SIMULATION ANALYSIS OF THE GROUND-WATER SYSTEM IN MESOZOIC ROCKS IN THE FOUR CORNERS AREA, UTAH, COLORADO, ARIZONA, AND NEW MEXICO

By Blakemore E. Thomas

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MANUEL LUJAN, JR., Secretary

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Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Room 1016 Administration Building
1745 West 1700 South
Salt Lake City, Utah 84104

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CONVERSION FACTORS

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

Multiply inch-pound unit	By	To obtain metric unit
acre	0.4047	square hectometer
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter
foot squared per day (ft^2/d)	0.0929	meter squared per day
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer

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." Altitude, as used in this report, is the height of land or water surface as related to sea level.

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ABSTRACT

The steady-state ground-water system in Mesozoic rocks in the Four Corners area, Utah, Colorado, Arizona, and New Mexico was simulated with a finite-difference digital-computer model to improve the understanding of the system. The simulated area is approximately 4,100 square miles, and it includes 12 sedimentary formations, which are grouped into three aquifers. The Entrada-Navajo aquifer is composed of the Wingate Sandstone, Kayenta Formation, Navajo Sandstone, Carmel Formation, and Entrada Sandstone. The Morrison aquifer is composed of the Junction Creek Sandstone, and the Bluff Sandstone, Recapture, Westwater Canyon, and Salt Wash Members of the Morrison Formation. The Dakota aquifer is composed of the Burro Canyon Formation and Dakota Sandstone.

A digital-computer model was calibrated on the basis of field information from previous investigations to improve the definition of hydraulic boundary conditions, to improve the estimate of the ground-water budget, and to gain a better understanding of vertical flow between aquifers. Six alternative simulations also were made to evaluate potential boundary conditions other than those used in the calibrated model.

The calibrated model provided a reasonable representation of the steady-state ground-water system. The simulation had a mean error (error is absolute value of measured minus simulated water level) of 70 feet for the Entrada-Navajo aquifer, 67 feet for the Morrison aquifer, and 79 feet for the Dakota aquifer.

Analysis of aquifer tests and core samples in previous studies resulted in a range in values of hydraulic conductivity of 0.02 to 2.1 feet per day for the Entrada-Navajo aquifer, 0.01 to 2.7 feet per day for the Morrison aquifer, and 0.09 to 3.3 feet per day for the Dakota aquifer, whereas the simulated hydraulic conductivity was uniform for each aquifer, and values were: 0.46 foot per day for the Entrada-Navajo aquifer, 0.47 foot per day for the Morrison aquifer, and 0.38 foot per day for the Dakota aquifer. The maximum and average thickness of each aquifer are: 1,250 and 900 feet for the Entrada-Navajo aquifer, 800 and 400 feet for the Morrison aquifer, and 360 and 250 feet for the Dakota aquifer.

An estimate of the range of recharge to the ground-water system made by investigators was 40,000 to 100,000 acre-feet per year, however, simulated inflow to the ground-water system was only 30,390 acre-feet per year. Forty-eight percent of the simulated inflow is from infiltration of rainfall and snowmelt within the model area and 42 percent of the inflow is from infiltration on the three mountain areas that border the model area. The remaining 10 percent is mostly inflow at the model boundaries and seepage from streams. The recharge from infiltration averaged 0.65 percent of the mean

annual precipitation within the model area and 7.6 percent within the mountain areas. The distribution of simulated outflow is 79 percent to perennial streams, 15 percent to seepage to alluvium in intermittent and ephemeral stream valleys, and 6 percent to springs and seeps on canyon walls. Simulated annual vertical flow was 2,560 acre-feet from the Dakota to Morrison aquifer, 7,270 acre-feet from the Morrison to Entrada-Navajo aquifer, and 6,120 acre-feet from the Entrada-Navajo to Morrison aquifer.

Simulations of alternative flow conditions through the confining units of the system showed that some vertical flow of water is needed between the Entrada-Navajo and Morrison aquifers to develop a reasonable representation of the system. Vertical flow between the Morrison and Dakota aquifers, however, is not needed to develop a reasonable simulation.

INTRODUCTION

This study was part of a larger study of the Upper Colorado River Basin aquifer system, which was part of the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey. Objectives of the RASA program are to: (1) classify strata into intervals of aquifers and confining units, (2) quantitatively describe the geometry, hydrology, and geochemistry of the aquifers, and (3) analyze regional ground-water flow systems.

Purpose and scope

The general purpose of this report is to improve the understanding of regional ground-water flow in Mesozoic rocks in the Upper Colorado River Basin. The study area includes parts of Utah, Colorado, Arizona, and New Mexico, where the four States share a common corner, hence the name, Four Corners area (fig. 1). The geohydrologic conditions of this area are fairly typical of the Upper Colorado River Basin. Specific objectives of this report are to improve the definition of hydraulic boundary conditions, to improve the estimate of the ground-water budget, and to gain a better understanding of vertical flow between aquifers.

A finite-difference digital-computer model was used to simulate the ground-water flow system. The ground-water flow system in the Four Corners area is complex and the available hydrologic data are meager, therefore, results of previous investigations were used to develop a generalized conceptual model. The conceptual model and various alternative models were evaluated by comparing simulated and measured water levels and estimates of gains and losses in the flow of streams.

Location and Extent of the Study Area

The study area is approximately 8,000 mi^2 and includes parts of the States of Utah, Colorado, Arizona, and New Mexico in the Four Corners area. The area selected for simulation includes 4,100 mi^2, as shown in figure 2. Subsequent maps in this report include the modeled area and, where required, some of the surrounding area. The area is sparsely populated as indicated by the population of the three largest towns in 1980; 7,095 in Cortez, Colorado, 3,118 in Blanding, Utah, and 1,929 in Monticello, Utah (U.S. Department of Commerce, 1980a, 1980b).

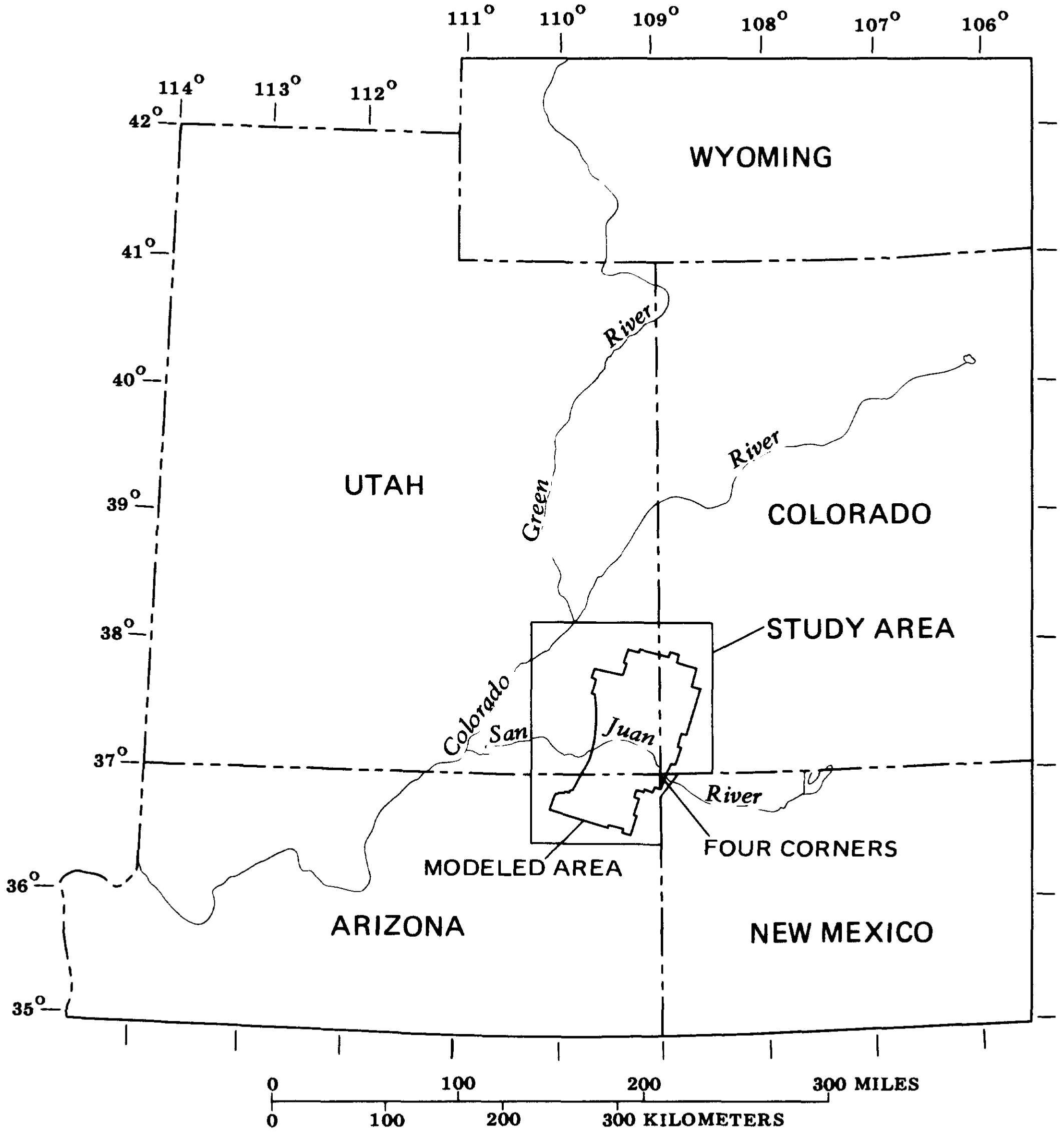


Figure 1.--Location of study and modeled areas.

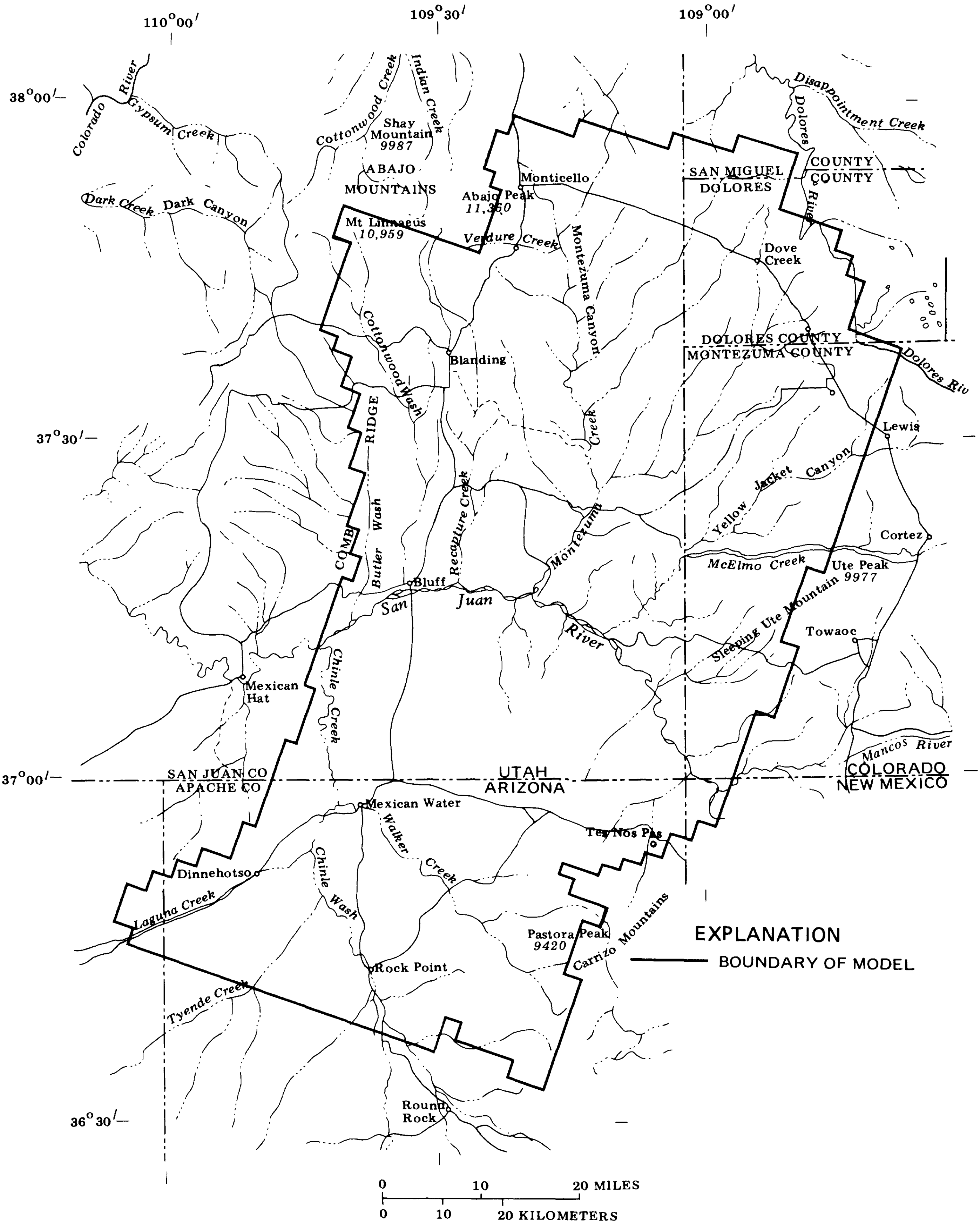


Figure 2.--Cultural and drainage features of the study area.

