugh (1988).	Helgesen and others (1993).

TABLE 1.—*Computer models used for simulation of predevelopment and development flow conditions in regional aquifer systems*—Continued

Regional aquifer system	Problem	Characteristics of model used	Computer program references	RASA report references
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 (in press)
Southern High Plains aquifer.	Simulation of flow in unconfined aquifer with very large ground-water withdrawals 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).
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).
Ozark Plateaus aquifer system.	Simulation of pre-development flow in predominantly carbonate-rock aquifers of Paleozoic age.	3–D finite-difference model; four active layers and 14-mile grid spacing.	McDonald and Harbaugh (1988).	Imes and Emmett (1994).
Madison aquifer of the Northern Great Plains.	Simulation of variable density flow in Paleozoic and Mesozoic bedrock aquifers before development of ground water and petroleum.	Two 3–D finite difference models; two to five active layers and variable grid spacing.	Trescott (1975), Weiss (1982).	Downey (1984, 1986).
Snake River Plain aquifer system.	Simulation of flow in basalt aquifers of eastern plain that involves large withdrawals and recharge by imported surface water.	2–D parameter estimation model and 3–D finite difference model; four active layers and 4-mi grid spacing.	Garabedian (1986), McDonald and Harbaugh (1988).	Garabedian (1992), Lindholm (1996).
Southeastern Coastal Plain aquifer system.	Simulation of deep flow in clastic coastal plain aquifers with locally heavy pumping.	3–D finite-difference model; three active layers and 8-mile grid spacing.	McDonald and Harbaugh (1988).	Miller (1992), Barker and Pernik (1994).

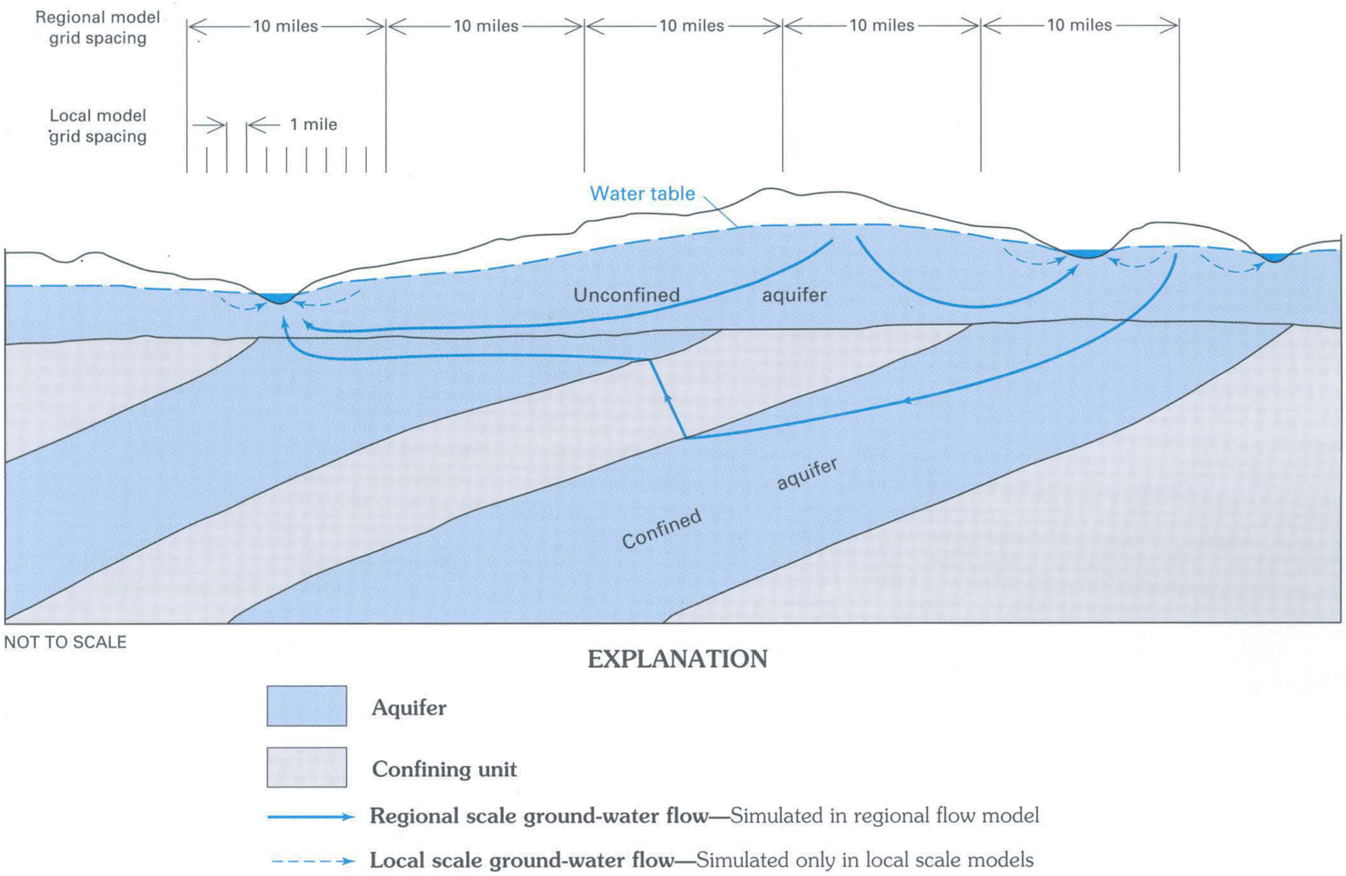


FIGURE 3.—Relation of local and regional scale ground-water flow to discretization in computer flow models.

exist, as in some karst areas, pumping causes virtually no increase in percolation to intermediate or regional flow regimes. This condition occurs in the Suwanee River drainage area of northern Florida, which is an internally drained karst area underlain by the Floridan aquifer system (fig. 2*B*). Simulated recharge to the intermediate-regional flow regimes in this karst area was about 5,800 ft^3/s for predevelopment and recent pumping conditions (Bush and Johnston, 1988, p. 45, figs. 22, 32, and 33). The pumpage in the Suwanee River drainage area is supplied by a decrease in springflow and discharge to surface-water bodies.

REGIONAL GROUND-WATER BUDGETS

Regional aquifer systems are grouped into four categories for presentation of regional ground-water budgets. The first category is the clastic-rock aquifer systems of the Atlantic and the Gulf Coastal Plains. The second category is the carbonate-rock aquifer systems in several physiographic provinces from the Atlantic Coastal Plain of Florida to the Great Basin of Nevada. The third category is the clastic-rock aquifer systems of the Central and the Western United States. The fourth category is the basaltic-rock aquifer systems of the Pacific Northwest. Of the 14 aquifer systems, 11 are extensively developed, and budgets are presented for predevelopment and development conditions for those systems. As of the early 1980's, three carbonate-rock aquifer systems had little ground-water development; only predevelopment budgets are presented for those systems. A summary of predevelopment recharge and discharge rates for the 14 regional aquifer systems is given in table 2.

The ground-water budgets for development conditions are dependent on the time period that was simulated. Each budget is a snapshot of a recent year or period of years and is not an average of long-term development conditions. In particular, the amount of water that comes from storage depends on the history of ground-water withdrawals and how close the system is to a new equilibrium. As an example of how ground-water budgets have changed since ground-water development began, the following discussions of the Gulf Coastal Plain aquifer systems describe budgets for several periods from predevelopment to 1985. For the other aquifer systems, one budget is described for a recent development period.

TABLE 2.—*Rates and characteristics of predevelopment recharge and discharge of regional aquifer systems*

[mi^2, square mile; in/yr, inch per year; ft^3/s, cubic feet per second; RASA, Regional Aquifer-System Analysis]

Regional aquifer system	Areal extent (mi^2)	Precipitation (in/yr)	Predevelopment recharge: Percolation and leakage rate [ft^3/s and (in/yr)]	Predevelopment recharge: Area (mi^2)	Predevelopment discharge: Discharge rate (ft^3/s)	Predevelopment discharge: Nature of discharge	RASA report references
California Central Valley aquifer system.	20,000	5–26	[1]280 (0.35)	10,900	280	Evapotransporation and upward leakage to streams.	Williamson and others (1989).
			[2]2,760 (3.4)		2,350 410	Evapotranspiration. To streams.	
Cambrian-Ordovician aquifer system of the northern Midwest.	161,000	30	570	([3])	570	To streams or as diffuse leakage.	Mandle and Kontis (1992).
Carbonate-rock province of the Great Basin.	100,000	3–60	[1]2,210	([3])	1,658 274 192 83	Evapotranspiration. To springs. To lakes and rivers. Other discharge.	Prudic and others (1995).
Columbia Plateau aquifer system.	[4]50,600	6–45	[2]7,120 (3.0)	32,700	2,750 3,945 425	To rivers. To small streams. To seepage faces.	Hansen and others (1994).
Edwards-Trinity aquifer system.	[4]55,700	10–32	[1]3,870 (1.01)	51,900	3,870	To springs and rivers.	Kuniansky and Holligan (1994).
Floridan aquifer system.	[5]94,000	53	[2]21,500 (4.4)	67,000	12,500 6,500 2,500	To springs. To streams and lakes. Diffuse drainage.	Bush and Johnston (1988).
Great Plains aquifer system.	[4]170,000	12–28	[1]340	([3])	290 50	Diffuse leakage. To streams.	Helgesen and others (1993).
Gulf Coastal Plain aquifer systems.	[5]230,000	24–60	[1]4,500 (0.48)	127,000	4,500	To streams and Gulf of Mexico or as diffuse leakage.	Williamson (in press).
Southern High Plains aquifer.	29,000	16–20	[1]270 (0.13)	29,000	270	To streams, springs, and seeps along eastern escarpment.	Luckey and others (1986); Gutentag and others (1984).
Northern Atlantic Coastal Plain aquifer system.	[5]55,000	47	[1]920 (0.5)	25,000	920	Diffuse, upward leakage.	Leahy and Martin (1993).
Ozark Plateaus aquifer system.	65,000	36–50	[1]7,091 (2.4)	40,000	4,035 3,056	To streams and lakes. To major rivers and adjoining aquifer systems.	Imes and Emmett (1994).

TABLE 2.—*Rates and characteristics of predevelopment recharge and discharge of regional aquifer systems*—Continued

Regional aquifer system	Areal extent (mi^2)	Precipitation (in/yr)	Predevelopment recharge: Percolation and leakage rate [ft^3/s and (in/yr)]	Predevelopment recharge: Area (mi^2)	Predevelopment discharge: Discharge rate (ft^3/s)	Predevelopment discharge: Nature of discharge	RASA report references
Madison aquifer of the northern Great Plains.	[4]210,000	10–20	[1]47	([3])	47	Diffuse leakage to adjoining aquifer systems.	Downey (1984).
Snake River Plain aquifer system (eastern part).	10,800	[6]8–10 [7]20–60	[8]7,460	10,800	[8]6,100	Seepage and spring flow to Snake River.	Garabedian (1992).
Southeastern Coastal Plain aquifer system.	210,000	51	[1]2,165 (0.6)	46,500	1,720 445	To streams. Diffuse leakage and outflow to adjoining aquifer systems.	Barker and Pernik (1994); Miller (1992).

[1] Deep regional flow regime only.
[2] Deep regional flow plus some local intermediate-scale flow.
[3] Size of recharge area is uncertain.
[4] Areal extent of RASA investigation; full extent of aquifer system is larger.
[5] Excludes offshore areas.
[6] On the plain.
[7] In tributary basins.
[8] Rates for the Snake River Plain aquifer system are for 1891 through 1895, before development of ground water. Some recharge was supplied by percolation of excess irrigation water from surface-water sources. Accretion of ground-water storage was about 1,360.

The details of the digital models used to simulate ground-water flow and to calculate ground-water budgets for aquifer systems are not described in this report. The interested reader is referred to the references listed in table 1 for those details. However, as an example, the following discussion of a regional ground-water budget (for the Gulf Coastal Plain aquifer systems) briefly describes how three large regional aquifer systems with complex boundary conditions are represented in a coarse-grid digital model.

CLASTIC-ROCK AQUIFER SYSTEMS OF THE ATLANTIC AND THE GULF COASTAL PLAINS

Several major aquifer systems that consist of unconsolidated to semiconsolidated clastic rocks underlie the Atlantic and the Gulf Coastal Plains of the Eastern and the Southern United States. These rocks are mostly of Cretaceous through Quaternary age and contain many prolific sand aquifers. The subdivision of this thick sequence of sands and fine-grained sediments into aquifer systems for investigation during the RASA Program was somewhat arbitrary. The sediments of the western Gulf Coast and the Mississippi Embayment were subdivided into three aquifer systems that are collectively referred to as the "Gulf Coastal Plain aquifer systems" (fig. 1). The laterally equivalent clastic sediments to the east were named the Southeastern Coastal Plain aquifer system, and those further northeast were named the Northern Atlantic Coastal Plain aquifer system (fig. 1); the Cape Fear Arch, which is located in the vicinity of the North Carolina–South Carolina State line, is a natural hydrogeologic boundary that separates those two aquifer systems.

GULF COASTAL PLAIN AQUIFER SYSTEMS

The Gulf Coastal Plain aquifer systems consist mostly of sediments of Cenozoic age that underlie about 290,000 mi^2; the aquifer systems extend from Texas to Florida and include the Mississippi Embayment, the 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. The thickness of the sediments increases toward the Gulf of Mexico in a general wedge shape; maximum thickness of more than 30,000 ft occurs in southern Louisiana.

According to Williamson (in press), recharge to the Gulf Coastal Plain aquifer systems is not related to the average rainfall, but rather to the capacity of the aquifer systems to transmit water away from the recharge areas—"where the flow capacity is limited by the small hydraulic gradient or by resistance to flow of the aquifer system, most of the rainfall which potentially would recharge the regional aquifer systems is discharged to local surface-water bodies." Pumpage from the Gulf Coastal Plain aquifer systems increased from about 870 ft^3/s in 1930 to 13,500 ft^3/s (8.7 Ggal/d) in 1985. The development of ground water has caused land subsidence, a lowering of hydraulic heads, and changes in aquifer storage, rates and locations of recharge and discharge, direction and magnitude of flow, and water quality (Williamson, in press).

Areally, the following aquifer systems were delineated on the basis of regional ground-water flow and sediment characteristics: the Mississippi Embayment, the Texas coastal uplands, and the coastal lowlands. For simulation in a regional flow model, these aquifer systems were divided into 11 regional aquifers and permeable zones and 6 regional confining units by Hosman and Weiss (1991) and Weiss (1992); most of these units are shown in the north–south section of figure 4. The resulting 17 model layers do not necessarily correspond to previously named geologic or geohydrologic units. For example, layer 11 in figure 4 represents the Mississippi River Valley alluvial aquifer in the northern part of the section and permeable zones in Holocene–upper Pleistocene-age deposits in the south part of the section. The two parts of layer 11 shown in figure 4 are actually connected hydraulically in central Louisiana (Williamson, in press).

Regional flow within the Gulf Coastal Plain aquifer systems was simulated with a finite-difference, variable-density flow model that was developed by Williamson (in press) and that used a computer solver code by Kuiper (1983, 1985). The density of ground water, although variable in space, was assumed to be constant in time. Figure 5 shows the representation of aquifers and confining units and boundary conditions in the model. A constant-head boundary was simulated in a shallow recharge–discharge layer above the top aquifer in figure 5. Heads in this layer do not vary with time. The base of the flow system is specified as a no-flow boundary at the top of either the Midway confining unit or the geopressured zone where it is above the Midway confining unit (figs. 4, 5). Most of the lateral aquifer system boundaries are specified as no flow except that estimated data may be used in some areas to extend the no-flow boundaries for some distance beyond the area of interest. Because of the very large study area, Williamson (in press) used a very coarse grid model to simulate

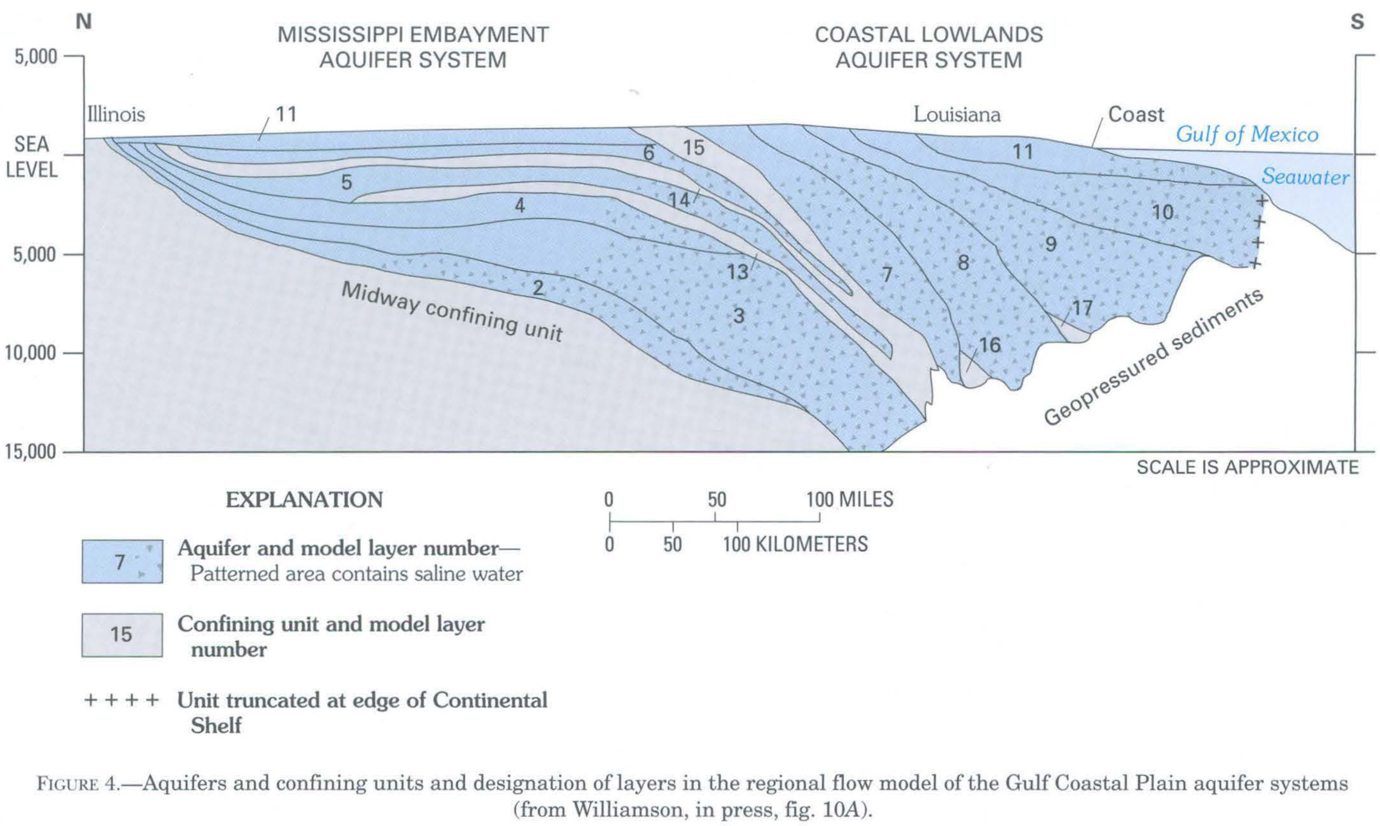


FIGURE 4.—Aquifers and confining units and designation of layers in the regional flow model of the Gulf Coastal Plain aquifer systems (from Williamson, in press, fig. 10A).

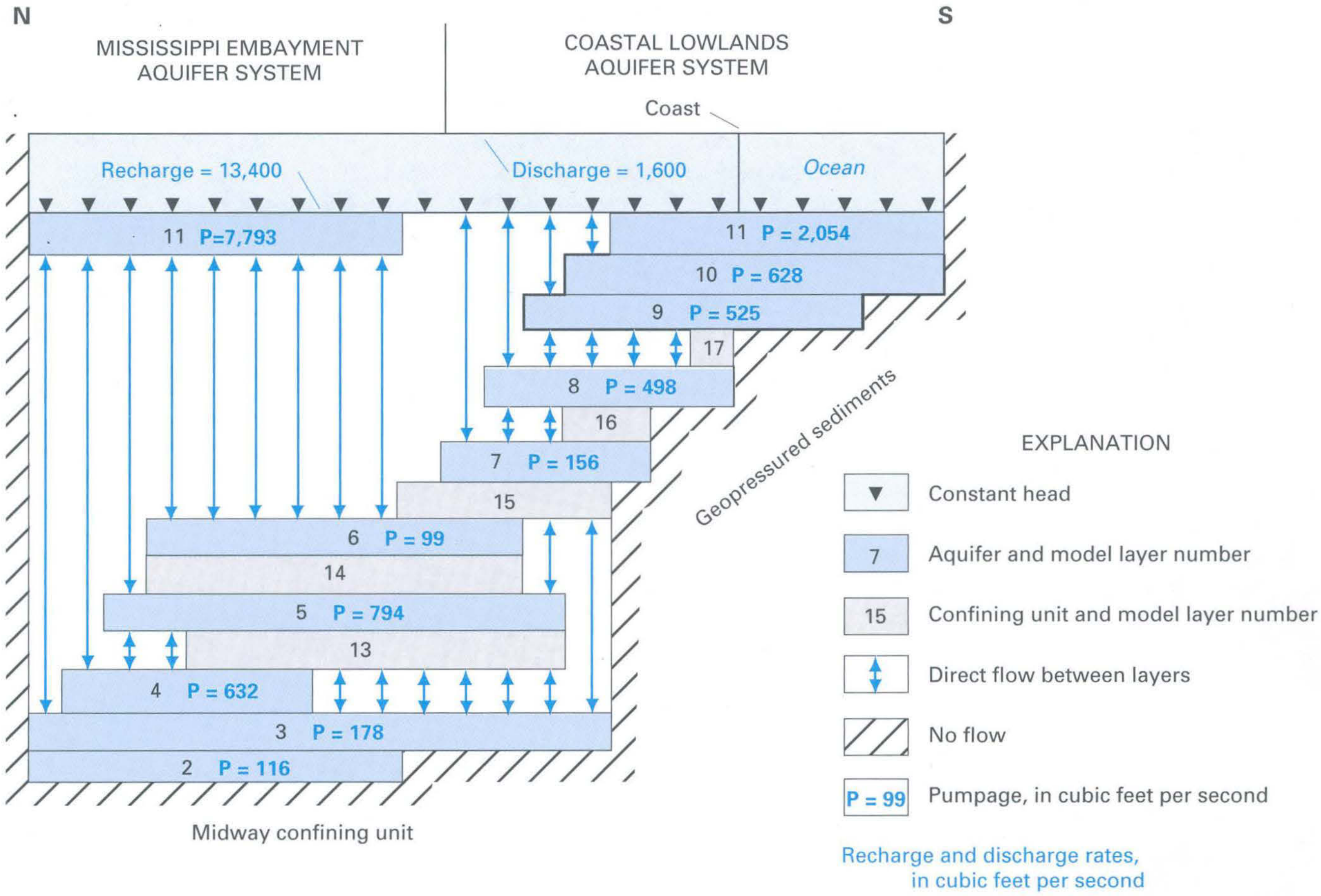


FIGURE 5.—Vertical structure of the regional flow model of the Gulf Coastal Plain aquifer systems and simulated 1985 rates of recharge, discharge, and pumpage (modified from Williamson, in press, fig. 10*B*).

regional ground-water flow. However, he stated that even with the 10-mi horizontal grid spacing, "the regional features affecting flow in the aquifer systems are generally preserved."

The model was used to simulate ground-water flow for predevelopment conditions (about 1900) and transient pumping conditions from 1930 through 1985. Simulated total recharge and discharge and pumpage from the principal aquifers for the 1985 pumping simulation are shown in figure 5. After using this model to simulate variable-density flow in the deeper saline parts of the aquifer systems, Williamson (in press) concluded that the density of the saline water probably has a significant effect on flow in the saline and freshwater parts of the aquifer systems.

Ground-water budgets for the Gulf Coastal Plain aquifer systems during predevelopment and for 1985 pumping conditions are shown in figure 6. Note that the rates of regional recharge and discharge have been substantially changed by ground-water pumping. The 1985 pumpage is about three times the predevelopment recharge rate. About two-thirds of the 1985 pumpage was supplied by increased percolation to regional aquifers in their outcrop and subcrop areas and by increased vertical flow to confined parts of regional aquifers (Williamson, in press). The remaining one-third was supplied by a decrease in discharge to surface-water bodies and evapotranspiration and, to a lesser extent, by loss of aquifer storage. Most of the loss from storage was accounted for by water-table declines in the Mississippi River Valley alluvial aquifer (model layer 11, fig. 5). Some loss of artesian storage has occurred in the Houston, Texas, and the Baton Rouge, Louisiana, areas, which has resulted in the inelastic compaction of fine-grained beds and land subsidence. Williamson (in press) noted that some aquifers are "self-supporting"; that is, most of their pumpage was supplied by increased recharge (in outcrop or subcrop areas) or by decreased discharge from the aquifer itself (model layers 5, 8–11, fig. 5). However, one major aquifer with a narrow outcrop and subcrop band (model layer 2) had

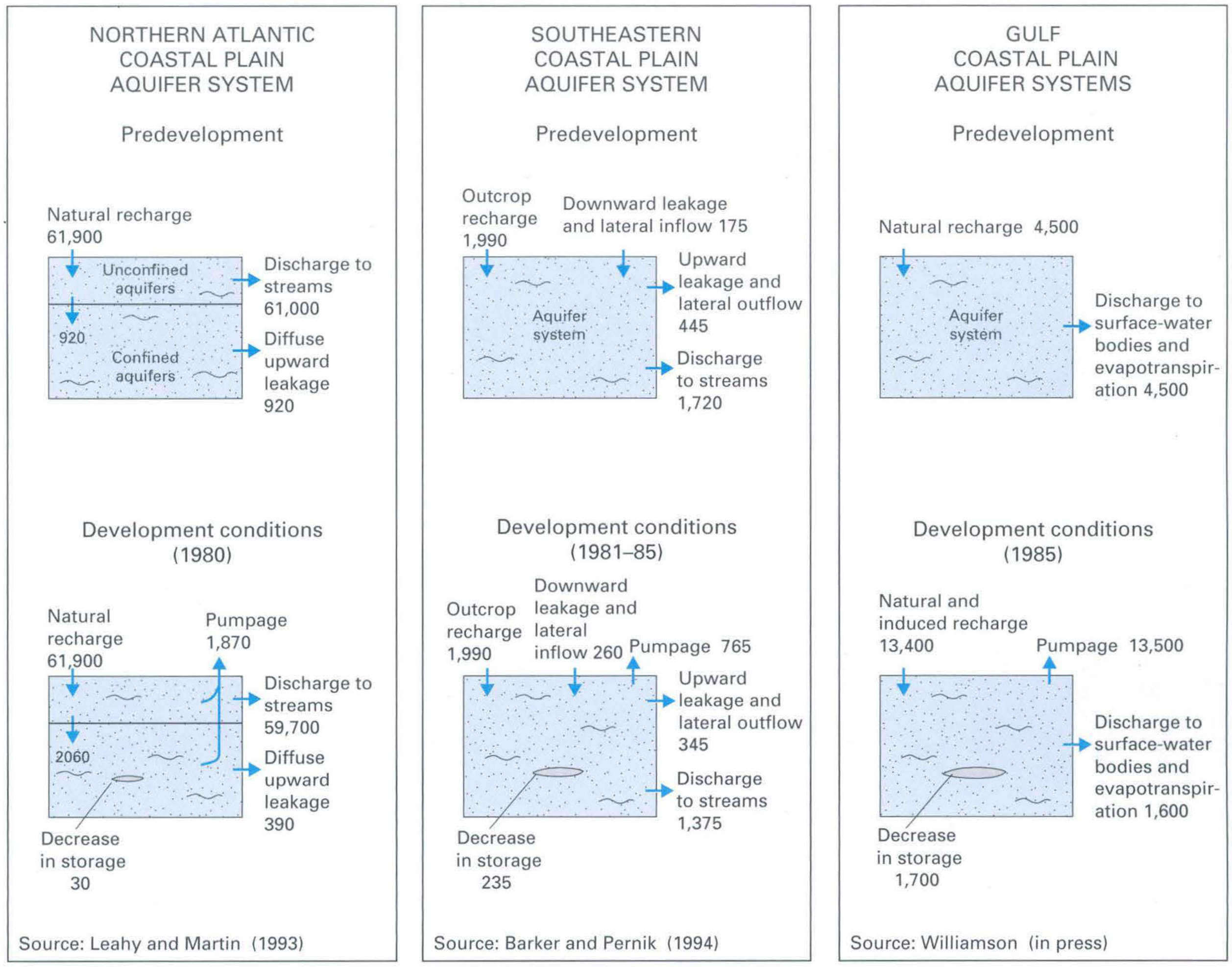


FIGURE 6.—Ground-water budgets before and after development of clastic-rock aquifer systems in the Atlantic and Gulf Coastal Plains. Values in cubic feet per second. Sum of outflows may not exactly equal sum of inflows as a result of independent rounding.