Previous Investigations

The geology and hydrology of the Four Corners area have been studied by many investigators. Geologic investigations include: Gregory (1917, 1938), Baker (1936), Sears (1956), Strobell (1956), Harshbarger and others (1957), Jobin (1962), Witkind (1964), Ekren and Houser (1965), Huff and Lesure (1965), and Johnson and Thordarson (1966). Four geologic maps used in this study were prepared by Shawe and others (1961), O'Sullivan and Beikman (1963), Haynes and others (1972), and Haynes and Hackman (1978). Hydrologic investigations include: Iorns and others (1965), Feltis (1966), Irwin (1966), Cooley and others (1969), Hanshaw and Hill (1969), Price and Arnow (1974), Eychaner (1983), Weir and others (1983), Whitfield and others (1983), and Avery (1986). Three maps showing ground-water conditions in the south part of the study area were done by Levings and Farrar (1977a, 1977b, 1977c). Hydrologic data for the study area are compiled in Davis and others (1963), Kister and Hatchett (1963), and McGavock and others (1966). Avery (1986) studied the bedrock aquifers in eastern San Juan County, Utah, and most of the data used in this study are from that report.

PHYSICAL SETTING

Physiography and Drainage

The study area is in the southeast part of the Colorado Plateau physiographic province described by Fenneman (1931, p. 274-325). Nearly horizontal sedimentary rock formations underlie most of the area and regional uplift and erosion has resulted in a topography of benches, mesas, and broad plateaus that are dissected by deep, narrow canyons.

A broad upland surface in the north part of the study area (fig. 2) has a maximum altitude of about 8,100 ft in the northeast. The surface has been deeply entrenched by Montezuma Creek and its tributaries. Montezuma Canyon has a maximum depth of 1,400 ft to the northeast of Blanding and other canyons are nearly as deep. The upland surface slopes gently southward, and in its south part, the canyons are wider and about 700 ft deep.

The San Juan River flows westward across the middle part of the study area. South of the San Juan River, the topography is mostly flat with a few isolated mesas. Chinle Creek flows through a deep narrow canyon in its lower reach. The maximum depth of this canyon is about 500 ft. Except in the extreme southeast corner of the study area, all other streams south of the San Juan River have canyons less than 400 ft deep.

Three mountain groups of laccolithic origin are in the study area. These are the Abajo Mountains in the northwest part, Sleeping Ute Mountain in the east-central part, and the Carrizo Mountains in the southeast part (fig. 2). The maximum altitude of these mountains is 11,360 ft in the Abajo Mountains, 9,977 ft at Sleeping Ute Mountain, and 9,420 ft in the Carrizo Mountains. The lowest altitude of the study area is about 4,200 ft in the lowermost reach of the San Juan River.

Streams that are perennial in the upper reaches and originate within the study area are Montezuma Creek, Verdure Creek, the stream in Yellow Jacket Canyon, and Walker Creek. Perennial streams that originate outside the study area are Chinle Creek and Laguna Creek, which originate to the south and southwest, the Dolores River and the San Juan River, which originate to the east in the San Juan Mountains in Colorado, and McElmo Creek, which originates to the east near Cortez, Colorado. Several other streams on the flanks of the mountains are perennial for short reaches of only a few miles. All other streams are intermittent or ephemeral. Flow in the San Juan River has been regulated by Navajo Reservoir in New Mexico since June 1962.

Climate and Vegetation

The climate of the study area ranges from arid (desert) at low altitudes near the San Juan River to humid continental with cool summers in the mountains (Trewartha, 1954, p. 230-237). Between the San Juan River and the mountains is the transition zone of a semiarid (steppe) climate. The definition of a dry climate (arid or semiarid) is that potential evaporation from the soil surface and from vegetation exceeds the average annual precipitation (Trewartha, 1954, p. 267). Precipitation, temperature, and evaporation data for the study area show that the climate is arid below an altitude of about 7,000 ft and humid above 7,000 ft (U.S. Weather Bureau, 1963a, b, c; National Oceanic and Atmospheric Administration, 1982a, b; Iorns and others, 1965).

Mean annual precipitation in the study area ranges from less than 6 to more than 30 in. (fig. 3) and potential annual evaporation generally ranges from 42 to 52 in. (Iorns and others, 1965, plate 8). This evaporation range applies to plateau areas and does not include the mountain areas.

Frontal storms produce either rain or snow and move through the area during late fall to early spring. In the areas above 8,000 ft, a considerable quantity of snow accumulates and may stay on the ground for more than 4 months. In the summer, infrequent thunderstorms produce high intensity rainfall of short duration. These thunderstorms result in little ground-water recharge, because they have flashy runoff that lasts for only a few hours.

The variation of types of vegetation in the study area is related to altitude, topographic features, and available water supply. Forests of spruce, fir, pine, and aspen are in the mountain areas above 7,500 ft. Pinyon, juniper, and sagebrush are the dominant vegetation in the plateau areas between 5,000 and 8,000 ft. Below 5,000 ft on the benches and low plateaus, the vegetation is sparse and includes shadscale, rabbitbrush, greasewood, and saltgrass. In the canyon bottoms where the water table is near land surface, the vegetation is fairly dense and includes cottonwoods and willows in addition to the shrubs and grasses found below 5,000 ft. Oak brush is widely distributed throughout the area, regardless of altitude (Gregory, 1938, p. 22, 23).

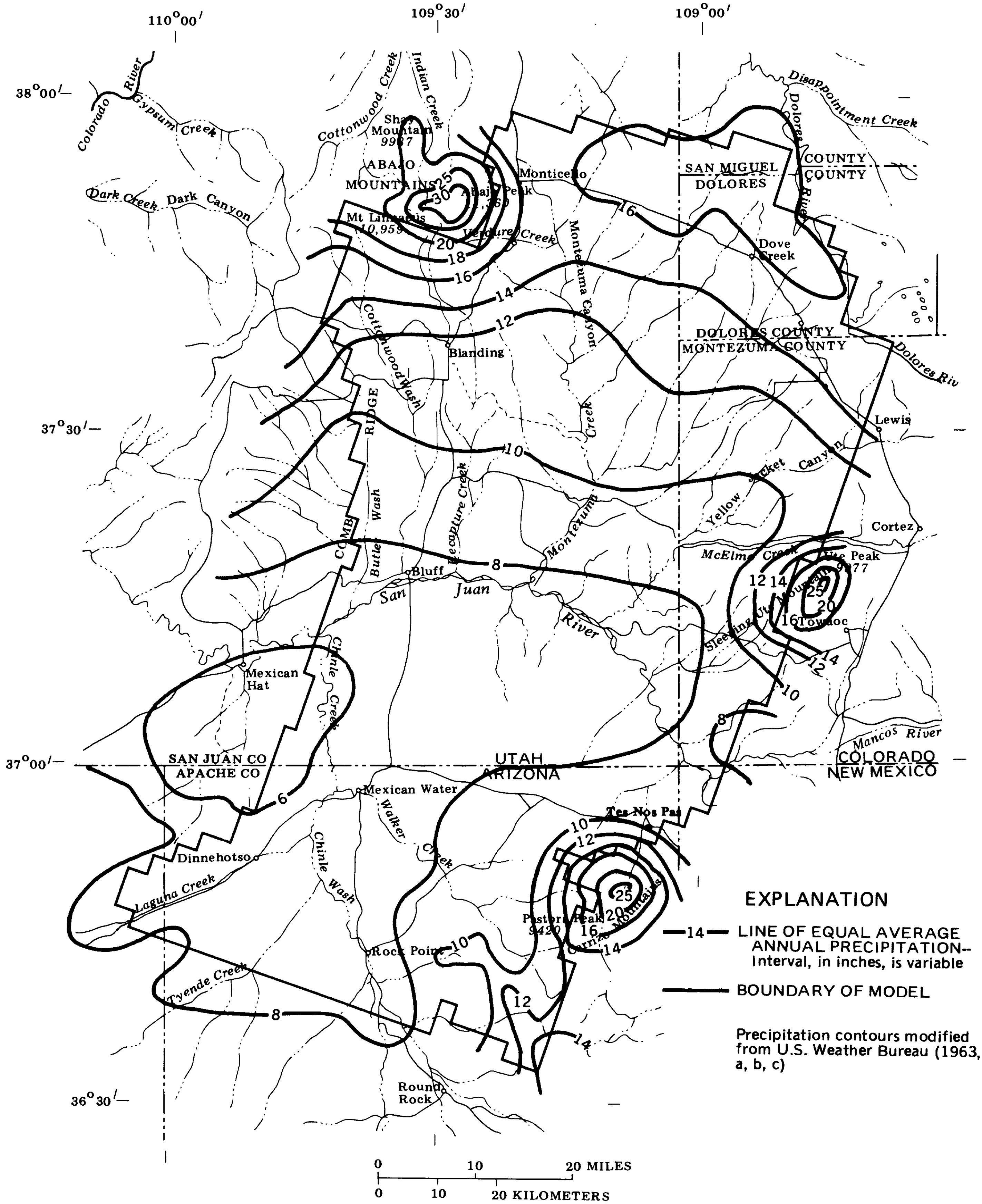


Figure 3.--Mean annual precipitation, 1931-60.

GEOHYDROLOGIC FRAMEWORK

Stratigraphy and Geohydrologic Units

Clastic sedimentary rocks of Mesozoic age that are exposed in the study area were deposited under both marine and continental conditions. A wide variety of lithologies ranging from uniform claystone to conglomerate are represented in these rocks. The lithology and maximum thickness of the 12 formations included in this study are summarized in table 1.

In the Four Corners area, water is present in all rock formations of Mesozoic age. The formations that consist mostly of sandstone or conglomerate are aquifers, and the formations that consist mostly of claystone, siltstone, or mudstone are confining units.

The classification of aquifers and confining units for this study is based on lithology of the rocks and the stratigraphic and hydrologic relationships between adjacent formations. Adjacent rock formations of similar lithology and permeability that lie between the major confining units are combined into three aquifers (table 1). Each aquifer is comprised of two or more formations, and the aquifers are assigned informal names that correspond to the principal water-yielding formations in the group. The confining unit names are derived from the formation names, because they each consist of just one formation.

The major confining units are the Chinle Formation of Triassic age, the Wanakah Formation of Jurassic age, the Brushy Basin Member of the Morrison Formation of Jurassic age, and the Mancos Shale of Cretaceous age. These are referred to as the Chinle confining unit, Wanakah confining unit, Brushy Basin confining unit, and Mancos confining unit in the report.

The Entrada-Navajo aquifer occupies the lowest position in the aquifer system, and it contains the Wingate Sandstone, Kayenta Formation, Navajo Sandstone, Carmel Formation, and Entrada Sandstone of Triassic and Jurassic age. The Chinle confining unit underlies the Entrada-Navajo aquifer and the Wanakah confining unit overlies the Entrada-Navajo aquifer. The Morrison aquifer, overlying the Wanakah confining unit, contains the Junction Creek Sandstone in Colorado and the Bluff Sandstone, Salt Wash, Recapture, and Westwater Canyon Members of the Morrison Formation of Jurassic age. The Brushy Basin confining unit overlies the Morrison aquifer. The Dakota aquifer, occupying the upper position, contains the Burro Canyon Formation and the Dakota Sandstone of Cretaceous age. In small parts of the study area, the Mancos confining unit overlies the Dakota aquifer. The generalized areas of outcrop of the geohydrologic units are shown in figure 4.

Several formations are combined into one aquifer because (1) the formations are of similar lithology and permeability, (2) a thick and fine-grained confining unit between the formations is absent, and (3) regionally, the formations act as a single hydraulic unit even though some confining beds exist locally within the aquifer.

Table 1.--Description of stratigraphic and geohydrologic units

[General lithology: Descriptions modified from Avery (1986), Whitfield and others (1983), and Irwin (1966). Geohydrologic unit is formed from the stratigraphic unit(s) -- indicates no available information.]

Age	Stratigraphic unit	General lithology	Maximum thickness (feet)	Geohydrologic unit
Cretaceous	Mancos Shale	Shale, mudstone, and siltstone.	350	Mancos confining unit
	Dakota Sandstone	Fine- to medium-grained sandstone and conglomeratic sandstone, interbedded with carbonaceous shale.	160	Dakota aquifer
	Burro Canyon Formation	Sandstone and conglomeratic sandstone, interbedded with mudstone.	200	
Jurassic	Morrison Formation			
	Brushy Basin Member	Variegated bentonitic mudstone and siltstone.	700	Brushy Basin confining unit
	Westwater Canyon Member	Fine- to coarse-grained sandstone, interbedded with shale and mudstone.	180	Morrison aquifer
	Recapture Member	Fine- to medium-grained sandstone, interbedded with siltstone and mudstone.	280	
	Salt Wash Member	Fine- to medium-grained sandstone, interbedded with siltstone and mudstone.	500	
	Bluff Sandstone Member	Fine- to medium-grained aeolian cross-bedded quartz sandstone. Present in Utah and Arizona.	300	
	Junction Creek Sandstone	Fine- to coarse-grained, poorly sorted sandstone. Present in Colorado and correlates with Bluff Sandstone Member of Morrison.	300	
	Wanakah Formation	Thin evenly bedded sandy shale, siltstone, shale, and mudstone.	200	Wanakah confining unit
	Entrada Sandstone		300	Entrada-Navajo aquifer
	Moab Member	Medium-grained, crossbedded sandstone.	--	
	Slick Rock Member	Fine- to medium-grained crossbedded sandstone.	--	
	Dewey Bridge Member	Sandy siltstone and sandstone.	--	
	Carmel Formation	Even thin-bedded silty shale, siltstone, and silty sandstone.	160	

Table 1.--Description of stratigraphic and geohydrologic units--Continued

Age	Stratigraphic unit	General lithology	Maximum thickness (feet)	Geohydrologic unit
Jurassic and Triassic(?)	Navajo Sandstone	Fine- to medium-grained cross-bedded quartz sandstone.	450	Entrada-Navajo aquifer
Triassic(?)	Kayenta Formation	Irregularly bedded sandstone and siltstone.	200	
Triassic	Wingate Sandstone		600	
	Lukachukai Member	Fine-grained massive cross-bedded sandstone	--	
	Rock Point Member	Thin-bedded siltstone and silty sandstone.	--	
	Chinle Formation	Siltstone, claystone, bentonitic mudstone, and sandstone.	1,400	Chinle confining unit

The Chinle confining unit underlies the entire modeled area and is exposed along the west boundary and part of the south boundary (fig. 4). The Chinle generally is more than 1,000 ft thick, and it consists mostly of claystone, mudstone, siltstone, and silty sandstone, which have little permeability.

The Entrada-Navajo aquifer underlies the entire modeled area, and it is exposed in a large area in the southwest, along Comb Ridge, west of the Abajo Mountains, and in the canyons of Montezuma and McElmo Creeks and of the Dolores and San Juan Rivers (fig. 4). Within the modeled area, the Entrada-Navajo aquifer has an outcrop area of 1,180 mi^2. The maximum thickness of the Entrada-Navajo aquifer is 1,250 ft and the average thickness is 900 ft.

The Wanakah confining unit has about the same areal extent as the Morrison aquifer and is exposed in narrow bands a few feet to about 2,000 ft wide between outcrops of the Entrada-Navajo and Morrison aquifers. The Wanakah is the most tenuous confining unit in the ground-water system because its thickness ranges from 70 to 200 ft, and it contains considerable interbedded sandstone.

The Morrison aquifer underlies most of the modeled area, except in the west and south. Within the modeled area, the Morrison aquifer has a total area of 2,920 mi^2 and an outcrop area of 1,160 mi^2. It is exposed in a large area south of the San Juan River and in most of the canyons north of the river (fig. 4). The maximum and average thickness of the Morrison aquifer are 800 and 400 ft, respectively.

The Brushy Basin confining unit is present in the same areas as the Dakota aquifer and has a slightly larger areal extent (fig. 4). Within the modeled area, the Brushy Basin confining unit has an outcrop area of 500 mi^2. Outcrops of the Brushy Basin form slopes between the steep cliffs of the more resistant overlying Burro Canyon Formation and Dakota Sandstone and the underlying sandstone members of the Morrison Formation. The Brushy Basin generally is more than 300 ft thick, and it consists mostly of mudstone and siltstone, which have little permeability.

The Dakota aquifer generally is exposed throughout its areal extent (fig. 4). Within the modeled area, the Dakota aquifer has a total area of 1,260 mi^2 and an outcrop area of 1,160 mi^2. The Dakota aquifer caps many of the mesas north of the San Juan River including the large upland area in the northeast part of the study area. Small isolated outcrops of the Dakota aquifer are found south of the San Juan River. The maximum and average thickness of the Dakota aquifer are 360 and 250 ft, respectively.

The Mancos confining unit overlies the Dakota aquifer on the east flank of the Abajo Mountains and on the west flank of Sleeping Ute Mountain (fig. 4). Within the modeled area, the Mancos has an outcrop area of 100 mi^2 and an average thickness of about 200 ft.

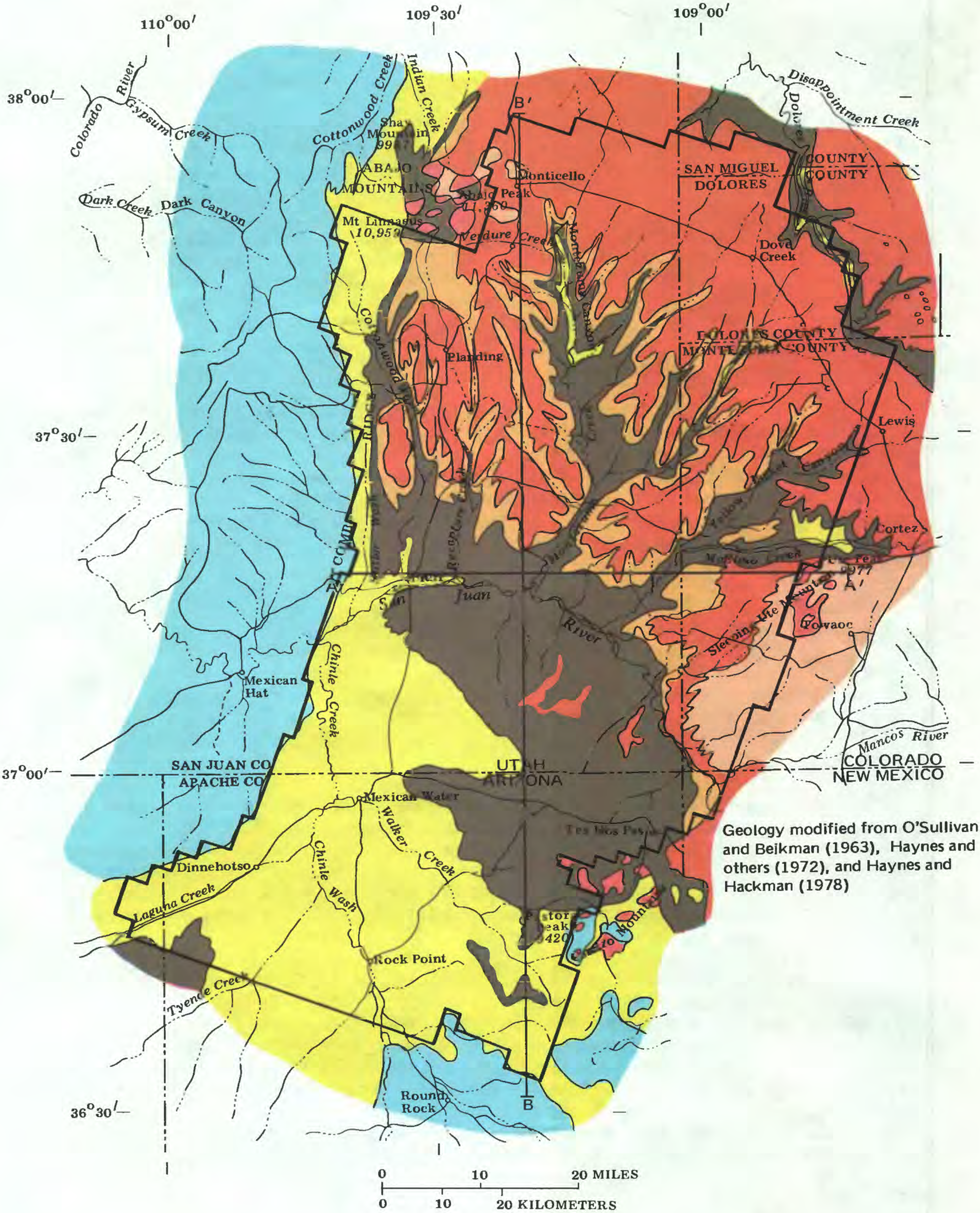
EXPLANATION

GEOHYDROLOGIC UNIT

- Igneous rocks
- Mancos confining unit
- Dakota aquifer
- Brushy Basin confining unit
- Morrison aquifer
- Wanakah confining unit and Entrada-Navajo aquifer
- Sedimentary rocks older than the Entrada-Navajo aquifer. Includes Chinle confining unit

——— BOUNDARY OF MODEL

A├──┤A′ LINE OF SECTION FOR FIGURE 5



Geology modified from O'Sullivan and Beikman (1963), Haynes and others (1972), and Haynes and Hackman (1978)

Figure 4.--Generalized areas of outcrop of geohydrologic units.

Structural Features

Throughout most of the study area, the rocks are flat-lying or slightly tilted. Two cross sections (fig. 5) show the layered formations with the Dakota Sandstone capping the mesas and the Chinle Formation underlying the entire modeled area.

The altitude of the base of the Entrada-Navajo aquifer is shown in figure 6, and altitude of the base of the Dakota Sandstone is shown in figure 7. The strike and dip of all formations considered in this study generally are similar, with some minor differences caused by depositional conditions and the uplift and erosion that followed deposition. Synclines and anticlines are steeper higher in the section (Wingate Sandstone versus Dakota Sandstone) as shown by comparing figures 6 and 7.

The two major structural features in the study area are the Monument uplift and the Blanding basin (fig. 6). These areas of nearly horizontal rocks are separated by Comb monocline, which trends mostly north and dips steeply to the east. Paleozoic rocks are exposed in the Monument uplift west of Comb monocline and Mesozoic rocks are exposed in the Blanding basin east of the monocline (figs. 4 and 6). The lowest point of the Blanding basin is about 15 mi northeast of Bluff, Utah. Rocks dip upward, generally less than 2 degrees, in all directions from this basin.

Faulting of the sedimentary beds has occurred in only a small part of the study area. An east-west zone of block faulting that contains several grabens extends across the area to the south and southeast of the Abajo Mountains (fig. 5). Faulting may affect ground-water flow by juxtaposing aquifers and confining units. The faults southeast of the Abajo Mountains probably impede a north-south movement of water in the Dakota aquifer, but the faults are too small to significantly affect movement of water in the Entrada-Navajo or Morrison aquifers.

The three mountain groups in the study area (fig. 4) were formed by igneous intrusion during late- to post-Mesozoic time (Witkind, 1964, p. 79-81). At each mountain group, several stocks intruded through the sedimentary rocks, and then associated laccoliths were injected parallel to the bedding of the sedimentary rocks. Thus, the stocks are encircled by a zone of shattered sedimentary rocks that are intruded by laccoliths, dikes, sills, and bosses (Witkind, 1964, p. 46).

The process of intrusion created fractured areas that probably allow substantial interformational movement of water. Hood and Danielson (1981, p. 21) noted, that for a similar situation of igneous intrusions into sandstone aquifers in the Henry Mountains about 50 mi east of the study area, that the emplacement of the igneous rock enhances the permeability of the sandstones by local fracturing and permits local recharge to move downward through several layers of sandstones and confining units. Cooley and others (1969, p. 41) also considered the shattered zone of sedimentary rocks that surround the Carrizo Mountains to be an effective avenue for ground-water recharge.

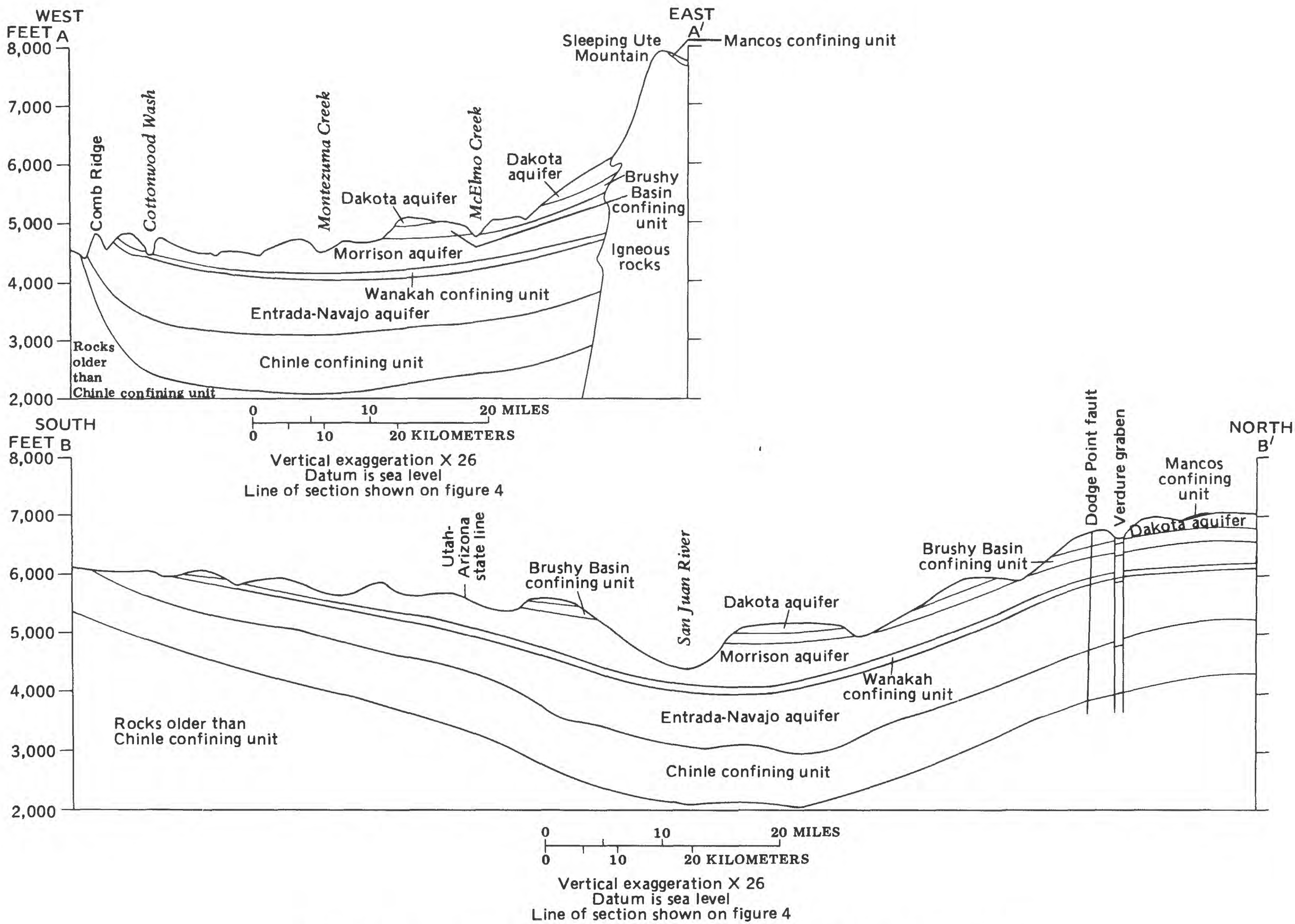


Figure 5.--Generalized sections of geohydrologic units in the Four Corners area.