80 percent of its pumpage supplied by downward leakage from an overlying aquifer.

Changes to the regional ground-water budget during the development era (1930–85) are shown in greater detail in figure 7. Pumpage steadily increased from 870 ft^3/s in 1930 to 14,700 ft^3/s (9.5 Ggal/d) in 1980 with a small decrease in 1985. Pumpage throughout the development period has been supplied mostly by steadily increasing recharge to the regional aquifers and, to a lesser extent, by decrease in natural discharge and loss of aquifer storage. For much of the period, the percentage of pumpage supplied from aquifer storage ranged from 8 to 16 percent. An exception occurred in 1950 when the storage contribution increased to 27 percent (fig. 7) as a result of primarily a large increase in pumpage from the Mississippi River Valley alluvial aquifer. Williamson (in press) stated that, although only a small part of the 1985 pumpage was supplied from aquifer storage, the system was far from equilibrium with 1985 pumping conditions.

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 underlies about 55,000 mi^2 (fig. 1). The aquifer system consists of consolidated and unconsolidated gravel, sand, silt, and clay of Jurassic to Holocene age (Trapp, 1993). These sediments form an eastward-thickening wedge that contains aquifers that are the major source of fresh ground water in the area. The sediments have been subdivided into 11 regional aquifers and 9 confining units on the basis of continuity of permeability (Trapp, 1993). Recharge to the aquifers is from infiltration of precipitation at rates that range from 10 to 25 in/yr. Most of this recharge flows through shallow aquifers and discharges to nearby streams; a small amount (about 0.5 in/yr) per-

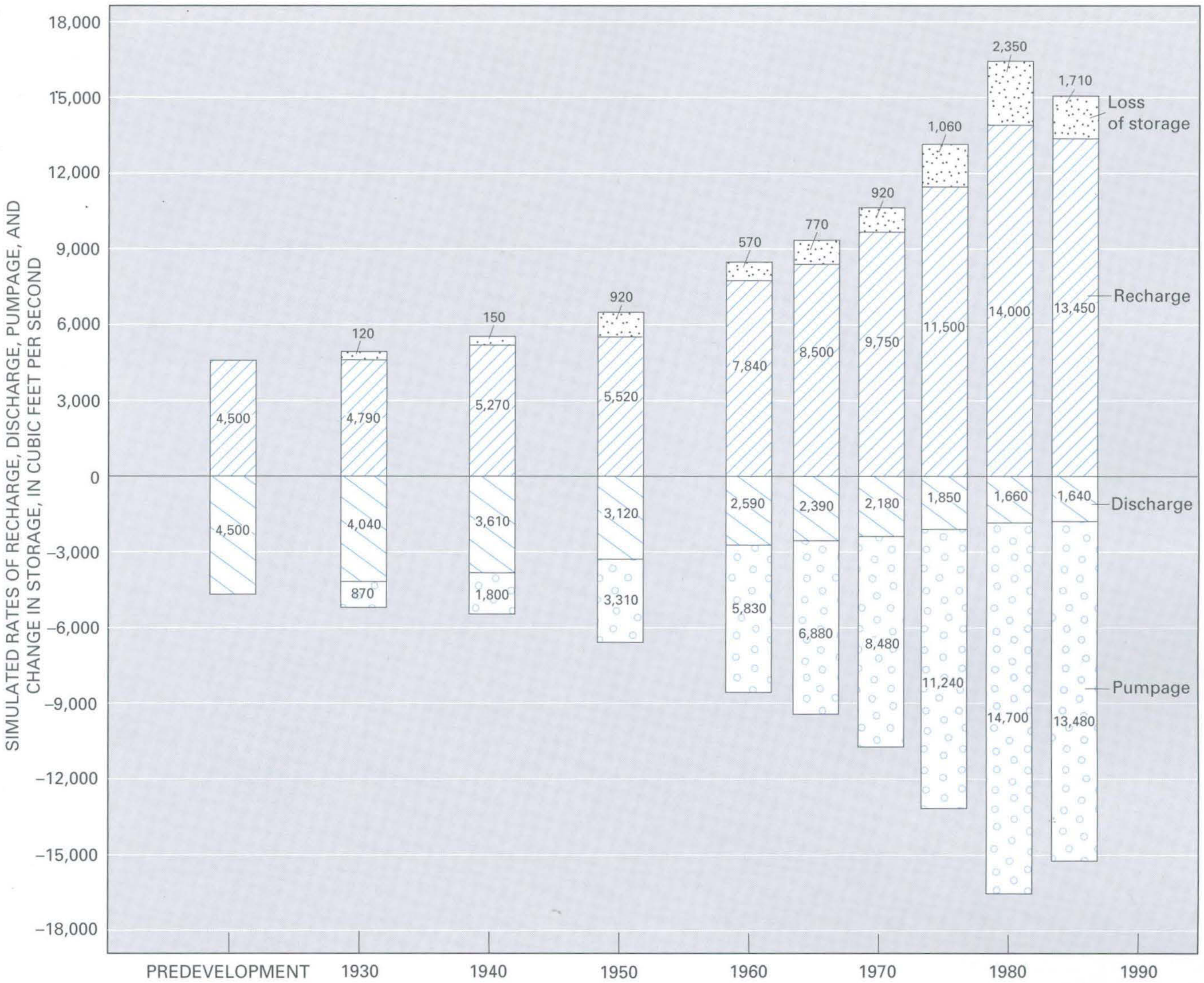


FIGURE 7.—Change in simulated regional ground-water budget of the Gulf Coastal Plain aquifer systems from predevelopment to 1985 (modified from Williamson, in press, fig. 45).

colates into the deeper confined aquifers. Ground-water pumpage (excluding irrigation and rural withdrawals) has increased from about 155 ft^3/s in 1900 to about 1,870 ft^3/s (1.2 Ggal/d) in 1980. As a result of pumpage for industrial and public supply, extensive cones of depression occur in New Jersey, the Delmarva Peninsula, and southern Virginia and adjacent North Carolina.

Simulations of steady-state flow in the aquifer system were made for predevelopment conditions, and simulations of transient pumping conditions were made for 10 pumping periods of varying duration from 1900 to 1980 by using a 10-layer finite-difference model (Leahy and Martin, 1993). For simulation of transient pumping conditions, the top boundary of the model in the onshore area was treated as a flux and a specified-head boundary. This boundary condition enabled the model to simulate transient heads in and near outcrop areas and allowed for variable rates of vertical flow to and from confined aquifers (Leahy and Martin, 1993, p. 18–21).

Ground-water budgets for the Northern Atlantic Coastal Plain aquifer system for predevelopment and 1980 conditions are shown in figure 6. Because these budgets represent the total ground-water flow system, the areal recharge rate is the same for predevelopment and 1980 conditions—about 62,000 ft^3/s. Note that pumpage in 1980 (1,870 ft^3/s) represents only about 3 percent of the recharge that entered the ground-water flow system. Pumpage, which is primarily from the confined aquifers, is supplied, for the most part, by an increase in downward percolation to the confined aquifers and a decrease in diffuse upward leakage and eventual discharge to surface-water bodies. At the end of the 1978 through 1980 pumping period, less than 2 percent of the pumpage was supplied by water derived from aquifer storage. However, Leahy and Martin (1993) emphasized that because withdrawals are not distributed evenly (spatially) 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 compared with predevelopment and the upward leakage from confined aquifers to occur at less than one-half the predevelopment rate. Because only a small volume of water was being released from storage at the end of each pumping period, Leahy and Martin (1993) concluded that the system adjusts rapidly (less than 3 years) to changes in withdrawal rates. Their simulations also suggested that the total volume of vertical flow (downward leakage) is much greater than lateral flow through aquifers from outcrop areas. This occurs because of the very large areal extent of the cones of depression in comparison with the much smaller cross-sectional areas of the aquifers through which lateral flow occurs. In general, vertical flow from overlying aquifers is the dominant source of pumpage from confined aquifers (Leahy and Martin, 1993).

SOUTHEASTERN COASTAL PLAIN AQUIFER SYSTEM

The Southeastern Coastal Plain aquifer system comprises a thick sequence of mostly poorly consolidated clastic rocks of Cretaceous to late Tertiary age (Miller, 1992). The aquifer system underlies an area of about 120,000 mi^2 of the Coastal Plains of Alabama, Georgia, Mississippi, and South Carolina (fig. 1) and contains numerous aquifers and confining units. However, for the purpose of simulating regional flow by using a coarse-mesh computer model, Renken (1996) grouped the rocks into four regional aquifers separated by three regional confining units.

Most of the recharge that occurred in aquifer outcrop areas (about 7 in/yr) infiltrates to shallow depths and discharges to nearby streams; only about 0.6 in/yr percolates to the deep confined parts of the aquifer system. A coarse-mesh finite-difference model (8-mi grid spacing) was used by Barker and Pernik (1994) to simulate deep regional ground-water flow. Simulation of predevelopment (steady-state) conditions indicated that deep regional flow was about 2,165 ft^3/s, of which about 80 percent discharged to large rivers and about 20 percent discharged upward as diffuse leakage to overlying aquifers or adjacent aquifer systems (fig. 6).

A more detailed ground-water budget, which was based on cross-sectional flow models and analysis of stream base flows, was presented by Faye and Mayer (1990) for part of the aquifer system in Georgia and the adjacent areas of Alabama and South Carolina. They concluded that total ground-water recharge in that area was about 9,000 ft^3/s, which ultimately discharged as follows: 5,150 ft^3/s (58 percent) to streams close to points of recharge (local flow), 1,950 ft^3/s (22 percent) to tributaries of major rivers (intermediate flow), 780 ft^3/s (9 percent) to major rivers (regional flow), 660 ft^3/s (8 percent) as riparian evapotranspiration, and 310 ft^3/s (3 percent) as leakage to overlying aquifers (regional flow). This analysis and the regional model results indicate about a 10 to 1 ratio of shallow (local to intermediate) recharge to regional recharge. This ratio "emphasizes the sharp contrast between the relatively large amount of water that circulates within the dynamic, shallow flow regime and the relatively small amount circulating within the less vigorous, deeper parts of the confined flow regime" (Barker and Pernik, 1994, p. C32).

By 1985, pumpage from the entire aquifer system was about 765 ft^3/s (495 Mgal/d) and water-level declines, which exceeded 100 ft, had locally developed in the downdip confined parts of the pumped aquifers. Except in a few places, water levels in outcrop areas were not affected by pumping in the confined parts of the aquifers. For this reason, according to Barker and Pernik (1994), recharge to outcrop areas was applied at the predevelopment rate (1,990 ft^3/s) for transient simulations of 1900 through 1985 development conditions. Where water levels have declined in or near outcrop areas, the percolation rate to the deep confined aquifers undoubtedly has increased; however, they further explain that with the large grid-cell size (8 x 8 mi), it is impossible to simulate head changes in very small areas. The greatest change from predevelopment to 1985 conditions is a simulated reduction of about 345 ft^3/s in the base flow of streams and a decrease of about 235 ft^3/s in aquifer storage. The decrease in storage is documented by long-term head declines in wells located in the principal pumping centers in the deep regional aquifers (Barker and Pernik, 1994, plates 6 and 7). A lesser amount of pumpage is supplied by induced leakage from overlying aquifers and reduced diffuse upward leakage to them (fig. 6).

CARBONATE-ROCK AQUIFER SYSTEMS

There are 27 major carbonate-rock terranes in North America (Brahana and others, 1988). Some of the carbonate-rock units are highly permeable and productive aquifers, whereas other units are characterized by low permeability and function, for the most part, as confining units. This wide variation in hydrogeologic characteristics results from the many geologic and hydrologic processes that affect the porosity and permeability of carbonate rocks (Brahana and others, 1988, table 1).

Non-Darcian (conduit) flow occurs in many carbonate-rock terranes, especially through large cavernous openings. However, the volume of rock affected by non-Darcian flow is usually small compared with the total volume of a regional carbonate-aquifer system. A major assumption in applying numerical models to simulate flow in carbonate-rocks is that the flow can be treated as flow through porous media. At the scale of a coarse-mesh regional model (grid-block spacing of a few miles or more), this assumption is considered to be reasonable (Bush and Johnston, 1988, p. 27).

Ground-water budgets are presented in this section for six regional carbonate-aquifer systems. Three of these systems—the Floridan, the Cambrian–Ordovician of the northern Midwest, and the Edwards–Trinity of Texas—are extensively developed and provide public water supplies to major cities. Budgets for predevelopment and recent development conditions are presented for these aquifer systems in figure 8. The other three systems—the Madison aquifer, the Ozark Plateaus aquifer system, and the carbonate-rock province of the Great Basin—were minimally developed (as of the 1980's) and only predevelopment water budgets could be defined during the RASA Program investigations, as shown in figure 9.