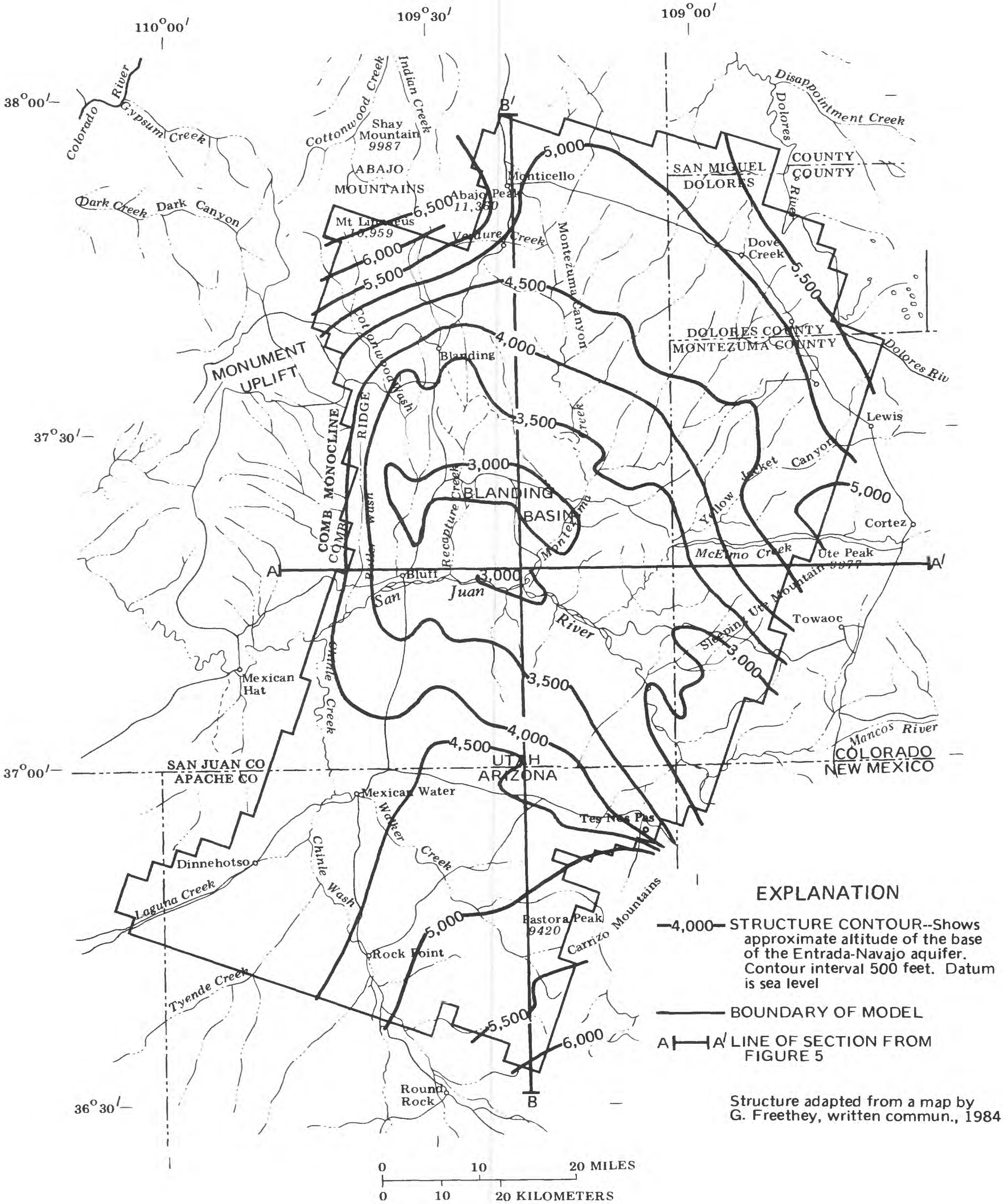


Figure 6.--Altitude of the base of the Entrada-Navajo aquifer.

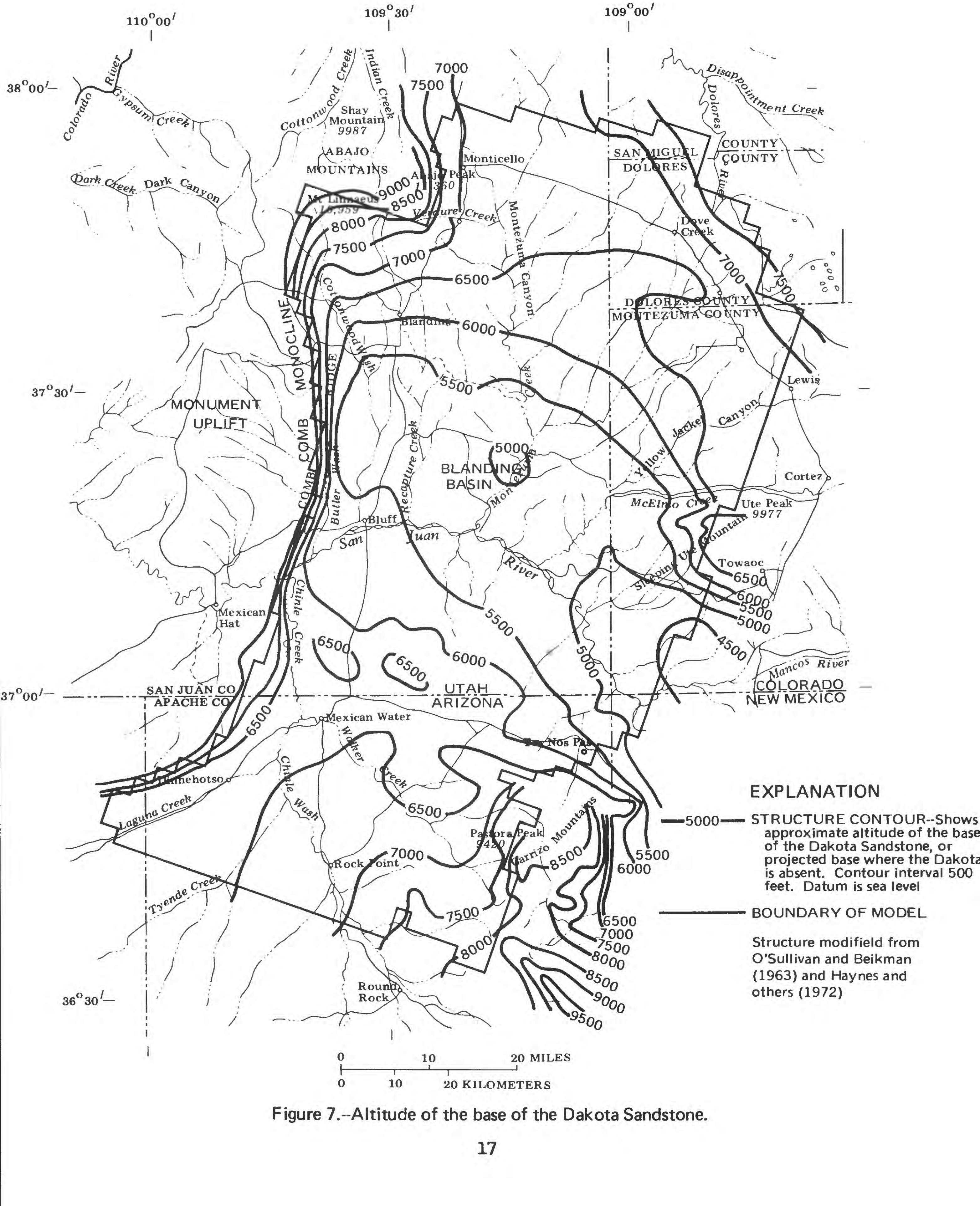


Figure 7.--Altitude of the base of the Dakota Sandstone.

GROUND-WATER SYSTEM

Ground water occurrence in Mesozoic rocks in the Four Corners area is complex. A generalized conceptual model was developed using available geologic and hydrologic information. The conceptual model includes ground-water boundaries, potentiometric surfaces of aquifers, and estimated ranges for values of hydraulic properties and rates of recharge and discharge.

The ground-water system described herein is assumed to be in a steady-state condition. Water-level measurements obtained during 1950 to 1983 indicated that man-caused stresses have affected the potentiometric surfaces of the 3 defined aquifers in less than 5 percent of the study area (Avery, 1986, table 6; Whitfield and others, 1983, p. 28 and 46). Where localized water-level declines or rises occurred, water levels measured prior to the ground-water development were used to represent the hydraulic heads of the steady-state condition.

In a 26 square-mile area near the town of Blanding, Utah, ground-water withdrawal from the Dakota aquifer and application of imported surface water for irrigation were coincident, and the net result was a slight rise in water levels from 1950 to 1983. Water levels before irrigation began in that area were not available, accordingly the hydraulic heads of the steady-state condition were not known.

Boundaries, Occurrence, and Movement

The following characteristics of the ground-water system examined in this study are defined to facilitate the discussion of boundaries, occurrence, and movement:

1. The ground-water system is a body of rock that is saturated with flowing ground water;

2. The region containing the ground water is bounded by a closed surface called the "boundary surface" of the flow system;

3. The ground-water system is in a steady-state condition, that is the quantity of inflow is balanced by the quantity of outflow. Under such conditions water levels may fluctuate seasonally in response to variations in precipitation, however, the long-term average of the water levels should remain constant.

4. Inflow and outflow of water occurs through part of the boundary surface (Franke and others, 1987, p. 2).

In order to describe a ground-water flow system, the position and ground-water flow conditions of the boundary surface must be specified. The position of the three-dimensional boundary surface defines the "external geometry" of the flow system. Assigned flow conditions are either finite flow, recharge (inflow) or discharge (outflow), or no-flow.

In a ground-water investigation, the boundary surface ideally should correspond to hydrogeologic features that comprise the natural "physical" boundaries of the ground-water system. Examples of physical boundaries are the water table or the physical limit of an aquifer: the top or bottom surface of an aquifer or the lateral terminus of an aquifer because of erosion or lack of deposition. Some of the lateral physical boundaries of each aquifer are outside the study area. In order to simulate the flow system within the study area, it is necessary to specify parts of the boundary surface that do not correspond to physical boundaries. The discussion of these parts of the boundary surface is deferred to the section of the report describing the simulation of the ground-water system.

The lower boundary of the ground-water system is the top of the Chinle confining unit. The Chinle underlies the entire modeled area, is more than 1,000 ft thick, and consists mostly of claystone and siltstone (figs. 4 and 5 and table 1), therefore, it forms a confining unit beneath the Entrada-Navajo aquifer that prevents significant vertical movement of water between the Entrada-Navajo aquifer and the underlying formations.

The upper boundary of the ground-water flow system is dependent on the conditions of occurrence of water in each aquifer. All three aquifers (Entrada-Navajo, Morrison, and Dakota aquifers) have areas of unconfined and confined conditions. The upper boundary of an unconfined aquifer is the water table (altitude of saturation), which is the boundary surface at which the saturated flow field is at atmospheric pressure. The upper boundary of a confined aquifer is the base of the overlying confining unit. The Morrison and Dakota aquifers have some areas of perched conditions. Perched conditions occur where an unconfined aquifer overlies another unconfined aquifer. Thus, the perched ground water is separated from an underlying body of ground water by a zone of unsaturated material.

Recharge occurs at the water table in most of the study area. Rainfall and snowmelt infiltrate the land surface and percolate to the water table. In the areas of perched conditions for the Morrison or Dakota aquifers, recharge also is assumed to occur at the water table of the aquifer underlying the perched areas. Water reaches the water table of the underlying aquifer by downward movement from the perched area through the unsaturated material.

Discharge occurs at the water table by seepage to rivers, drains, or to alluvium and subsequent evapotranspiration in many of the stream valleys in the study area where the water table is within a few feet of land surface.

Each aquifer is in contact laterally with the igneous intrusions that form the mountains in the study area (figs. 4 and 5). These mountains are effective areas of recharge for the surrounding bedrock aquifers, because of the large mean annual precipitation on the mountains (fig. 3) and the enhanced infiltration and percolation of rainfall and snowmelt through the fractured igneous and sedimentary rocks.

Entrada-Navajo Aquifer

The lower boundary of the Entrada-Navajo aquifer is the top of the Chinle confining unit. The Chinle probably prevents significant vertical movement of water between the Entrada-Navajo aquifer and the underlying formations. The upper boundary of the Entrada-Navajo aquifer is the altitude of the water table in the unconfined areas and the base of the overlying Wanakah confining unit in the confined areas. Areas of confined and unconfined conditions are shown in figure 8. The line delineating confined and unconfined conditions is more certain in Utah and Arizona than in Colorado.