CAMBRIAN–ORDOVICIAN AQUIFER SYSTEM OF THE NORTHERN MIDWEST

The Cambrian-Ordovician aquifer system comprises mainly marine sandstone and carbonate rocks that underlie an area of about 161,000 mi^2 in Illinois,

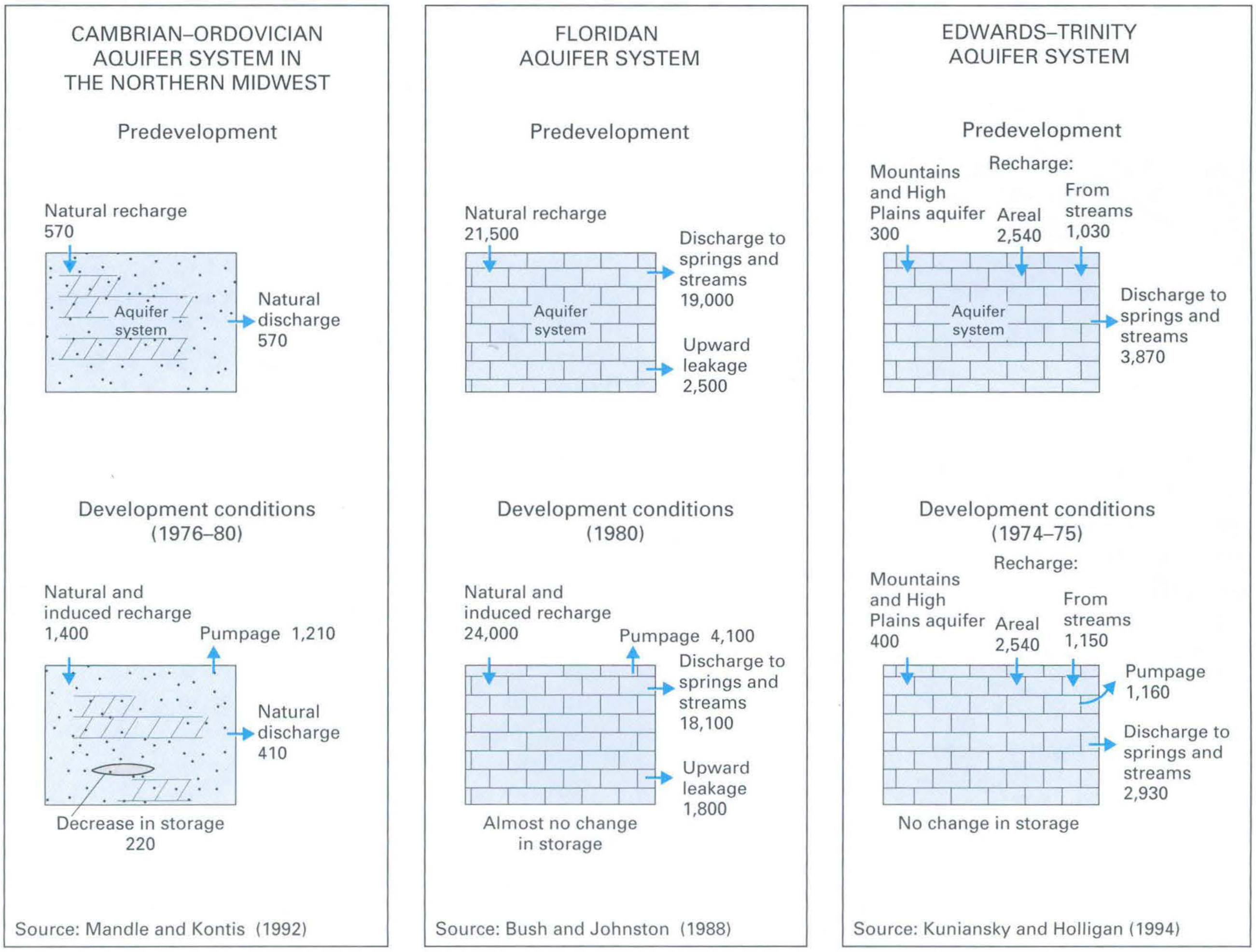


FIGURE 8.—Ground-water budgets before and after development of carbonate-rock aquifer systems in the Midwestern and Southern United States. Values in cubic feet per second. Sum of outflows may not exactly equal sum of inflows as a result of independent rounding.

Indiana, Iowa, Wisconsin, Minnesota, and Missouri (fig. 1). The aquifer system was divided into an upper shale confining unit, three major aquifers (sandstone and dolomite), and two internal confining units (shale, siltstone, and dense dolomite) by Young (1992). Generally, the aquifer system is directly overlain by and hydraulically connected to a Silurian–Devonian aquifer (limestone and dolomite). In much of the area, rocks of Paleozoic-age are covered by a veneer of glacial drift.

Most recharge and discharge in the northern Midwest occurs in local flow systems within the glacial drift. Some water enters the Devonian–Silurian aquifer and the Cambrian–Ordovician aquifer system and moves along intermediate or regional flow paths away from high areas in the north to low areas in the south and east. Principal discharge areas for regional flow are the Mississippi and the Missouri Rivers, the Illinois and the Michigan structural basins, and Lake Michigan. Simulations indicate that the Cambrian and Ordovician rocks constitute a regionally continuous aquifer system because of the similarity of the flow patterns within the aquifers and locations of their recharge and discharge areas (Mandle and Kontis, 1992, p. 95).

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 with hydraulic heads that were more than 100 ft above the water level of Lake Michigan at Chicago, Illinois, and Milwaukee, Wisconsin. By 1980, large-scale pumping had caused the hydraulic heads to decline as much as 375 ft at Milwaukee and 900 ft at Chicago (Young, 1992).

A steady-state simulation of predevelopment conditions and transient simulations of pumping conditions (1861–1980) in the Cambrian–Ordovician aquifer system were made by using a coarse-grid (16-mi grid spacing) finite-difference model (Mandle and Kontis, 1992). The model incorporated an additional computer code to calculate withdrawal rates from individual aquifers tapped by a multiaquifer well.

The predevelopment ground-water budget (fig. 8) indicates that flow through this bedrock aquifer system was comparatively small (570 ft^3/s) considering the large areal extent of the system. The 1976 through 1980 pumpage of 1,210 ft^3/s (782 Mgal/d) is more than double the predevelopment recharge rate. This pumpage was supplied, for the most part, by an increase in recharge into the confined Cambrian–Ordovician aquifer system (830 ft^3/s) from overlying glacial drift and rocks of Cretaceous age and, to a lesser extent, by a decrease in natural discharge to streams (160 ft^3/s) and a release of water from aquifer storage (220 ft^3/s). A detailed simulation of flow in the Cambrian–Ordovician aquifer system in the Chicago–Milwaukee area indicates that recharge to the aquifer system occurs most readily where it subcrops beneath glacial drift (Young, 1992).

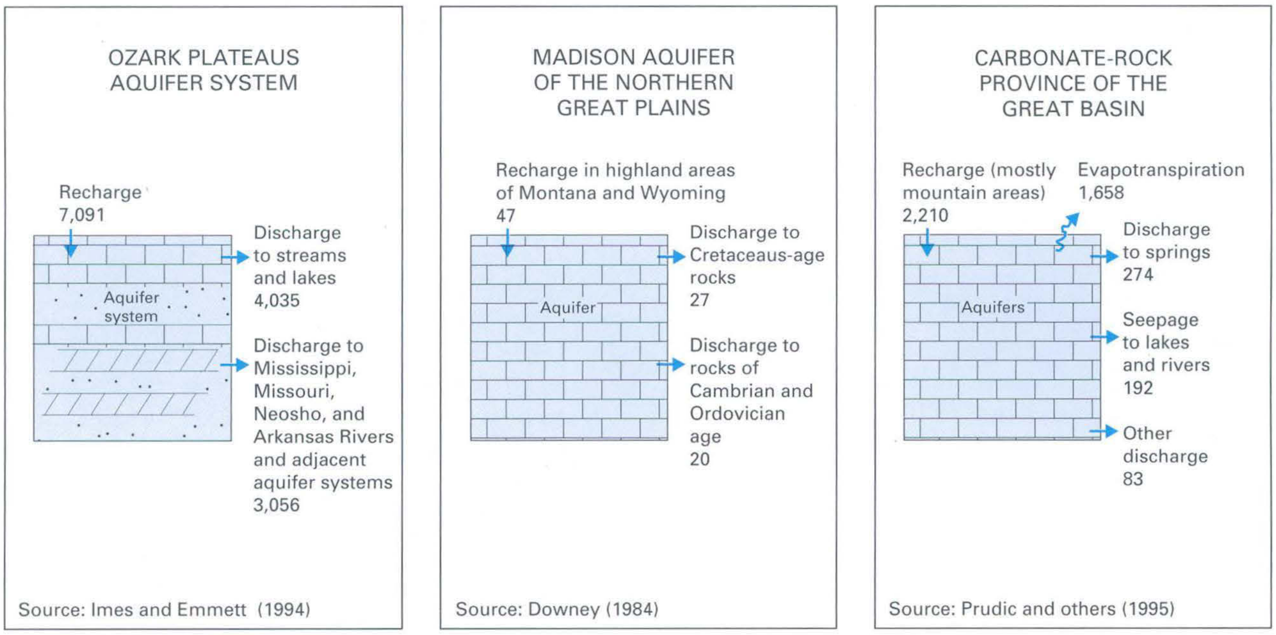


FIGURE 9.—Predevelopment ground-water budgets of carbonate-rock aquifer systems in the Ozark Plateaus, the Northern Great Plains, and the Great Basin. Values in cubic feet per second. Sum of outflows may not exactly equal sum of inflows as a result of independent rounding.

FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system is a thick sequence of hydraulically connected carbonate rocks (limestone and dolomite) that range in age from late Paleocene to early Miocene (Miller, 1986). This highly productive aquifer system underlies an area of about 100,000 mi^2 and includes Florida, most of southern Georgia, and smaller areas of Alabama and South Carolina (fig. 1). The aquifer system generally consists of an upper aquifer and a lower aquifer that are separated by a less permeable confining unit. Transmissivity of the upper aquifer in the Floridan aquifer system ranges from more than 1,000,000 ft^2/d in the unconfined karst areas of central and northern Florida to less than 50,000 ft^2/d in areas where the aquifer is confined by thick clay sections (Bush and Johnston, 1988). Large average rainfall (about 53 in/yr) in conjunction with topography characterized by plains and low hills provides abundant recharge to the Floridan aquifer system.

The distribution of natural recharge, discharge, and flow is strongly influenced by the degree of confinement of the Floridan aquifer system by overlying fine-grained clastic sediments. In the unconfined and semiconfined karst areas of central and northwestern peninsular Florida and southwestern Georgia, recharge rates are large (10–20 in/yr), surface drainage is sparse, and ground water moves along flow paths of intermediate length (generally a few tens of miles) to discharge at large springs or streams (fig. 2*B*). In contrast, in the hilly outcrop areas of central Georgia, where surface drainage is well developed, ground water moves primarily within the sandy hills that overlie the Floridan aqifer system for short distances to streams; only a small fraction of the recharge enters the Floridan aquifer system and moves into the deep confined parts of the aquifer system (Bush and Johnston, 1988). Thus, the simulated ground-water budgets for the Floridan aquifer system (fig. 8) represent virtually 100 percent of the total ground-water flow in the karst areas, but only a small percentage of the total flow in the hilly outcrop areas.

Steady-state simulations of flow in the Floridan aquifer system for predevelopment and 1980 conditions were made by using a coarse-grid finite-difference computer model (table 1). A transient simulation of development conditions was not feasible because the time required for the system to reach a new steady-state condition following a change in pumpage can range from days in highly transmissive semiconfined areas to years in less transmissive, tightly confined areas (Bush and Johnston, 1988, p. 22–25).

The first wells were constructed into the Floridan aquifer system during the late 1880's, and withdrawals, which have increased steadily since then, totaled about 3 Ggal/d by the early 1980's. Pumping caused long-term water-level declines of more than 50 ft in three large areas—coastal Georgia and nearby Florida and South Carolina, west-central Florida, and the western panhandle of Florida. Ancillary effects of pumping include saltwater intrusion in a few coastal areas, induced collapse of sinkholes in karst areas, and a minor amount of land subsidence in one area as a result of the inelastic compaction of fine-grained sediments that overlie the Floridan aquifer system.

Before development, total discharge from the Floridan aqifer system was about 21,500 ft^3/s, of which about 19,000 ft^3/s (88 percent) was discharge to springs and streams, which are mainly in the unconfined and semiconfined areas (fig. 8). Diffuse upward leakage, which occurred mostly in the confined areas, accounted for 2,500 ft^3/s (12 percent) of the predevelopment discharge. Although pumpage had reached 4,100 ft^3/s by 1980, ground-water development has not greatly affected the ground-water budget of the Floridan aquifer system. Simulation of 1980 pumpage indicated that the recharge and discharge rates have increased by only about 2,500 ft^3/s to about 24,000 ft^3/s. Recharge to the Floridan system increased as a result of expansion of the recharge area from about 67,000 mi^2 before development to about 76,000 mi^2 by 1980. About 75 percent of the 1980 Floridan aquifer system discharge was to springs and streams; the remaining 25 percent consisted of pumpage (17 percent) and diffuse upward leakage (8 percent). Pumpage was supplied almost entirely by diversion of natural discharge and induced recharge with almost no loss of water from aquifer storage (Bush and Johnston, 1988).

EDWARDS–TRINITY AQUIFER SYSTEM

The Edwards–Trinity aquifer system underlies an area of about 80,000 mi^2 in central Texas, southeastern Oklahoma, and southwestern Arkansas (fig. 1). However, the area investigated under the RASA Program was limited to about 55,000 mi^2 in west-central Texas, which includes the most productive parts of the aquifer system. The aquifer system comprises three carbonate-rock aquifers of Cretaceous age—the Edwards, the Trinity, and the Edwards–Trinity. The Edwards aquifer comprises mostly fractured and dissolutioned limestone, and regional flow is controlled by a complex pattern of faults. The Edwards aquifer is characterized by large transmissivity (200,000–2,000,000 ft^2/d) and the capacity to accept large quantities of recharge during wet periods (Maclay and Small, 1986). Because of these factors, no long-term loss of water from storage as a result of ground-water withdrawals has occurred in the Edwards aquifer. In contrast, the Trinity and the

Edwards–Trinity aquifers comprise less permeable carbonate and clastic rocks, and transmissivities generally are less than 10,000 ft^2/d.

During the late 1980's, an estimated 1,650 ft^3/s was withdrawn from the Edwards–Trinity aquifer system for all uses. Almost one-half of this pumpage, which was primarily for municipal and industrial uses in the San Antonio metropolitan area (which is about 3 percent of the aquifer system area), was from the Edwards aquifer.

Simulation of regional flow in the Edwards–Trinity aquifer system is complicated by the large areal variation of fracturing and dissolution of the carbonate rocks and the areal distribution of pumping. The finite-element method was chosen for the flow simulations because of the ability to vary areally the direction of anisotropy and because of the flexibility in designing an irregularly spaced mesh of elements (Kuniansky and Holligan, 1994). Steady-state simulations were completed for predevelopment conditions and for pumping conditions during winter 1974–75 (selected because of the availability of an accurate regional potentiometric surface map).

Simulations indicate that total flow through the aquifer system is similar for predevelopment and 1974–75 development conditions—about 4,000 ft^3/s. However, the distribution of discharge has changed (fig. 8). Most of the pumpage (1,160 ft^3/s) is now supplied by a reduction of natural discharge to streams and springs rather than by induced recharge. Discharge to streams after development has been 20 percent less than the predevelopment discharge; springflow following development has been 30 percent less than the predevelopment spring discharge (Kuniansky and Holligan, 1994). The discharges of several major springs that discharge from the aquifer have been reduced or eliminated as a result of ground-water pumpage.

OZARK PLATEAUS AQUIFER SYSTEM

The Ozark Plateaus aquifer system comprises carbonate and clastic rocks of Paleozoic age that contain mostly freshwater and are surrounded by rocks that contain mostly saline water. The areal extent of the aquifer system is about 65,000 mi^2; it underlies most of northwestern Arkansas and southern Missouri and adjacent areas of Kansas and Oklahoma (fig. 1). The aquifer system has been subdivided into three regional aquifers and two confining units (Imes and Emmett, 1994). Locally, a well-developed, near-surface karst terrane has developed where the carbonate rocks crop out, and discharge to springs is substantial within the karst areas.