Recharge to the Entrada-Navajo aquifer occurs at the water table in the unconfined areas. Discharge occurs at the water table by seepage to alluvium in the intermittent and ephemeral stream valleys shown in figure 9. Recharge or discharge occurs at the upper boundary of the aquifer in its confined areas (base of Wanakah confining unit), and the flow condition is a function of the hydraulic gradient between the Entrada-Navajo aquifer and the overlying Morrison aquifer.

An upward gradient from the Entrada-Navajo to Morrison aquifer occurs in a band about 10-15 mi wide on either side of the San Juan River, which is a discharge area for both aquifers (figs. 8 and 10). In the areas where vertical gradients between the Entrada-Navajo and Morrison aquifers exist, vertical gradients within the Entrada-Navajo aquifer also occur. In the lower Montezuma Creek area, Avery (1986, p. 25, table 6) identified more than a 300 ft water-level difference in the Entrada-Navajo aquifer between a well 400 ft deep and a well 1,300 ft deep. Other recharge and discharge areas probably have similar head differences within the Entrada-Navajo aquifer.

The general direction of water movement in the Entrada-Navajo aquifer is shown by the potentiometric contours in figure 8. Water flows from recharge areas in the north and south towards the San Juan River. The discharge mechanism is either directly to the river or through upward movement to the overlying Morrison aquifer then to the river, depending upon whether the river cuts through the Morrison aquifer or not. The direction of ground-water flow at the east side of the study area is uncertain because of meager water-level data. Water is assumed to move from a recharge area at the Dolores River to discharge into McElmo Creek and the San Juan River. Water is assumed to move from a recharge area at Sleeping Ute Mountain to discharge by upward movement to the Morrison aquifer and then to the San Juan River. The potentiometric surface (fig. 8) shows that water moves as subsurface inflow into the study area between Laguna Creek and Chinle Wash. A ground-water divide is oriented west to east across the north part of the study area between the Abajo Mountains and the outcrop of rocks older than the Entrada-Navajo aquifer in the Dolores River canyon (Avery, 1986, p. 28, fig. 14).

The lateral physical boundaries of the Entrada-Navajo aquifer correspond to its physical limits. The Entrada-Navajo aquifer extends beyond the study area in all directions except to the west and southeast where older rocks are exposed (fig. 9). There is also a small area of exposure of older rocks in the Dolores River canyon in the northeast part of the study area. An insignificant quantity of water crosses the contact between the Entrada-Navajo aquifer and older rocks, because the Chinle confining unit is exposed adjacent to the contact (figs. 5 and 9) and forms an effective barrier to flow of water. In the three mountains, recharge occurs at the contact between the Entrada-Navajo aquifer and igneous rocks (fig. 9) by subsurface inflow from fractured igneous rocks.

Morrison Aquifer

The lower boundary of the Morrison aquifer is the top of the Wanakah confining unit. Water moves across this boundary, and the direction of flow is a function of the hydraulic gradient between the Entrada-Navajo and Morrison aquifers. The areas of upward and downward gradients between aquifers were described in the preceeding section. Vertical gradients within the Morrison aquifer probably occur in the same areas as the vertical gradients within the Entrada-Navajo aquifer (see page 20).

The upper boundary of the Morrison aquifer is the altitude of the water table in the unconfined areas and the base of the overlying Brushy Basin confining unit in the confined areas. Based on measured heads, confined conditions occur in the Morrison aquifer near Blanding, between lower Montezuma Creek and lower McElmo Creek, and just west of Sleeping Ute Mountain (fig. 10). The Morrison aquifer is assumed to be confined in the same area just east of the Abajo Mountains in which the Entrada-Navajo aquifer is also confined (fig. 8). Perched water occurs in the Morrison aquifer where it overlies the unconfined Entrada-Navajo aquifer in the northeast part of the study area (fig. 8).

Recharge to the Morrison aquifer occurs at the water table in the unconfined areas. Discharge occurs at the water table by seepage to alluvium in many of the intermittent and ephemeral stream valleys north of the San Juan River (fig. 11). Recharge moves downward into the Morrison aquifer from the overlying Brushy Basin confining unit in the confined areas because the hydraulic gradient is downward from the Dakota to Morrison aquifer in all areas.

The general direction of water movement in the Morrison aquifer is shown by the potentiometric contours in figure 10. Water generally moves from recharge areas near the Abajo, Sleeping Ute, and Carrizo mountains to discharge into the San Juan River. The direction of ground-water flow at the northeast side of the study area is uncertain because of meager water-level data. Water is assumed to move from a recharge area at the Dolores River to discharge into McElmo Creek. A ground-water divide may exist west to east across the north part of the study area between the Abajo Mountains and the Dolores River because there are ground-water divides in the Entrada-Navajo and Dakota aquifers in the same general areas (Avery, 1986, figs. 14 and 19).

The lateral physical boundaries of the Morrison aquifer correspond to its physical limits. The Morrison aquifer extends beyond the study area to the north and east (fig. 11). Most of the physical limits of the aquifer within the study area are at canyon walls where erosion has cut a canyon completely through the aquifer. No flow occurs at the canyon walls in the areas where ground water flows away from or parallel to the canyon walls. Discharge through springs and seeps occurs where ground-water flow is toward the canyon walls (fig. 11). Other physical limits are on gentle slopes where the aquifer pinches out or an uplift brought older rocks to land surface. An insignificant quantity of water crosses these physical limits, because the direction of ground-water flow is away from or parallel to them. In the three mountains, recharge occurs at the contact between the Morrison aquifer and igneous rocks (fig. 11) by subsurface inflow from fractured igneous rocks.

EXPLANATION

GENERAL AREA OF OUTCROP OF:

(stippled box)	IGNEOUS ROCKS
(hatched box)	ROCKS OLDER THAN ENTRADA-NAVAJO AQUIFER--Area where aquifer is absent
—5000—	POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface, 1950-83. Contour interval 200 feet. Datum is sea level
Confined ? Unconfined	BOUNDARY BETWEEN UNCONFINED AND CONFINED CONDITIONS--Queried where uncertain
———	BOUNDARY OF MODEL
• 5403	WELL--Number is measured altitude of potentiometric surface, in feet, 1950-83

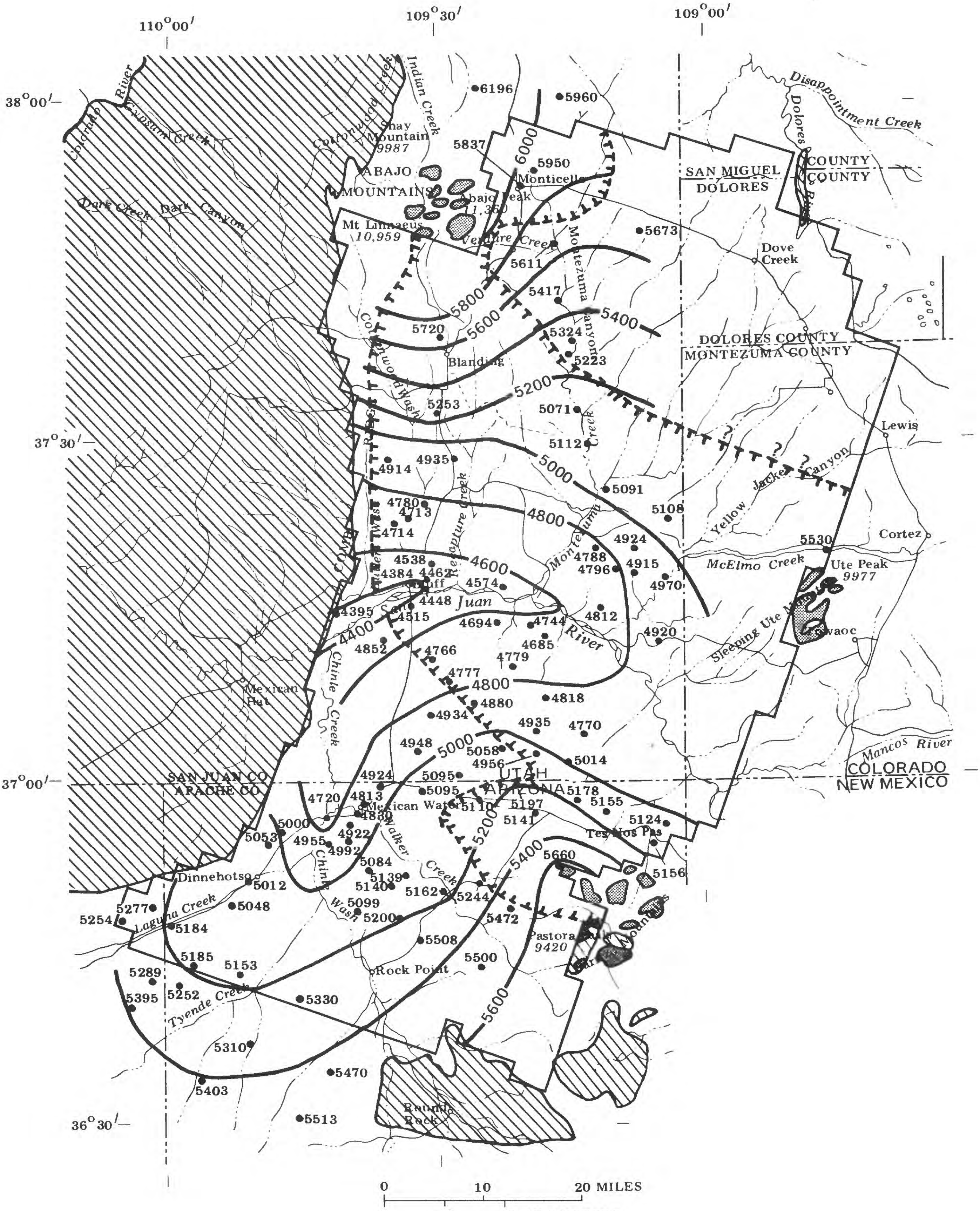


Figure 8.--Steady-state potentiometric surface of the Entrada-Navajo aquifer, 1950-83.

EXPLANATION

GENERAL AREA OF OUTCROP OF:

- IGNEOUS ROCKS
- ROCKS YOUNGER THAN ENTRADA-NAVAJO AQUIFER
- ENTRADA-NAVAJO AQUIFER
- ROCKS OLDER THAN ENTRADA-NAVAJO AQUIFER--Area where aquifer is absent

PHYSICAL LIMIT OF AQUIFER--Contact with relatively impermeable rocks and a no-flow boundary

PERENNIAL STREAM--Ground-water recharge or discharge

INTERMITTENT OR EPHEMERAL STREAM--Ground-water discharge by seepage to alluvium

BOUNDARY OF MODEL

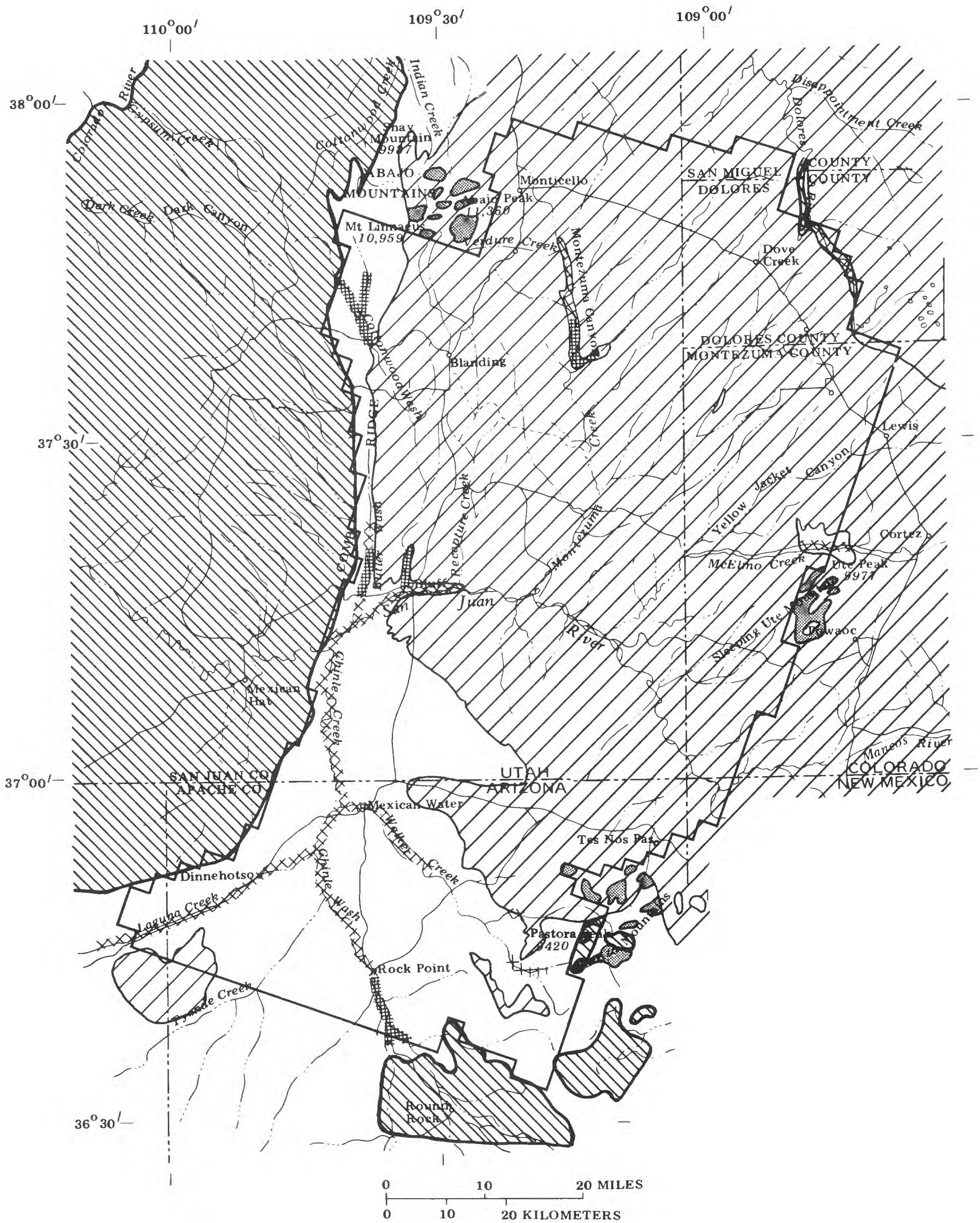


Figure 9.--Hydrogeologic features of the Entrada-Navajo aquifer.

EXPLANATION

GENERAL AREA OF OUTCROP OF:

IGNEOUS ROCKS

ROCKS OLDER THAN MORRISON AQUIFER--Area where aquifer is absent

—5000— POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface, 1950-83. Contour interval 200 feet. Datum is sea level

———— BOUNDARY OF MODEL

•4909 WELL--Number is measured altitude of potentiometric surface, in feet, 1950-83. Circle around number indicates that aquifer is confined, no circle indicates unconfined conditions

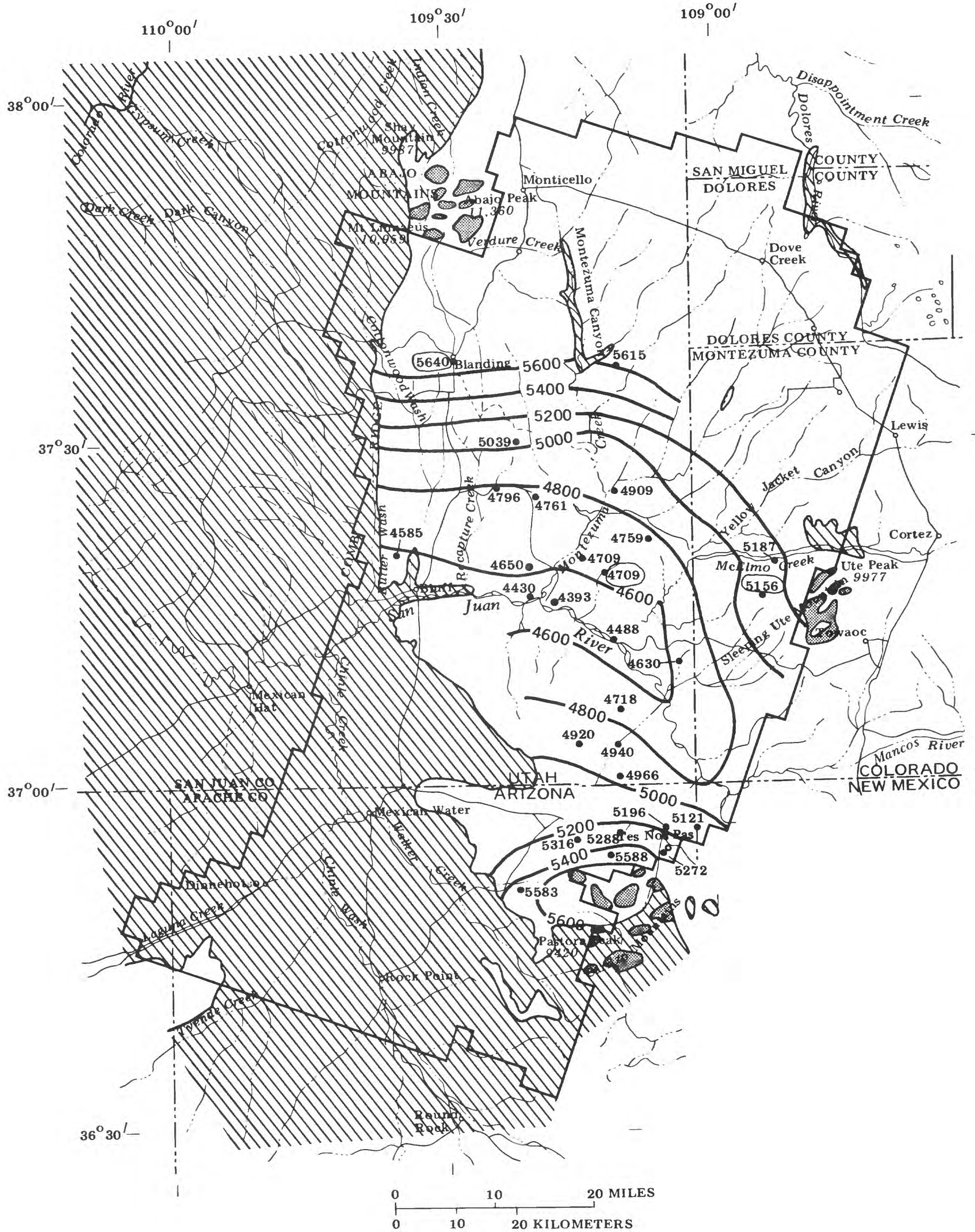


Figure 10.--Steady-state potentiometric surface of the Morrison aquifer, 1950-83.

EXPLANATION

GENERAL AREA OF OUTCROP OF:

IGNEOUS ROCKS

ROCKS YOUNGER THAN MORRISON AQUIFER

MORRISON AQUIFER

ROCKS OLDER THAN MORRISON AQUIFER--
Area where aquifer is absent

PHYSICAL LIMIT OF AQUIFER--No-flow boundary based on direction of ground-water movement

PHYSICAL LIMIT OF AQUIFER--Observed or assumed area of ground-water discharge through springs and seeps on canyon walls

PERENNIAL STREAM--Ground-water recharge or discharge

INTERMITTENT OR EPHEMERAL STREAM--
Ground-water discharge by seepage to alluvium

BOUNDARY OF MODEL

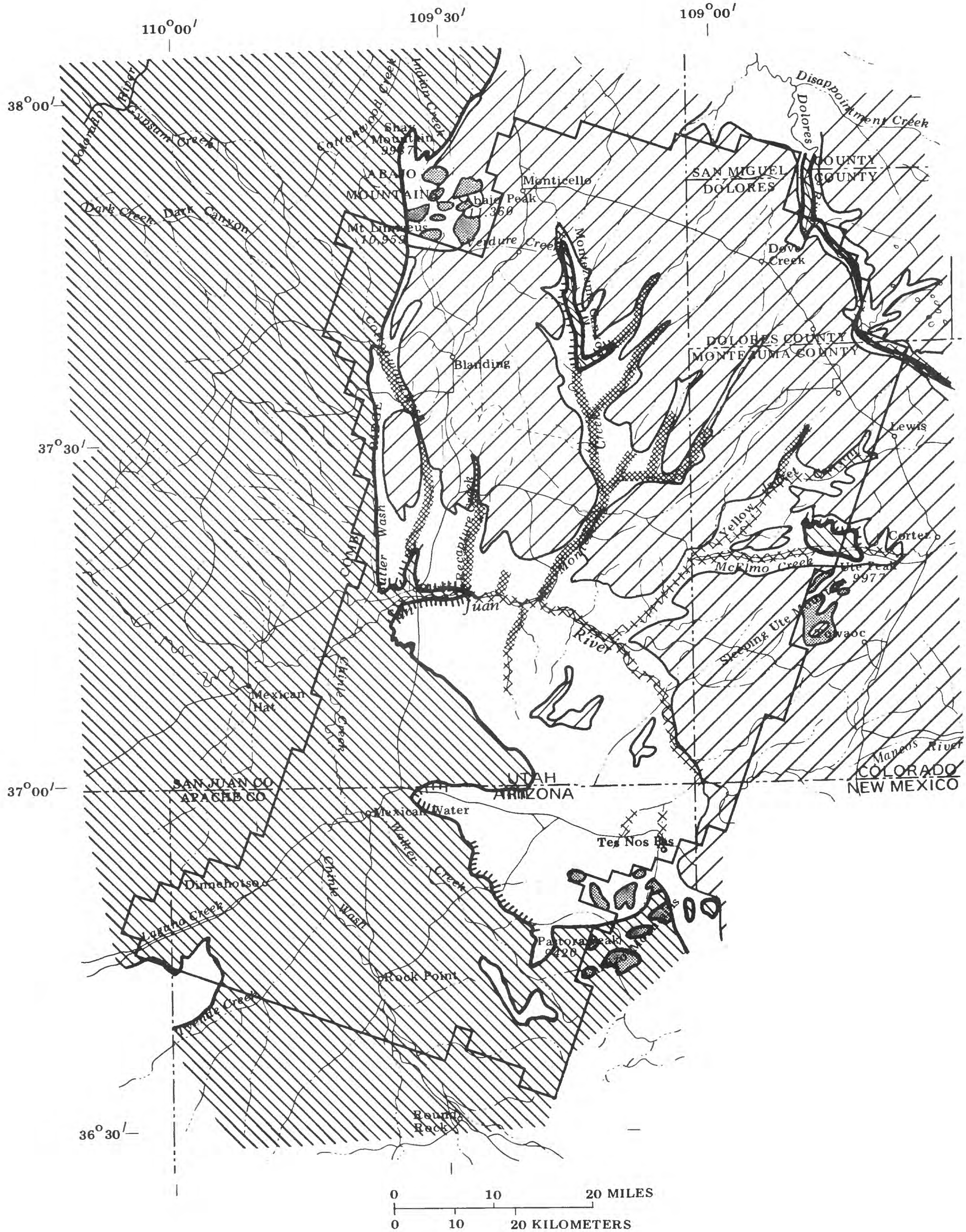


Figure 11.--Hydrogeologic features of the Morrison aquifer.

Dakota Aquifer

The lower boundary of the Dakota aquifer is the top of the Brushy Basin confining unit. Discharge occurs at the lower boundary, because the hydraulic gradient is downward in all areas from the Dakota to Morrison aquifer. The upper boundary of the Dakota aquifer is the altitude of the water table in unconfined areas and the base of the overlying Mancos confining unit in confined areas.

Most of the Dakota aquifer is under unconfined conditions. Based on measured heads, confined conditions occur southwest of Sleeping Ute Mountain (fig. 12). In addition, the Dakota aquifer probably is confined in a small area on the east slopes of the Abajo Mountains where the Mancos confining unit exists (fig. 13). Perched conditions occur in a large part of the aquifer where it overlies the unconfined Morrison aquifer. The areas where the Dakota aquifer is not perched are where confined conditions occur in the Entrada-Navajo and Morrison aquifers just east of the Abajo Mountains, the Blanding area, a small area between lower Montezuma Creek and lower McElmo Creek, and the area west of Sleeping Ute Mountain (figs. 8 and 10).

Recharge to the Dakota aquifer occurs at the water table in the unconfined areas. A small quantity of recharge probably occurs at the upper boundary of the Dakota aquifer in confined areas from percolation of rainfall and snowmelt through the Mancos confining unit.

The general direction of water movement in the Dakota aquifer is shown by the potentiometric contours in figure 12. Ground water generally moves from north to south. In the outcrop area near Sleeping Ute Mountain, water moves radially away from the mountain to the west, southwest, and south. Measured water levels show a gradient from east to west in the area between the Dolores River and Sleeping Ute Mountain, therefore subsurface inflow probably enters the study area through the east boundary of the study area. A ground-water divide in the Dakota aquifer is oriented west to east across the north part of the study area between the Abajo Mountains and the Dolores River (Avery, 1986, fig. 19).

The lateral physical boundaries of the Dakota aquifer correspond to its physical limits. The Dakota aquifer extends beyond the study area to the north and east (fig. 13). All the physical limits of the aquifer within the study area are at canyon walls where erosion has cut a canyon completely through the aquifer. No flow occurs at the canyon walls in the areas where ground water flows away from or parallel to the canyon walls. Discharge through springs and seeps occurs where ground-water flow is toward the canyon walls (fig. 13). In the Abajo Mountains and Sleeping Ute Mountain, recharge occurs at the contact between the Dakota aquifer and igneous rocks (fig. 13) by subsurface inflow from fractured igneous rocks.

Hydraulic Conductivity of Aquifers and Confining Units

The analysis of aquifer tests in the Entrada-Navajo aquifer resulted in a range of hydraulic conductivity of 0.02 to 0.34 ft/d (Avery, 1986, p. 30). The analysis of core samples by Jobin (1962, figs. 14, 17, 20, and 23) resulted in a range of hydraulic conductivity of 0.13 to 0.98 ft/d. Eychaner (1983, p. 7) reported a range of hydraulic conductivity of 0.05 to 2.1 ft/d, from aquifer tests, for an aquifer in northeast Arizona consisting of Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. In his digital-computer model of that aquifer, Eychaner (1983, p. 15) used an average hydraulic-conductivity value of 0.65 ft/d, with a range of 0.32 to 0.97 ft/d.

The hydraulic conductivity of the Morrison aquifer is estimated to range from 0.01 to 2.7 ft/d (Avery, 1986, p. 40). The analysis of two aquifer tests in the Dakota aquifer resulted in values of hydraulic conductivity of 0.35 and 0.77 ft/d and laboratory analysis of core samples resulted in a range of 0.09 to 3.3 ft/d (Avery, 1986, p. 49).

The analyses of core samples and aquifer tests result in a wide range of hydraulic conductivity. Laboratory core analyses often result in a wide range of conductivity because of differences in depth of samples, degree of weathering of samples, size of core, laboratory procedures, and so forth. The actual hydraulic conductivity of the aquifers, on a regional basis, probably does not vary as much as the variability shown in the values reported in Jobin (1962) and Avery (1986).