Although about 25 percent of the precipitation (36-50 in/yr) infiltrates to the water table, only about 6 percent of the precipitation (about 7,000 ft^3/s) is inflow to the regional ground-water flow regime. Most ground-water recharge discharges as local flow to nearby streams and springs. Differentiation between local and regional flows was made on the basis of stream base flows and topography (Imes and Emmett, 1994). Withdrawals of ground water are small (about 320 ft^3/s from 1970 through 1979) compared with the rates of natural recharge and discharge. Although water levels have declined at several pumping centers, regional decline of heads is not apparent in the aquifer system.

A very coarse mesh (14-mi grid spacing) finite-difference model was used for steady-state simulations of regional flow in the Ozark Plateaus aquifer system before development (table 1). Because recent withdrawal rates are small compared with the large rates of natural recharge and discharge, Imes and Emmett (1994, p. 116) concluded, "the predevelopment regional ground-water budget of the Ozark Plateaus aquifer system is probably similar to the present-day regional budget." Simulation indicates that predevelopment recharge was about 7,000 ft^3/s. About 4,000 ft^3/s discharged to streams and springs; about 3,000 ft^3/s discharged to major rivers located along the boundary of the aquifer system and to adjacent aquifer systems (fig. 9). Simulated flow from the Ozark Plateau aquifer system into the Mississippi Embayment aquifer system (located to the southeast) is substantial (about 880 ft^3/s), according to Imes and Emmett (1994, p. 116).

MADISON AQUIFER OF THE NORTHERN GREAT PLAINS

The northern Great Plains of Montana, Wyoming, and North and South Dakota are underlain by a thick sequence of Paleozoic and Mesozoic sedimentary rocks that contain five regionally extensive, deep, confined aquifers (Downey, 1986). One of these aquifers—the Madison—was the subject of a 5-year intensive investigation to evaluate the water-supply potential for possible development of coal reserves. The brief discussion of the Madison aquifer presented in this report is included as an example of a deep confined aquifer characterized by limited recharge, little development (as of the late 1970's), and generally sluggish regional flow.

The Madison aquifer comprises Mississippian marine carbonate rocks (limestone and dolomite) and evaporites. The aquifer underlies an area of about 210,000 mi^2 in parts of Montana, Wyoming, and North and South Dakota (fig. 1); in addition, it underlies a considerable area in the Canadian Provinces of Manitoba and Saskatchewan. The Madison aquifer crops out only in the western recharge areas (the highlands of Montana and Wyoming and the Black Hills of South Dakota). The outcrop areas are characterized by development of karst features that include enlarged joints, caves, and sinkholes. The general pattern of predevelopment flow in the Madison aquifer is recharge from precipitation in the highland areas of Montana, Wyoming, and South Dakota; regional flow to the northeast and east; and discharge by leakage to Cretaceous rocks in eastern South Dakota and by leakage to Cambrian and Ordovician rocks in Manitoba (Downey, 1984; p. 28–35, figs. 39, 41). A large part of the recharge water is discharged from springs and seeps within the highland areas after moving only a short distance in the aquifer. The remaining fraction of the recharge water enters the regional flow system and moves along flow paths that extend up to 600 mi in length.

Steady-state simulations of regional predevelopment (before 1950) flow were completed for the Madison aquifer by using two very large finite-difference flow models with variable grid spacing. The initial model simulated flow in the Madison aquifer and an underlying Cambrian–Ordovician aquifer (Downey, 1984); a later expanded model simulated flow in the full sequence of Paleozoic and Mesozoic rocks, which include the Madison aquifer and four other regional aquifers in the Northern Great Plains (Downey, 1986). Flow of water of variable density was simulated by using a computer code by Weiss (1982) and estimates of fluid density calculated from field measurements of fluid temperature, pressure, and dissolved solids content. Both flow models indicated that regional flow through the Madison aquifer is only 47 ft^3/s (fig. 9). Discharge was about 27 ft^3/s to rocks of Early Cretaceous age in the Dakotas and about 20 ft^3/s to rocks of Cambrian and Ordovician age in Manitoba, Canada. Regional flow velocities generally are small—less than 20 ft/yr in most of the area underlain by the Madison aquifer and less than 2 ft/yr in much of Wyoming and in the deep Williston Basin of North Dakota (Downey, 1984). A body of brine occurs in the Williston Basin that impedes regional flow, and much of the freshwater flow through the basin is apparently deflected around the brine or leaks into overlying aquifers.

CARBONATE-ROCK PROVINCE OF THE GREAT BASIN

The carbonate-rock province of the Great Basin is an area of about 100,000 mi^2 that encompasses eastern Nevada, western Utah, and adjacent areas in Arizona, California, and Idaho (fig. 1). The climate of the province generally is arid to semiarid; however, the precipitation is highly variable and ranges from less than 3 in/yr in some desert valleys to more than 60 in/yr in the higher mountain ranges. The province is characterized by a complex ground-water system made up of shallow basin-fill deposits underlain by permeable Paleozoic carbonate rocks (Prudic and others, 1995). Evidence for deep widespread interbasin flow through carbonate-rock aquifers has been presented by many workers (see, for example, Winograd and Thordarson, 1975).

Prudic and others (1995) conceptualized ground-water flow in the province as consisting of "relatively shallow flow primarily through basin-fill deposits and adjacent mountain ranges superimposed over deeper flow through primarily carbonate rocks." Regional ground-water flow in the province was simulated by using a coarse-grid, two-layer, finite-difference model (table 1). The upper model layer was used to simulate flow through the basin fill, and the lower layer, to simulate deep flow through the underlying carbonate rocks (beneath mountain ranges and basin fill). All simulations were for steady-state predevelopment conditions. Simulations suggested that flow in the carbonate rocks could be subdivided into five deep-flow regions and that flow in the basin fill occurs in 17 shallow-flow regions that generally coincide with shallow-flow systems, which were defined on the basis of topography, water levels, discharge areas, and water budgets (Prudic and others, 1995). Simulated predevelopment recharge to and discharge from the five deep-flow regions total about 2,200 ft^3/s (fig. 9). Recharge that ultimately reaches the deep-flow system occurred primarily in the mountain ranges and was about 3 percent of the total precipitation. About 75 percent of the discharge from the five deep-flow regions occurred as evapotranspiration before reaching terminal sinks. The simulated values of recharge and discharge given in figure 9 should be considered highly approximate, as noted by Prudic and others (1995), because amounts of recharge and discharge are only approximately known, water-level data are not available for many parts of the modeled area, and several simplifying assumptions were made in designing the simulation model.

CLASTIC-ROCK AQUIFER SYSTEMS OF THE CENTRAL AND THE WESTERN UNITED STATES

The clastic-rock aquifer systems of the Central and the Western United States include the two most intensely pumped ground-water systems in the Nation—the High Plains aquifer and the California Central Valley aquifer system. The combination of very large ground-water withdrawals and large return flows from irrigation (which is supplied by ground-water pumpage in the High Plains aquifer and largely by imported surface water in the California Central Valley aquifer system) has altered regional flow and dramatically changed the water budgets of both aquifer systems. Although withdrawals from the Great Plains aquifer system have been small, the water budget also has changed considerably as a result of development.

GREAT PLAINS AQUIFER SYSTEM (DAKOTA SANDSTONE AND ASSOCIATED UNITS)

The Great Plains aquifer system comprises mostly sandstone and shale of early Cretaceous age (Helgeson and others, 1993). These clastic rocks occur throughout the Great Plains of North America. However, the hydrologic investigation of the aquifer system conducted under the RASA Program was limited to an area of about 170,000 mi^2 in the central Great Plains (fig. 1). Helgeson and others (1993) defined the aquifer system as comprising three regional geohydrologic units—the Apishapa aquifer (Cheyenne Sandstone and equivalents), the Apishapa confining unit (Kiowa Shale and equivalents), and the Maha aquifer (Dakota Sandstone and equivalents). The aquifer system was recognized by Darton (1905) as being a major artesian reservoir characterized by a regional flow system that extends several hundred miles from west to east in the "Dakota water horizons."

Confined conditions occur throughout most of the aquifer system, and much of the ground water is brackish. Regional flow is generally from west to east. Water is transmitted very slowly through the aquifer system; water in the deeply buried parts of the system is virtually stagnant except in terms of geologic time (Helgeson and others, 1993).

Regional flow was simulated by using a very coarse mesh (14-mi grid spacing), four-layer, finite-difference flow model (table 1). Simulation of steady-state conditions before development indicate that the natural recharge to and discharge from this very large aquifer system was only 340 ft^3/s, as shown in figure 10.

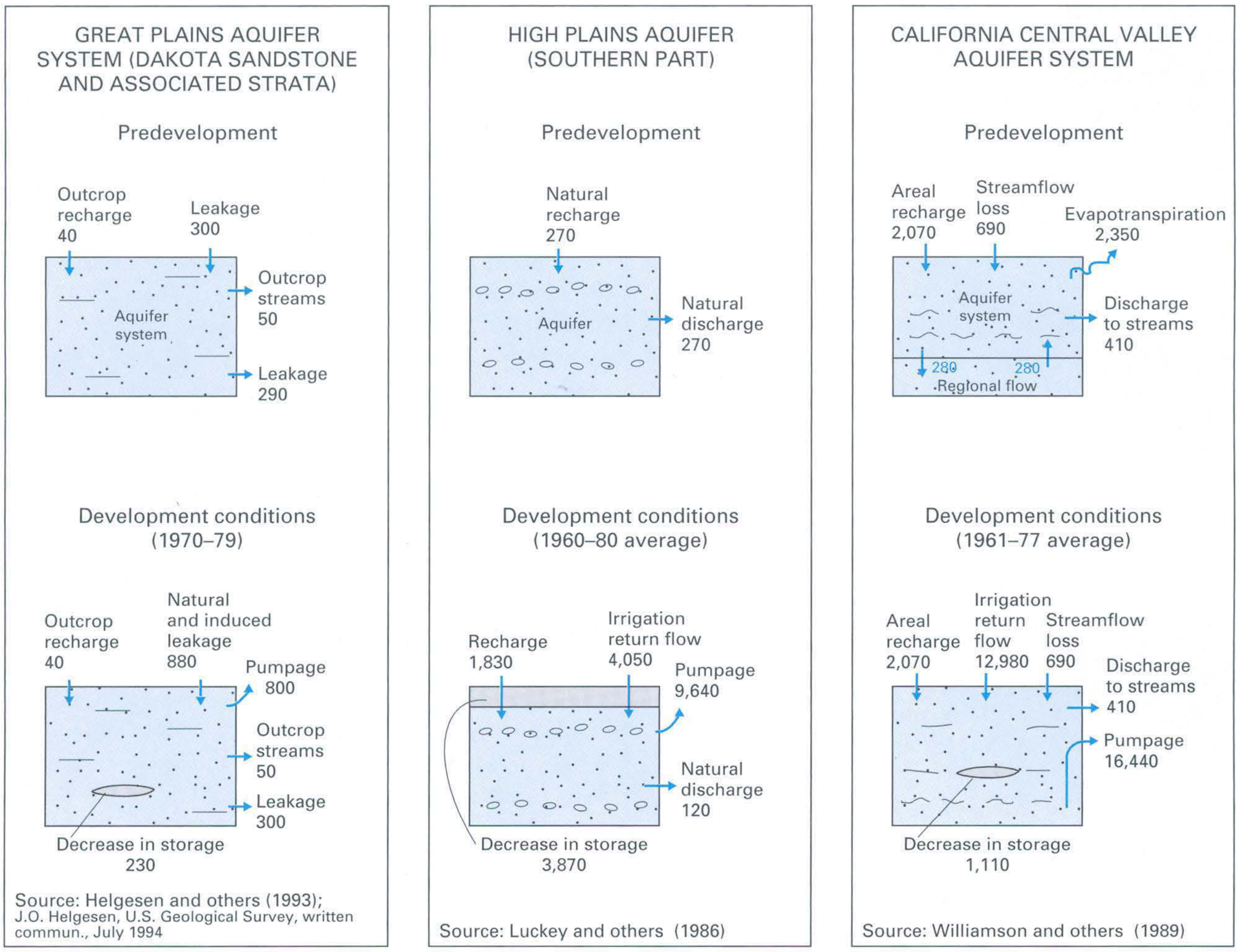


FIGURE 10.—Ground-water budgets before and after development of clastic-rock aquifer systems in the Central and the Western United States. Values in cubic feet per second. Sum of outflows may not exactly equal sum of inflows as a result of independent rounding.

Recharge occurred mostly as vertical leakage from overlying units rather than directly in the outcrop areas of the aquifer system. The low rate of outcrop recharge (40 ft^3/s) is due to the small extent of the outcrop areas (less than 5 percent of the aquifer system areally), the small hydraulic conductivity of the aquifer system in outcrop areas, and faulting, which offsets the aquifer system in outcrop areas and cuts off recharge and lateral flow downgradient (Helgeson and others, 1993). Predevelopment discharge occurred mostly as vertical leakage to rock units that underlie and overlie the aquifer system and, to a lesser extent, as discharge to streams or as evapotranspiration or spring flow in outcrop areas.

Fresh ground water is withdrawn from the upper 1,000 ft of the system, and oil and gas is withdrawn from the system below 3,000 ft. Transient simulations of development conditions were completed for four 10-year periods from 1940 through 1979. For simulation of 1970 through 1979 conditions, an average withdrawal rate of 800 ft^3/s was specified in the model; this is more than twice the predevelopment recharge rate. As shown in figure 10, about 70 percent of the pumpage is supplied by an increase in leakage, primarily from overlying units. Helgeson and others (1993) stated that the rate of adjustment to pumpage was extremely slow and that storage depletion was probably substantial. They further explained that leakage is readily induced where the aquifer system is in direct contact with the overlying High Plains aquifer and that storage loss is minimized if leakage continues. However, where pumping has lowered heads in the High Plains aquifer (described in the following section), upward leakage from the Great Plains aquifer system has increased. For this reason, leakage out of the Great Plains aquifer system is slightly greater for 1970 through 1979 conditions than for predevelopment conditions (fig. 10).

HIGH PLAINS AQUIFER

The High Plains aquifer is a regionally extensive water-table aquifer that comprises mostly near-surface sand and gravel deposits of late Tertiary and Quaternary age (Gutentag and others, 1984). The aquifer underlies 174,000 mi^2 of the Central United States, (fig. 1). Rainfall is moderate in this area (16–28 in/yr), and estimated recharge rates vary from 0.02 in/yr in Texas to 6 in/yr in south-central Kansas. Regional ground-water flow is generally from west to east at a rate of about 1 ft/d.

The High Plains aquifer is the most intensely pumped ground-water system in the United States. Pumpage is principally for irrigation; during 1980, about 170,000 wells pumped about 25,000 ft^3/s. This pumpage has resulted in widespread ground-water-level declines, particularly in the southern High Plains. The saturated thickness of the High Plains aquifer has decreased by more than 25 percent in an area of 14,000 mi^2, which is mostly in the High Plains of Texas and western Kansas. As a result, declining well yields have caused a decrease in the average number of acres irrigated per well (Weeks and others, 1988).

Simulations of steady-state conditions before development and transient simulations of the 1940 through 1980 pumping conditions in the High Plains aquifer were made by using three coarse-mesh (10-mi grid spacing) finite-difference models, as described by Luckey and others (1986). Two-dimensional models were used because on a regional scale, vertical flow components were considered to be small enough to be neglected. The three models simulated flow in the aquifer in the southern High Plains (area south of about latitude 35°N), the central High Plains (area between latitude 35°N and 39°N), and the northern High Plains (area north of latitude 39°N). Only the simulated ground-water budgets for the southern High Plains (where the impacts of development have been greatest) will be discussed here.

Under natural conditions, evapotranspiration demand is much greater than precipitation, and there is little or no recharge to the High Plains aquifer except in sandy soils with large infiltration rates, high permeability, and low field capacity (Weeks and others, 1988). Simulation indicates that the total recharge before development in the southern High Plains was only 270 ft^3/s (fig. 10).

Withdrawals from the aquifer in the southern High Plains, which includes 29,000 mi^2 in eastern New Mexico and the western Panhandle of Texas (fig. 1), totaled about 140 million acre-ft (9,600 ft^3/s) from 1960 through 1980. As a result of this large withdrawal, the water budgets for the aquifer in the southern High Plains are radically different for predevelopment and 1960 through 1980 conditions (fig. 10). The contrast between the predevelopment and the development ground-water budgets for the southern High Plains aquifer is probably greater than any other major aquifer in the United States. Note that the 1960 through 1980 average pumpage exceeds natural recharge by more than 35 times, and depletion of aquifer storage occurs at a rate that is about 14 times greater than that of natural recharge. Most inflow to the aquifer from 1960 through 1980 was return flow from irrigation (Luckey and others, 1986).

CALIFORNIA CENTRAL VALLEY AQUIFER SYSTEM

The California Central Valley aquifer system comprises mostly continental deposits (lenses of gravel, sand, silt, clay) of post-Eocene age (Bertoldi and others, 1991). The aquifer system is in a long, narrow, structural trough that occupies about 20,000 mi^2 of flatland between the Sierra Nevada and the coast ranges of California (fig. 1). Before the RASA study, investigators generally described the deposits in the northern part—the Sacramento Valley—as a water-table aquifer and those in the southern part—San Joaquin Valley—as consisting of two aquifers separated by a regional clay confining unit. However, Williamson and others (1989) suggested a new concept in which all continental deposits constitute one aquifer system characterized by varying vertical leakance and confinement that depend on the proportion of fine-grained sediments.

The climate in the Central Valley is a Mediterranean type with precipitation that ranges from 13 to 26 in/yr in the Sacramento Valley and from 5 to 16 in/yr in the San Joaquin Valley. Recharge is from rainfall on the valley floor and infiltration of streamflow that enters the Central Valley from the Sierra Nevada and the Klamath Mountains.

Ground-water pumpage for irrigation, which began about 1880, increased dramatically during the 1940's and 1950's. During the 1960's and 1970's, withdrawals from wells averaged about 16,440 ft^3/s (11.5 million acre-ft/yr) and provided about one-half of the water for irrigation (Williamson and others, 1989). The large withdrawals caused water levels to decline more than 400 ft in the southern and western parts of the San Joaquin Valley. Since the drought of 1976–77, surface-water imports have increased, ground-water pumpage has decreased, and local ground-water levels have recovered (Bertoldi and others, 1991).

Computer simulations of regional flow in the Central Valley aquifer system before and after development used a coarse-mesh (6-mi grid spacing), multilayer, finite-difference model, as described by Williamson and others (1989). Initially, the model was calibrated for transient conditions with hydrologic data observed from 1961 through 1975; later, steady-state simulations of predevelopment conditions and transient simulations of pumping conditions from 1961 through 1977 were completed. The computer program of Trescott (1975) was modified to simulate the effects of land subsidence as a result of inelastic compaction of clays by using a procedure described by Meyer and Carr (1979).

Simulation of predevelopment conditions indicated that areal recharge from precipitation provided about 75 percent of predevelopment recharge (fig. 10). Seepage from stream channels (mostly along the upper reaches of large streams that enter the valley from surrounding mountains) provided about 25 percent of the predevelopment recharge. Simulated percolation to the deep regional ground-water flow regime was slightly more than 10 percent of total recharge (Williamson and others, 1989).

Development of ground water involved the construction of about 100,000 irrigation wells in the Central Valley; many of these wells have long intervals of perforated casing that provide hydraulic connection between permeable zones within the aquifer system. Simulations described by Williamson and others (1989) suggest that the average vertical leakage of the aquifer system was effectively increased by an order of magnitude as a result of to the hydraulic connection provided by the multizone wells. Consequently, the comparisons of predevelopment and development conditions presented here, are for the entire ground-water flow regime, not simply the deep regional flow regime.

The combination of large ground-water withdrawals and large imports of surface water for irrigation has completely changed the ground-water budget of the Central Valley aquifer system. Figure 10 shows that the average recharge rate for the 1961 through 1977 development period is nearly six times larger than the predevelopment recharge rate. Of the total recharge (15,740 ft^3/s), most (12,980 ft^3/s) is irrigation return flow; the recharge rates from precipitation and streamflow have not changed. Nearly all ground-water discharge is from pumping wells under development conditions. During the 1961 through 1977 period, depletion of storage in the aquifer system occurred at a rate equivalent to about 40 percent of the rate of natural recharge, and about 7 percent of the pumpage was being supplied from water in storage. The decrease in aquifer system storage during the 1961 through 1977 period (about 1,100 ft^3/s) was due to water released from inelastic compaction of fine-grained sediments (57 percent) and decline of the water table (43 percent). However, during the early 1980's, ground-water pumpage decreased, water-levels rose in many areas, and depletion of ground water in storage virtually stopped (Bertoldi and others, 1991). The principal effects of development on the ground-water flow system, as described by Williamson and others (1989), can be summarized as follows:

- Before development, ground water flowed toward the axial part of the Central Valley and discharged as evapotranspiration from marshes that formerly existed there. By the 1970's, ground-water flow was mostly from areas recharged by imported surface water toward areas of wells pumped for irrigation.
- After development, most ground-water discharge is from pumping wells rather than from evapotranspiration or discharge to streams.
- From the start of development until 1977, an estimated 60 million acre-ft of aquifer storage had been lost.
- In the western and southern parts of the San Joaquin

Valley, the large decline of hydraulic head caused inelastic compaction of fine-grained sediments, which resulted in land subsidence that is unequaled anywhere else in the world. About 5,000 mi^2 of the Valley has undergone subsidence of more than 1 ft, and, at one location, subsidence is nearly 30 ft.

BASALTIC-ROCK AQUIFER SYSTEMS OF THE PACIFIC NORTHWEST

A thick sequence of Tertiary and Quaternary volcanic rocks underlies an area of about 140,000 mi^2 in parts of Washington, Oregon, Idaho, California, and Nevada. The name "Columbia Lava Plateau" was applied to this area by Heath (1984) in his classification of the ground-water regions of the United States. Two extensive basalt units, the Columbia River Basalt Group and the Snake River Group, occur throughout nearly one-half of the Columbia Lava Plateau. For investigation under the RASA Program, the two basalt units and associated Quaternary and Tertiary sedimentary rocks were designated as the "Columbia Plateau aquifer system" and the "Snake River Plain aquifer system" (fig. 1). These two basaltic-rock aquifer systems are characterized by very high transmissivity and yield large quantities of good-quality water (Lindholm and Vaccaro, 1988). Water development has been primarily for irrigation in both aquifer systems, and development has proceeded in similar manner—surface-water diversions first and ground-water withdrawals later.

SNAKE RIVER PLAIN AQUIFER SYSTEM

The Snake River Plain occupies an area of about 15,600 mi^2 in southern Idaho and easternmost Oregon (fig. 1). For study purposes under the RASA Program, the Snake River Plain was divided into eastern and western parts on the basis of geology and hydrology. The eastern plain (10,800 mi^2) is a downwarp filled mostly with Quaternary basalt; the western plain (4,800 mi^2) is a graben filled predominantly with fine-grained Tertiary and Quaternary sedimentary rocks (Lindholm, 1996). The discussion here is limited to the aquifer system that underlies the eastern plain.

The thickness of the basaltic-rock aquifer system in the eastern plain is largely unknown; however, it is estimated to be as much as 5,000 ft; a maximum of 3,500 ft may be saturated (Lindholm, 1996). Individual lava flows average about 20 ft in thickness. The fractured, rubbly tops of individual flows typically are very porous and permeable. Simulation and pumping tests suggest that the transmissivity of the Quaternary basatlic-rock aquifer system ranges from about 4,000 to 10,000,000 ft^3/d (Garabedian, 1992).

The regional ground-water flow system in the eastern plain was simulated in two steps—initially, a two-dimensional steady-state model that included a nonlinear least-squares regression technique was used to estimate aquifer properties, and later, a three-dimensional model was developed for simulating steady-state and transient conditions. Calibration consisted of comparing measured changes in water-levels and ground-water discharges with simulated values (Garabedian, 1992). This model was designed with four active layers and a moderately coarse mesh (4-mi grid spacing). The model was used to simulate transient development conditions from 1891 through 1980 (involving eighteen 5-year stress periods). The predevelopment budget described here is for 1891 through 1895, which is before the development of ground water but after the diversion of surface water for irrigation had begun.

Use of surface water for irrigation began in the Snake River Plain during the 1880's and initially caused an increase in ground-water recharge as a result of percolation of excess applied water (Lindholm, 1996). The period from the 1890's to the early 1950's was characterized by accretion of ground-water storage. Since 1950, the use of ground water for irrigation has increased greatly, and the rate of depletion has generally been higher than that of accretion of storage (Garabedian, 1992). The recent loss of storage has been attributed to several factors, which include decreased use of surface water for irrigation, increased pumpage of ground water, conversion from flood to sprinkler irrigation, and the occurrence of dry years during which ground-water pumpage increased and recharge from surface water decreased.

The ground-water budget for the aquifer system in the eastern Snake River Plain has changed markedly since the late 1800's as a result of imports of surface water for irrigation and increased pumpage from wells as shown in figure 11. During the early 1890's, most recharge was supplied by losses from the Snake River and by losses of streamflow and ground-water underflow from tributary basins to the Snake River Plain. Most of the northern tributary streams lost their flow to basalt aquifers within a short distance after entering the plain (Lindholm and Vaccaro, 1988). The remainder of the recharge was derived from precipitation on the plain and by percolation of excess irrigation water from surface-water sources (fig. 11). All natural discharge from the aquifer system primarily as spring flow, was to the Snake River. Along a 90-mi reach of the Snake River, 11 springs have discharges of more than 100 ft^3/s (Lindholm and Vaccaro, 1988).

As a result of irrigation practices, recharge to the aquifer system in the Eastern Snake River Plain increased about 50 percent by 1980 (fig. 11). All the

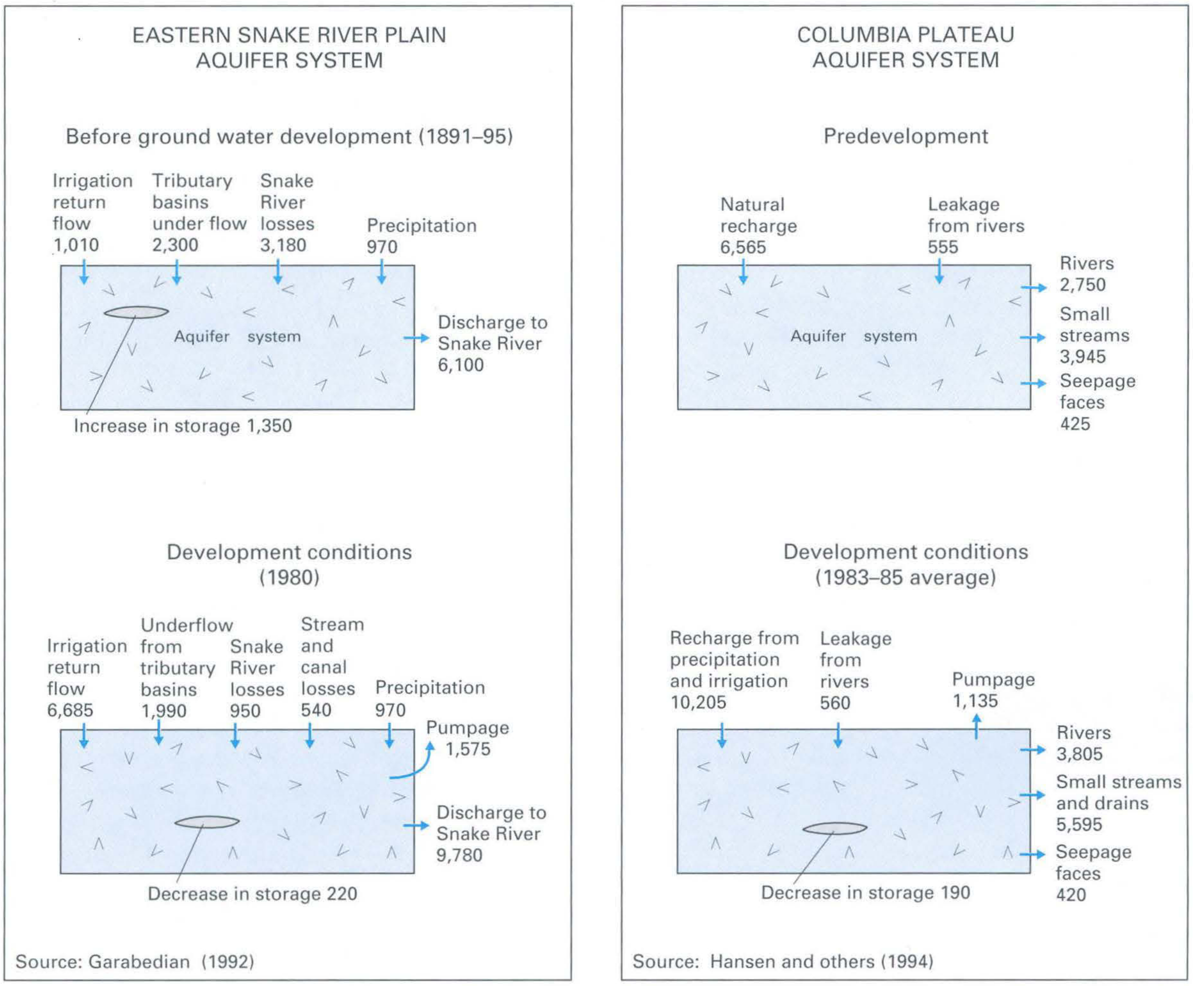


FIGURE 11.—Ground-water budgets before and after development of basaltic-rock aquifer systems in the Pacific Northwest. Values in cubic feet per second. Sum of outflows may not exactly equal sum of inflows as a result of independent rounding.

additional recharge was derived from percolation of excess irrigation water. Net ground-water pumpage in 1980 was 1,570 ft^3/s (1.1 million acre-ft/yr), or about 14 percent of the total ground-water discharge. The decrease in aquifer storage (220 ft^3/s) represents about 2 percent of the total 1980 ground-water budget.