The assumption for this study is that the regional hydraulic conductivity is uniform for each aquifer throughout the entire study area, but the value may range from 0.1 to 1.0 ft/d for each aquifer. The assumption of uniform values areawide is based on the lack of any regional trends in values across the study area (Avery, 1986, p. 30, 40, 49). Also, the structure and lithology of the formations in the study area provides no evidence for large areal changes in hydraulic conductivity. Fractures can have a significant effect on hydraulic conductivity, but in the Four Corners area, fractures are not widespread. The rock formations are relatively undisturbed, except on the margins of the study area where large folds and igneous intrusions exist.

Data on hydraulic conductivity are meager for the Chinle, Wanakah, and Brushy Basin confining units. The lithology of the formations indicates that the Chinle has the smallest permeability and the Wanakah has the largest. Eychaner (1983, p. 9) used vertical hydraulic conductivity values of 10^{-8} to 10^{-7} ft/d for the Carmel Formation and medial silty member of the Entrada Sandstone in his study of ground-water flow in the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone in northeast Arizona. In this study, those values are used for reference, and the vertical hydraulic conductivity is assumed to be smaller than that used by Eychaner (1983) for the Brushy Basin, about the same for the Wanakah, and zero for the Chinle.

Recharge

Recharge to the ground-water system in the study area is from infiltration of rainfall and snowmelt, subsurface inflow from adjoining areas, seepage from streams, and seepage from unconsumed irrigation water. The quantity of recharge is difficult to estimate because of meager data. An estimate of recharge based on the following analysis is about 40,000 to 100,000 acre-ft/yr.

EXPLANATION

GENERAL AREA OF OUTCROP OF:

IGNEOUS ROCKS

ROCKS OLDER THAN DAKOTA AQUIFER–Area where aquifer is absent

—6800— POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface, 1950-83. Contour interval 200 feet. Datum is sea level

——— BOUNDARY OF MODEL

• 6690 WELL--Number is measured altitude of potentiometric surface, in feet, 1950-83. Circle around number indicates that aquifer is confined, no circle indicates unconfined conditions

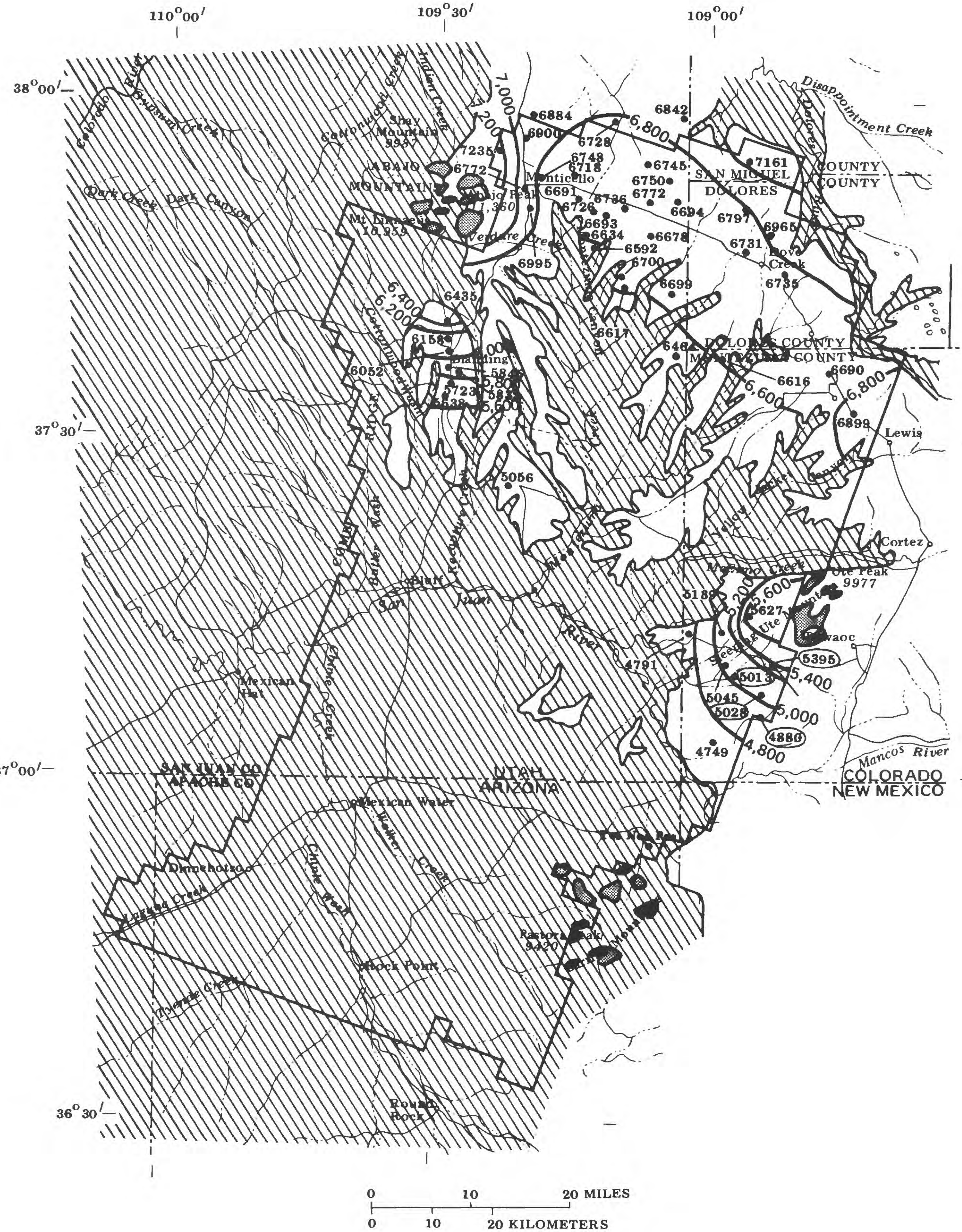


Figure 12.--Steady-state potentiometric surface of the Dakota aquifer, 1950-83.

EXPLANATION

GENERAL AREA OF OUTCROP OF:

IGNEOUS ROCKS

ROCKS YOUNGER THAN DAKOTA AQUIFER

DAKOTA AQUIFER

ROCKS OLDER THAN DAKOTA AQUIFER--Area where aquifer is absent

PHYSICAL LIMIT OF AQUIFER--No-flow boundary based on direction of ground-water movement

PHYSICAL LIMIT OF AQUIFER--Observed or assumed area of ground-water discharge through springs and seeps on canyon walls

XXXXXX PERENNIAL STREAM--Ground-water discharge

BOUNDARY OF MODEL

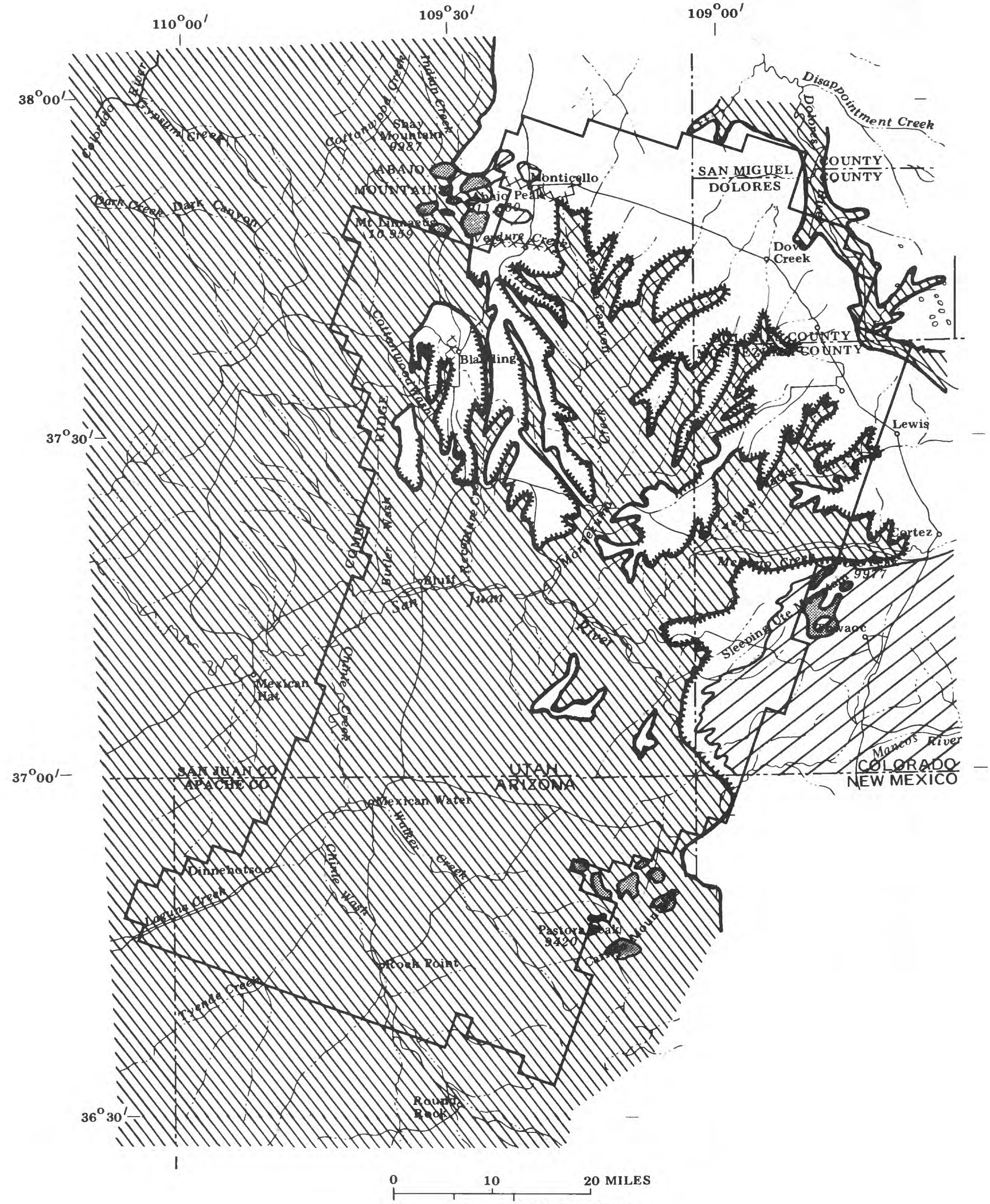


Figure 13.--Hydrogeologic features of the Dakota aquifer.

Infiltration of Rainfall and Snowmelt

Estimates of recharge by infiltration of rainfall and snowmelt often are based on the distribution of mean annual precipitation over a study area and estimates of the percentage of this precipitation that percolates to the ground-water system. Four previous ground-water investigations near this study area estimated recharge from infiltration of rainfall and snowmelt. In southeast Utah and southwest Colorado, Whitfield and others (1983, p. 30) assumed that no recharge occurs in areas below an altitude of 6,900 ft and 2 percent of mean annual precipitation becomes ground-water recharge in the areas above 6,900 ft. Avery (1986, p. 25, 38, 41, table 1) used the same classification of aquifers as this study in a ground-water investigation in eastern San Juan County, Utah, and he assumed that 5 percent of mean annual precipitation in all areas becomes recharge to the outcrop areas of the Entrada-Navajo, Morrison, and Dakota aquifers.

In a ground-water model of an aquifer consisting of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone in northeast Arizona, areal recharge was assumed to be 1 percent of mean annual precipitation in areas below an altitude of 6,500 ft and 3 percent in areas above 6,500 ft (Eychaner, 1983, p. 10). Danielson and Hood (1984, p. 8, 18) measured infiltration to the Navajo Sandstone at a site that is about 70 mi northeast of the study area. The site has an altitude of 8,500 ft, mean annual precipitation of 30 in., and a mantle of colluvium that is 10 to 15 ft thick. The measured infiltration rate was 14 percent of the precipitation during a 2-month period (July 13 to September 16, 1977).

Estimates of the percentage of mean annual precipitation that recharges the ground-water system used in this study are based on the characteristics of the study area and comparison with previous studies. The characteristics of the study area that affect rates of infiltration and percolation to the ground-water system are: quantity of mean annual precipitation, air temperatures and associated rates of evapotranspiration, altitude, topography, characteristics of surficial material (colluvium, alluvium, or loess), type and density of vegetation, and the quantity of fractures in the bedrock.

The study area is separated into a plateau area and mountain areas for estimating recharge, because the different characteristics of the areas result in much different rates of infiltration of rainfall and snowmelt. The boundary between the plateau and mountain areas is at an altitude of 8,000 ft for the Abajo Mountains, and at 7,000 ft for Sleeping Ute Mountain and the Carrizo Mountains. The altitude boundary is based on the estimated boundary between humid and arid climates (see page 6), the point where the land-surface slope starts becoming much steeper, and the general lower limit for altitude of the igneous intrusions that comprise most of the mountain areas.

Plateau area

The plateau area simulated in this study (fig. 2) has a topography of benches, mesas, and broad plains that are separated by deep narrow canyons. The altitude ranges from 4,200 to 8,000 ft. About 20 percent of the area has a surficial cover of alluvial or eolian deposits, which probably enhances the infiltration of rainfall or snowmelt. Vegetation is sparse and mean annual precipitation ranges from 6 to 20 in., with less than 16 in. in 92 percent of the area. The climate of 94 percent of the plateau area (below an altitude of 7,000 ft) is arid or semiarid.