COLUMBIA PLATEAU AQUIFER SYSTEM

The Columbia Plateau aquifer system underlies an area of about 50,600 mi^2 in Washington and Oregon and adjacent areas of Idaho (fig. 1). The aquifer system comprises mostly Miocene basalt flows of the Columbia River Basalt Group, which has a maximum thickness of 16,000 ft near the center of the plateau (Hansen and others, 1994). The basalts and interbedded sediments were divided into several units for regional analysis—three basalt aquifers (Saddle Mountains, Wanapum, Grande Ronde) and two confining units. Overlying the basalt flows in the central and western parts of the Plateau are unconsolidated sedimentary rocks of Miocene to Quaternary age, that are known as the Overburden aquifer, and that also are part of the aquifer system (fig. 2). Mean annual precipitation varies throughout the plateau according to the land-surface altitude and ranges from 6 in. in the central lowlands to more than 45 in. in the surrounding mountains.

In 1984, ground-water withdrawals which exclude domestic and stock uses, were about 1,140 ft^3/s from an estimated 3,500 large capacity wells. Of the total pumpage, 75 percent was from the three basalt aquifers (fig. 2), and 25 percent was from the Overburden aquifer (Hansen and others, 1994). Nearly 90 percent of the pumpage was used to irrigate about 500,000 acres of cropland. Irrigation with surface water is practiced in a larger area, and return flow from excess applied irrigation water has significantly increased ground-water recharge (Hansen and others, 1994).

Ground-water flow was simulated throughout a 32,700-mi^2 area of the Columbia Plateau by using a finite-difference model with five active layers and 8,500- by 15,000-ft grid cells. Because of the small cell size (compared with other regional flow models listed in table 1), local flow, as well as regional and intermediate flows, could be simulated in this model. Most of the local flow occurs in the upland areas and the Overburden aquifer (fig. 2). Simulations of steady-state flow in the aquifer system were made for predevelopment and recent pumping conditions. The model was calibrated to average hydrologic conditions for the period from spring 1983 to spring 1985; after accounting for the change in storage (190 ft^3/s) during this period, the model was considered to approximate steady-state conditions (Hansen and others, 1994).

Before development, recharge to and discharge from the aquifer system totaled about 7,120 ft^3/s (fig. 11). Water development, which included pumping from wells beneath irrigated areas and irrigation with surface water withdrawn from dammed rivers, has caused flow through the aquifer system to increase more than 50 percent—from about 7,120 ft^3/s to nearly 10,800 ft^3/s. The increase in recharge (about 3,640 ft^3/s) is mostly return flow from surface-water-supplied irrigation. Rises of ground-water levels have been more widespread than declines because the area irrigated with surface water is larger than that irrigated with ground water (Hansen and others, 1994). Vertical flow through the basalt units in the aquifer system has been enhanced because most of the wells are uncased below the top of the basalt and, thus, are open to all units penetrated (Hansen and others, 1994).

SOURCES OF WATER SUPPLYING PUMPAGE FROM REGIONAL AQUIFER SYSTEMS

The response of an aquifer to withdrawals from wells was succinctly explained by Theis (1940). He noted that the following essential factors control aquifer response: the character of the recharge and its distance from pumping wells, the distance to the localities of natural discharge, and the character of the cones of depression, which are dependent on the rate and length of pumping and hydraulic properties of the aquifer and its confining units, surrounding the pumped wells. Theis further explained that all water withdrawn from wells is balanced by a loss of water somewhere. To some extent, this loss is from storage in the aquifer and also can include an increase in recharge (if recharge was previously rejected) and a decrease in natural discharge.

Theis' concepts were presented in the following equation (Lohman, 1972, p. 63):

$$R + \Delta R = D + \Delta D + q + S\frac{\Delta h}{\Delta t}$$

where R = recharge rate per unit area,
ΔR = change in recharge rate per unit area,
D = natural discharge rate per unit area,
ΔD = change in discharge rate per unit area,
q = rate of withdrawal from wells per unit area, and
$S\frac{\Delta h}{\Delta t}$ = rate of change in storage per unit area (equal to 0 under steady-state conditions).

The mechanisms by which a change in recharge is caused by pumping from wells require some explanation. Total ground-water recharge in a region is rarely, if ever, increased except by artificial means, such as importation of water for irrigation, removal of native vegetation, or removal of low-permeability soils that impede recharge. However, flow of water into the deeper confined parts of aquifers can be increased during development by the following mechanisms:

- Capture of local ground-water flow that would naturally discharge in the outcrop or shallow subcrop areas of a regional aquifer and diversion of that flow into the deeper parts of the aquifer. This can occur when cones of depression that are created by pumping from wells completed in a confined aquifer extend into its outcrop or subcrop area. The resulting transfer of ground water from local to intermediate or regional flow systems has occurred to some extent in the aquifer systems in humid areas that are discussed in this report.
- Vertical leakage across confining units that overlie or underlie a pumped confined aquifer. This mechanism is potentially a major source of water where the size of outcrop or subcrop areas is small compared with areal extent of a confined aquifer. The importance of this mechanism was demonstrated by simulations of flow in the Gulf Coastal Plain aquifer systems [see previous discussion of this aquifer system; Williamson (in press)].
- Infiltration of excess water applied on irrigated lands and percolation into the deeper parts of an aquifer. Where the irrigation source is imported surface water, this process is a major source of new recharge. Where ground water is used for irrigation, the process is simply recirculation. Percolation of excess applied irrigation water is a major component of the ground-water budgets of the heavily pumped California Central Valley aquifer system (surface and ground water) and the High Plains aquifer (mostly ground water) (fig. 10).

The decrease in natural discharge as a result of ground-water withdrawals has been documented for a few aquifer systems by long-term records of springflow or stream discharge (see, for example, the discussion of the Edwards–Trinity aquifer system and fig. 8). However, if the decrease in natural discharge consists mostly of diffuse upward leakage from confined aquifers, then it cannot be confirmed by field measurements—it can be only estimated from simulation results. Note that the capture of "local flow" and diversion into deep confined aquifers could be considered to be either an increase in recharge or a decrease in natural discharge. Where the flow of small streams in aquifer outcrop areas decreases, many hydrologists would refer to this as an increase in recharge owing to capture of previously rejected recharge [following the principles of Theis (1940)]. Where simulation indicates a reduction in diffuse upward leakage, most hydrologists would probably call this a decrease in discharge.

Pumping from wells always results in some loss of water from storage in the aquifer system, as noted by Theis (1940). The largest decreases in storage owing to pumping have occurred in the southern High Plains aquifer and the California Central Valley aquifer system, both of which are located in arid to semiarid areas of the Western United States (fig. 10). In the High Plains aquifer, water-table declines caused by pumping have decreased the saturated thickness of the aquifer by more than 25 percent in more than one quarter of the High Plains of New Mexico and Texas (Weeks and others, 1988). The total volume of storage loss in the aquifer was estimated to be 160 million acre-ft as of 1980. In the California Central Valley, large head declines that resulted from pumping have caused inelastic compaction of fine-grained sediments and the largest volume of land subsidence in the world. Long term field measurements indicate that loss of storage in the Central Valley aquifer system was an estimated 60 million acre-ft by the late 1970's (Williamson and others, 1989).

The sources of water that supply pumpage from 11 of the 14 regional aquifer systems discussed in this report are summarized in table 3. The amount of water supplied by each source (induced downward percolation and leakage, infiltration of excess irrigation water, reduction of natural discharge, loss of aquifer storage) is based on differences between flow rates in the predevelopment and development hydrologic budgets of the aquifer systems (figs. 6, 8–11).

Figure 12 shows the sources of water as percentages withdrawn from the aquifer systems after development. The percentages from each source are for the times, pumping rates, and locations of pumping from the most recent simulation described in the references given in table 3. If pumping were to continue indefinitely at the rates and location used in the most recent simulations, then the quantity of water supplied from storage would approach zero. The source of water pumped would then be a combination of recharge and (or) leakage and a decrease in natural discharge that is different from the proportions shown in figure 12.

Several factors affect the percentage contributed by the three sources indicated on figure 12 as follows:

- Most of the 11 aquifer systems have been characterized by steadily increasing withdrawals during recent years. In turn, this has caused the percentage contribution from the sources to change, which depends on the timing and locations of the pumpage increase. As an example, figure 7 shows changes in simulated ground-water budget components as pumpage from the Gulf Coastal Plain aquifer system increased from 1930 through 1985.
- The time required for the aquifer systems in figure 12 to reach a new steady-state condition after a change in pumpage varies greatly. The Floridan aquifer system and the Edwards–Trinity aquifer systems equilibrate rapidly after pumping changes and are in a quasi-steady-state condition much of the time. Because only steady-state simulations could be accomplished for these systems, therefore, no change in storage is indicated in figure 12 or table 3. However, locally and for short periods of time (days or weeks) after changes in pumpage, the quantity of water supplied from storage may not be negligible. The North Atlantic Coastal Plain aquifer system equilibrates within a few years, and only 2 percent of the 1980 pumpage was supplied from storage (table 3). In contrast, the deeply buried Great Plains aquifer system, where storage supplied about 30 percent of the 1970 through 1979 pumpage, may require hundreds or thousands of years for a new equilibrium to be reached (Helgeson and others, 1993).
- The sources of pumped ground water from the four aquifer systems where irrigation return flow provided significant recharge can vary greatly from year to year. Dry years generally lead to increased pumpage from wells, reduced recharge from irrigation return flow supplied by imported surface water, and increased storage contribution to ground-water pumpage. Wet years cause the opposite effects.

Quantitative comparisons of the "snapshot values" in figure 12 are not appropriate because the values represent different stages of ground-water development. All but two of the aquifer systems, however, are located within the quarter of the diagram where more than 50 percent of pumpage is supplied by "increased recharge"; that is, by some combination of induced downward percolation, increased leakage, and (or) irrigation return flow.

Most of the ground-water budgets described in this report were derived from coarse-mesh digital models

TABLE 3.—*Sources of water that supply pumpage from regional aquifer systems*

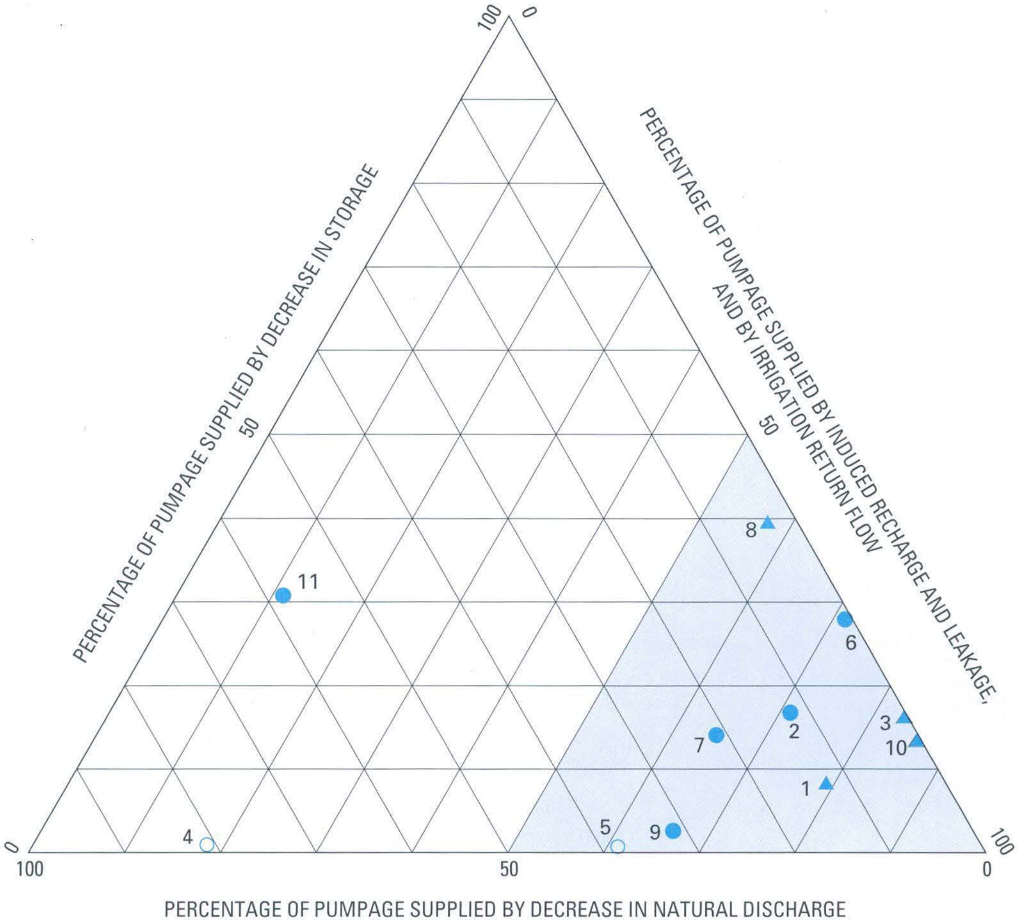
[Vaules in cubic feet per second; percentage (%) of pumpage from individual sources in parenthesis; --, not applicable; RASA, Regional Aquifer-System Analysis]

Regional aquifer system	Period of pumping	Pumpage	Induced downward percolation and leakage	Infiltration of irrigation water	Reduction in natural discharge	Decrease in storage	RASA report references
California Central Valley aquifer system.	1961–77	16,440	--	12,980 (79%)	2,350 (14%)	1,110 (7%)	Williamson and others (1989).
Cambrian-Ordovician aquifer system of the northern Midwest.	1976–80	1,210	830 (69%)	--	160 (13%)	220 (18%)	Mandle and Kontis (1992).
Columbia Plateau aquifer system.	1983–85	1,140	[1]950 (83%)	--	--	190 (17%)	Hansen and others (1994).
Edwards-Trinity aquifer system.	1974–75	1,160	220 (19%)	--	940 (81%)	([2])	Kuniansky and Holligan (1994).
Floridan aquifer system.	1980	4,100	2,500 (61%)	--	1,600 (39%)	([2])	Bush and Johnston (1988).
Great Plains aquifer system (Dakota Sandstone and associated units).	1970–79	800	570 (71%)	--	--	230 (29%)	Helgesen and others (1993).
Gulf Coastal Plain aquifer systems.	1985	13,500	8,900 (66%)	--	2,900 (21%)	1,700 (13%)	Williamson (in press).
Southern High Plains aquifer.	1960–80	9,640	1,560 (16%)	4,050 (42%)	150 (2%)	3,870 (40%)	Luckey and others (1986).
Northern Atlantic Coastal Plain aquifer system (confined aquifers).	1980	[3]1,700	1,140 (67%)	--	530 (31%)	30 (2%)	Leahy and Martin (1993).
Eastern Snake River Plain aquifer system.	1980	1,570	--	1,350 (86%)	--	220 (14%)	Garabedian (1992); Lindholm (1996).
Southeastern Coastal Plain aquifer system.	1981–85	765	85 (11%)	--	445 (58%)	235 (31%)	Barker and Pernik (1994); Miller (1992).

[1] Includes some infiltration of irrigation water.
[2] Sources of water that supply pumpage on the basis of simulation of steady-state conditions; no change in storage is, therefore, indicated.
[3] Pumpage is from confined aquifers only.

designed to simulate regional flow, and thus, small local flow systems were not simulated. Even under these conditions, however, the model-derived budgets indicate diversion of local flow into regional flow regimes and increased downward leakage into deep aquifers. Circulation in the regional flow regimes that may have been sluggish under natural conditions becomes more vigorous as pumping increases. Figure 13 shows the increase in simulated recharge–leakage rates for the regional aquifer systems as withdrawals have increased.

Development has resulted in large increases in recharge–leakage rates for the three most heavily pumped aquifer systems. From predevelopment to



EXPLANATION

7 ● Pumpage supplied by induced recharge and leakage, decreased natural discharge, and loss of storage. Number indicates aquifer system

4 ○ Pumpage supplied by induced recharge and leakage, decreased natural discharge. No change in storage. Number indicates aquifer system

1 ▲ Pumpage supplied partly by irrigation return flow. Number indicates aquifer system

AQUIFER SYSTEMS

1 California Central Valley aquifer system (1961–77)

2 Cambrian–Ordovician aquifer system of the northern Midwest (1976–80)

3 Columbia Plateau aquifer system (1983–85)

4 Edwards–Trinity aquifer system (1974–75)

5 Floridan aquifer system (1980)

6 Great Plains aquifer system (1970–79)

7 Gulf Coastal Plain aquifer systems (1985)

8 High Plains aquifer (southern part) (1960–80)

9 Northern Atlantic Coastal aquifer system (1980)

10 Eastern Snake River Plain aquifer system (1980)

11 Southeastern Coastal Plain aquifer system (1981–85)

FIGURE 12.—Sources of water that supply pumpage from regional aquifer systems.

recent years, the simulated recharge–leakage rate has increased 22 times for the southern High Plains aquifer, 6 times for the California Central Valley aquifer system, and 3 times for the Gulf Coastal Plain aquifer systems. About 70 percent of the increase for the High Plains aquifer is return flow from irrigation, and 30 percent is mostly increased recharge from precipitation on croplands (Luckey and others, 1986). In the California Cen-

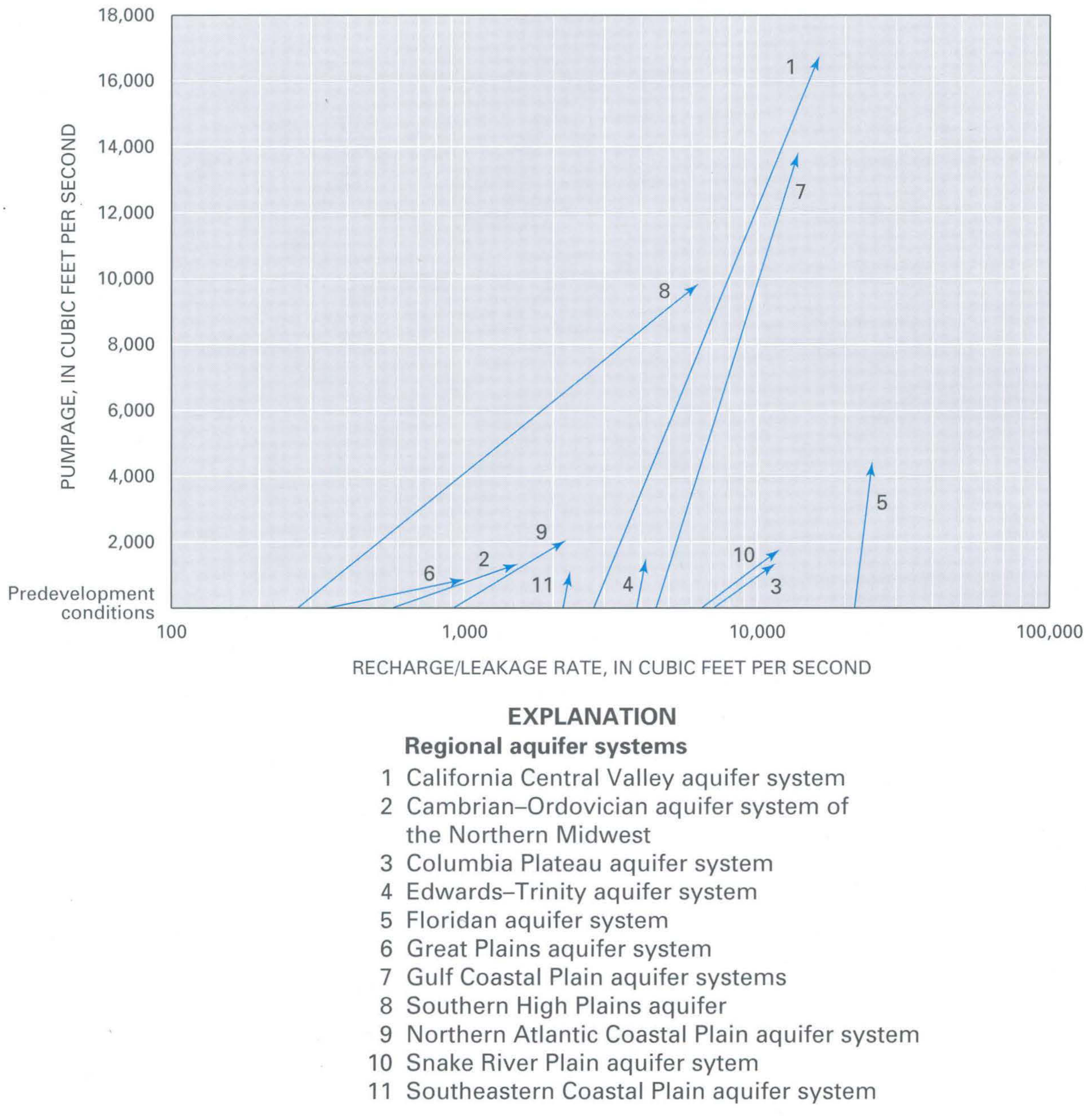


FIGURE 13.—Change of recharge–leakage rates to regional aquifer systems, predevelopment to recent pumping conditions.

tral Valley aquifer system, most of the increase is due to irrigation return flow supplied by imported surface water (Williamson and others, 1989). In the Gulf Coastal Plain aquifer systems, downward vertical flow increased substantially in all aquifers as a result of ground-water pumpage and the consequent reversal of vertical hydraulic gradients (Williamson, in press). A large part of the increased regional recharge is captured local discharge.

The smallest percentage increases in regional recharge–leakage rates have occurred in the Floridan aquifer system, the Edwards–Trinity, and the Southeastern Coastal Plain aquifer systems (fig. 13). Regional recharge rates to the Floridan aquifer system are naturally large as a result of high average rainfall, flat to gently rolling topography, and the dominance of intermediate to regional flow systems in the karst areas where the aquifer system crops out or is thinly covered (fig. 2). Although 60 percent of the pumpage from the Floridan aquifer system is derived from increased regional recharge and leakage, this represents only a 12 percent increase over the predevelopment recharge–leakage rate. The small increase in the recharge–leakage rate in the Southeastern Coastal Plain aquifer system is probably due to the location of the largest head declines in middip confined areas. According to Barker and Pernik (1994), "most of the induced downward leakage is simulated to have occurred updip, while the reduced upward leakage occurs in middip and downdip areas." The capacity of the Edwards–Trinity aquifer system to accept almost all of the available recharge into its regional flow system before development and lack of change since indicates that development can never cause a significant increase in the recharge–leakage rate.

Before development, rates of recharge to the regional flow regimes of the Great Plains aquifer system and the Cambrian-Ordovician aquifer system of the northern Midwest were small, and both flow systems were sluggish. The rate of recharge into deep confined aquifers of the Cambrian-Ordovician system has more than doubled as a result of development; likewise, the rate of downward leakage into the Great Plains aquifer system also has more than doubled. Induced recharge or leakage provides more than 70 percent of the pumped water from both aquifer systems.

SUMMARY AND CONCLUSIONS

The predevelopment hydrologic budgets of the 14 regional aquifer systems in the United States indicate a wide variation in regional flow activity. Recharge to and discharge from these systems range from 47 ft^3/s for the Madison aquifer to 21,500 ft^3/s for the Floridan aquifer system (table 2). Climate, topography, and the hydrogeologic setting (especially the nature and extent of unconfined and confined areas and the hydraulic properties of aquifers and confining units) are the principal natural controls on rates of recharge and discharge. A generalized classification of the 14 aquifer systems, which is based on regional flow activity before development, is as follows:

	Flow activity	Aquifer systems
1.	Vigorous regional flow systems.	Edwards–Trinity Floridan Ozark Plateaus Columbia Plateau Snake River Plain
2.	Restricted regional flow systems (humid climates).	North Atlantic Coastal Plain Gulf Coastal Plain Southeastern Coastal Plain Cambrian-Ordovician (of the northern Midwest)
3.	Restricted regional flow systems (arid to semiarid climates).	Southern High Plains California Central Valley Carbonate-rock province of the Great Basin
4.	Sluggish to virtually stagnant regional flow systems.	Great Plains Madison aquifer

The occurrence of fractured and dissolutioned carbonate rock in outcrop/recharge areas and generally high transmissivity enable the Edwards–Trinity, the Floridan, and the Ozark Plateaus aquifer systems to accept large amounts of recharge during wet periods and transmit much water, thus resulting in vigorous flow systems. Similarly, the Columbia Plateau and the Snake River Plain aquifer systems are characterized by high transmissivity and the ability to accept and transmit large quantities of water. These two basaltic-rock aquifer systems are located in arid to semiarid areas; however, they receive most recharge from the surrounding highlands, which receive much more precipitation. The ability of these five carbonate- and basaltic-rock aquifer systems to transmit large quantities of ground water is attested by the fact that 66 of the 78 first-magnitude springs (discharge greater than 100 ft^3/s) in the United States discharge from these five systems. [References on first-magnitude springs are listed in Rosenau and others (1977).]

In contrast, the clastic-rock aquifer systems of the North Atlantic, the Southeastern, and the Gulf Coastal Plains and the Cambrian–Ordovician (carbonate-rock) of the northern Midwest, which are located in humid areas, have "restricted" regional flow systems. Under natural conditions, the combination of topography, size and patterns of outcrop/subcrop recharge areas, and small hydraulic gradients restrict flow into and through the deep confined aquifers that constitute the regional flow systems. Most of the recharge is rejected; that is, it flows through shallow aquifers and discharges at nearby streams. Therefore, only a small fraction of total ground-water flow occurs within the deep confined aquifers. Much recharge is available for "capture" when heads decline as a result of pumping from deep confined aquifers in these four systems.

Under predevelopment conditions, three extensive aquifer systems in the Central and the Western United States—the Southern High Plains, the California Central Valley, and the carbonate-rock province of the Great Basin—had limited recharge and regional flow. The "restricted" flow systems occur primarily because of the arid to semiarid climates with high evapotranspiration rates that exceed precipitation. The Madison aquifer and the Great Plains aquifer system (principally the Dakota Sandstone and associated units) have vast regional flow systems that extend several hundred miles from west to east. Water is transmitted very slowly through these mostly confined aquifer systems; water in the deeply buried parts of these two systems is virtually stagnant and is highly saline.

Water development has dramatically altered the regional flow systems and hydrologic budgets of the three most heavily pumped aquifer systems in the United States—the High Plains, the California Central Valley, and the Gulf Coastal Plain aquifer systems. Pumpage from the Central Valley aquifer system from 1961 through 1977 was about 6 times the prepumping recharge rate; pumpage from the southern High Plains aquifer from 1960 through 1980 was about 35 times the prepumping recharge rate; and pumpage from the Gulf Coastal Plain aquifer systems during 1985 was about 3 times the prepumping recharge rate (figs. 7, 10). Inflow to the three regional flow systems increased markedly as a result of development. The increased inflow to the High Plains and the Califorina Central Valley aquifer systems was derived mostly from irrigation return flow (supplied either by imported surface water or pumped ground water). Increased inflow to the regional flow system in the Gulf Coastal Plain aquifer systems was supplied largely by increased percolation to regional aquifers in their outcrop/subcrop areas (that is, by capture of shallow ground water that would have naturally discharged to nearby streams) and by increased vertical leakage to confined aquifers. Pumpage also has resulted in depletion of confined aquifer storage in the California Central Valley aquifer system as a result of inelastic compaction of fine-grained sediments. This has been accompanied by the largest volume of land subsidence observed anywhere in the world. Long-term decline of the water table in the southern High Plains aquifer has resulted in more than 25 percent decrease in saturated thickness of the aquifer in more than one quarter of the High Plains of New Mexico and Texas. Loss of storage was much less in the Gulf Coastal Plain aquifer systems, and most of the loss was due to decline of the water table in the Mississippi River Valley alluvial aquifer.

Eight of the regional aquifer systems with less intensive ground-water development (withdrawals ranged from about 800 to 4,100 ft^3/s) were characterized by smaller changes in regional ground-water budgets as a result of pumping. In six aquifer systems (Cambrian–Ordovician, Columbia Plateau, Floridan, Great Plains, North Atlantic Coastal Plain, and Snake River Plain), the most significant budget change was increased inflow to the regional flow system by some combination of increased percolation from outcrop/subcrop areas into deeper and generally confined aquifers in the system, induced vertical leakage from overlying or underlying aquifers, or irrigation return flow (only in the Columbia Plateau and the Snake River aquifer systems). In two aquifer systems (the Edwards–Trinity and the Southeastern Coastal Plain), the major budget change was a decrease in aquifer discharge either to streams and springs or as diffuse upward leakage.

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