On the basis of previous discussion, the estimated ground-water recharge is 1 to 3 percent of mean annual precipitation. The volume of mean annual precipitation on the plateau area is 2,253,000 acre-ft, which results in an estimated range of ground-water recharge of 23,000 to 68,000 acre-ft/yr.

Mountain areas

The steep mountain areas (Abajo Mountains, Sleeping Ute Mountain, and the Carrizo Mountains) consist of igneous intrusions as well as folded and fractured sedimentary rocks. The range in altitude is 7,000 to 11,360 ft. Vegetation is fairly dense and mean annual precipitation ranges from 14 to 30 in. A large quantity of snow accumulates during the winter, and the subsequent slow melting during the cool spring creates an advantageous situation for ground-water recharge. The climate is humid continental, with cool summers.

Ground-water recharge in the mountain areas is estimated to be 5 to 15 percent of mean annual precipitation. The large infiltration rate is assumed because of the humid climate, abundant fractures in the igneous and sedimentary rocks, long melting period of snow, dense vegetation of conifer trees, and forest litter. Part of the boundary of the mountain areas is adjacent to the plateau area. The rest of the boundary of the mountain areas is the surface-water divide where water flows toward the plateau area. This surface-water divide is assumed to coincide with the ground-water divide for the plateau area. The mountain areas, thus, include 145 mi^2 and the mean annual precipitation is 165,000 acre-ft. Volumes of mean annual precipitation are 83,000 acre-ft for the Abajo Mountains, 31,000 acre-ft for Sleeping Ute Mountain, and 51,000 acre-ft for the Carrizo Mountains. Applying the 5 and 15 percent values results in an estimated ground-water recharge from the mountain areas of 8,000 to 25,000 acre-ft/yr.

Subsurface Inflow From Adjoining Areas

Ground water moves into the study area from the southwest as subsurface inflow in the Entrada-Navajo aquifer between Laguna Creek and Chinle Wash. Eychaner (1983, p. 11) estimated the flow through part of this area in his ground-water flow model of an aquifer consisting of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. The subsurface flow averaged 50 acre-ft/yr per mile of cross section, and this totals 1,500 acre-ft/yr for the 30-mi cross section of this study area.

Some ground water may flow from east to west and enter the study area between the Dolores River and Sleeping Ute Mountain. This subsurface inflow may enter all three aquifers, however, it is not possible to estimate the quantity. The hydraulic gradient and saturated thickness can not be estimated because of meager water-level data.

Seepage from Streams

Ground-water recharge probably occurs where a perennial or intermittent stream flows over the outcrop of an aquifer, and where the water-table altitude in the aquifer is lower than the altitude of the stream surface. Streams were determined to be perennial or intermittent by using the classification of streams on 7.5 and 15-minute topographic maps (figs. 9, 11, and 13). Possible areas where seepage from streams might be occurring are the Dolores River, the upper reaches of Montezuma Creek, Recapture Creek, Cottonwood Wash, and the stream in Yellow Jacket Canyon.

Avery (1986, table 3) measured the discharge of selected streams in the study area during October and November of 1982-83. Ground-water recharge from seepage from streams can be estimated on the basis of decreases in measured streamflows between two sections. These estimates for recharge to bedrock aquifers may have large errors, because of measuring errors due to the small quantity of flow and the interaction of water in the stream with ground water in alluvium in the stream valleys. Nevertheless, recharge to the Entrada-Navajo aquifer was estimated to be 2,200 acre-ft/yr in middle Montezuma Creek. Recharge to the Morrison aquifer was estimated to be 550 acre-ft/yr from upper Cottonwood Wash and 2,200 acre-ft/yr from middle Montezuma Creek.

Seepage from Unconsumed Irrigation Water

About 17,000 acres of crops in the northeast part of the mesa near Blanding are under irrigation. Since the early 1920's, surface water has been diverted from Indian Creek north of the Abajo Mountains for irrigation of crops in the Blanding area. Since the 1940's, water from the Dakota aquifer has been pumped for irrigation as a supplemental supply to the surface water. The net effect of the irrigation has been recharge to the Dakota aquifer, which is shown by a water-level rise of 12, 14, and 34 ft in three wells during 1950-83 (Avery, 1986, fig. 22). No estimate is made of the quantity of recharge from this source, because the quantity of applied irrigation water is not measured.

Discharge

Ground water discharges to perennial streams, springs, seeps, and stream-valley alluvium. The quantity of discharge is difficult to estimate because of the meager data and the numerous factors that affect the discharge.

Seepage to Perennial Streams

Perennial streams that are areas of ground-water discharge are the San Juan River, Verdure Creek, the stream in Yellow Jacket Canyon, McElmo Creek, Chinle Creek, Laguna Creek, and parts of Butler Wash, Montezuma Creek, Chinle Wash, and Walker Creek (figs. 9, 11, and 13). Evidence of ground-water discharge to reaches of these perennial streams is: field observation of streamflow during October 1979 (Whitfield and others, 1983, p. 31), measurements of streamflow during late Fall of 1982 and 1983 (Avery, 1986, table 3), higher aquifer water levels near streams, and results of a study of an aquifer in northeast Arizona consisting of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone (Eychaner, 1983, p. 10).

The San Juan River is the major discharge area for the Entrada-Navajo and Morrison aquifers. Whitfield and others (1983, p. 42-43) estimated base flow of the San Juan River to be 13,000 or 21,000 acre-ft/yr from measurements of streamflow upstream and downstream of the study area in October 1979 and July

1959. Avery (1986, p. 18) estimated base flow of the San Juan River to be 48,000 acre-ft/yr from a water budget calculated for November 1980. The estimates of ground-water discharge from base flow of the San Juan River include water from all aquifers, which could include water from Paleozoic rocks, as well as Mesozoic rocks. The smaller estimates of base flow from Whitfield and others (1983) probably are more accurate because the method based on measured streamflow has less uncertainty than the water budget used by Avery (1986). Using Darcy's Law, Avery (1986, p. 31) estimated 5,000 acre-ft/yr of discharge from the Entrada-Navajo aquifer into a 17.5 mi reach of the San Juan River upstream from Comb Ridge.

During 1965-78, mean winter streamflow of Chinle Wash near Mexican Water gaging station, which is 5 mi downstream from the mouth of Laguna Creek, was about 2,900 acre-ft/yr (Eychaner, 1983, p. 10). This flow is assumed to be the base flow of the stream, and it includes ground-water discharge from the Entrada-Navajo aquifer into Laguna Creek and Chinle Wash upstream of the gaging station.

Ground-water discharges estimated by Avery (1986, table 3) are 190 acre-ft/yr from the Entrada-Navajo aquifer to upper Cottonwood Wash (intermittent stream), 1,500 acre-ft/yr from the Morrison aquifer to McElmo Creek from the Utah-Colorado stateline to the confluence with the San Juan River, and 2,800 acre-ft/yr from the Morrison and Dakota aquifers to upper Montezuma Creek.

Flow through Springs and Seeps

For this study, a spring is defined as having a rate of flow large enough to be measured. A seep is a spring with a rate of flow so small that the water evaporates as it flows onto land surface, or the water flows downhill along the land surface as a thin film. Most of the springs and seeps in this study area are along canyon walls where the bottom of the aquifer is exposed above the canyon bottom.

Whitfield and others (1983, table 8) counted springs on 7.5 and 15-minute topographic maps in southeast Utah and southwest Colorado, and Davis and others (1963) inventoried springs in northeast Arizona. Using the results of those studies, the minimum number of springs in the study area was determined to be 75 for the Entrada-Navajo aquifer, 67 for the Morrison aquifer, and 24 for the Dakota aquifer. Seeps are not generally shown on topographic maps, thus the location of seeps is inferred from directions of ground-water movement, the physical limit of an aquifer, and some field observations. Most of the springs discharging from the Entrada-Navajo aquifer are in the valleys of the lower part of Butler Wash, throughout Chinle Creek and Chinle Wash, and in the middle part of Walker Creek. Most of the springs and seeps discharging from the Morrison and Dakota aquifers are along canyon walls. The areas of observed or assumed ground-water discharge through springs and seeps on canyon walls are shown in figures 11 and 13.

The total quantity of flow from springs and seeps in the study area is difficult to estimate because the rate of flow has only been measured for a few springs in the area. Avery (1986, table 10) and Davis and others (1963) measured or estimated the discharge from 41 springs in the Entrada-Navajo aquifer, 29 springs in the Morrison aquifer, and 5 springs in the Dakota aquifer. An extremely rough estimate of the minimum total springflow from each aquifer was made by multiplying the total number of springs in each aquifer by the average rate of flow from measurements in Avery (1986, table 10) and Davis and others (1963). Average and total rates of flow are 4.0 acre-ft/yr and 300 acre-ft/yr for the Entrada-Navajo aquifer, 4.2 acre-ft/yr and 280 acre-ft/yr for the Morrison aquifer, and 6.8 acre-ft/yr and 160 acre-ft/yr for the Dakota aquifer, respectively.

Seepage to Stream-Valley Alluvium

Some water from the bedrock aquifers flows into alluvium in many of the stream valleys in the study area. Discharge from bedrock aquifers to valleys with perennial streams either flows directly to the stream or is intercepted by evapotranspiration from the alluvium and vegetation in the valleys. Most of the discharge from bedrock to alluvium in intermittent or ephemeral stream valleys moves to the atmosphere by evapotranspiration. The quantity of discharge by seepage to stream-valley alluvium is difficult to estimate because of the uncertainty about rates of evapotranspiration; the interaction of water in bedrock, in alluvium, and in the stream; and a lack of field verification of saturated or dry areas of alluvium. No estimates were made of evapotranspiration from alluvium in perennial stream valleys, however, estimates of the areas and rates of evapotranspiration were made for intermittent and ephemeral stream valleys.

Reaches of intermittent and ephemeral stream valleys that are assumed to be areas of seepage from bedrock aquifers to alluvium are shown in figures 9 and 11. These reaches were delineated based on preliminary determinations by Whitfield and others (1983, plate 2), comparison of aquifer water levels and altitudes of stream valleys, and the percentage of penetration of the stream valley into the aquifer. It was assumed that a stream valley had to incise a minimum of 20 percent of the aquifer thickness in order to intercept water from the aquifer. In the northeast part of the study area, where no water levels are available, the stream valley had to incise 50 percent of the aquifer thickness.

Some rough estimates were made of the quantity of evapotranspiration from the alluvium in intermittent and ephemeral stream valleys. Whitfield and others (1983, p. 31) estimated the quantity of evapotranspiration by phreatophytes in the same general area to be 0.33 to 3.3 ft/yr. For this study, the evapotranspiration rate was assumed to range from 1 to 3 ft/yr. The stream valleys shown in figures 9 and 11 were assigned widths of 100 ft, except Montezuma Creek, lower Cross Canyon, and Chinle Wash south of Rock Point, which were assumed to be 200 ft wide. Using these values for rates of evapotranspiration and areas of stream valleys results in a range of discharge of 470 to 1,400 acre-ft/yr for the Entrada-Navajo aquifer and 1,700 to 5,000 acre-ft/yr for the Morrison aquifer.

SIMULATION OF GROUND-WATER SYSTEM

Procedures and Assumptions

The ground-water system in the Four Corners area is complex and the available hydrologic data are meager. The approach used during this study was to formulate a generalized conceptual model based on previous investigations of the area. This conceptual model was simulated and modified until a best fit was achieved to available field information. The resultant calibrated model is considered to be the most likely representation of the ground-water system. In a few areas, the assigned boundary conditions in the calibrated model were uncertain because of meager data. Therefore, some alternative flow conditions were simulated and evaluated at these uncertain boundaries.

The objectives of the study were to improve the definition of hydraulic boundary conditions, to improve the estimate of the ground-water budget, and to gain a better understanding of vertical flow between aquifers. Results of the calibrated model were used to estimate the steady-state ground-water budget and rates of vertical flow between the three aquifers. The hydraulic boundary conditions for horizontal and vertical flow were evaluated by comparing the results of the calibrated model with results of simulations of alternative boundary conditions.

The lateral boundary of the model was divided into 10 segments to provide a framework for testing different combinations of boundary conditions. Each segment has uniform flow conditions and is based on a physical feature of the ground-water system. Locations of the boundary segments are shown in figure 14 and the flow conditions hypothesized for those segments are listed in table 2. All boundary segments apply to the Entrada-Navajo aquifer. Parts of the physical limits of the Morrison and Dakota aquifers are inside the lateral boundary of the model, thus, seven of the 10 boundary segments apply to the Morrison aquifer and six boundary segments apply to the Dakota aquifer. Seven boundary segments, which constitute 81 percent of the model boundary, have flow conditions defined by field information. The northeast (Dolores River), east, and southeast boundaries, which constitute 19 percent of the model boundary, have uncertain flow conditions because of meager water-level data (fig. 14 and table 2). The testing for lateral boundaries is based on simulating different ground-water flow conditions at these three boundary segments. In addition, two alternatives about flow through confining units are simulated to examine vertical flow between aquifers.

Simplifying assumptions used in the simulations are:

1. The ground-water system is in a steady-state condition, that is, the quantity of inflow to the system is balanced by an equal quantity of outflow, and water levels do not change with time.

2. The aquifers act as isotropic, porous media. This assumption is not strictly true, because the aquifers are fractured in parts of the area, and water moves more readily through these fractures than through the interstitial pores in the aquifers. Despite this, the model is considered to approximately represent the aquifer system because the aquifers probably act as isotropic, porous media in the large cells used in the model (range in area of 1.44 to 4.0 mi^2).

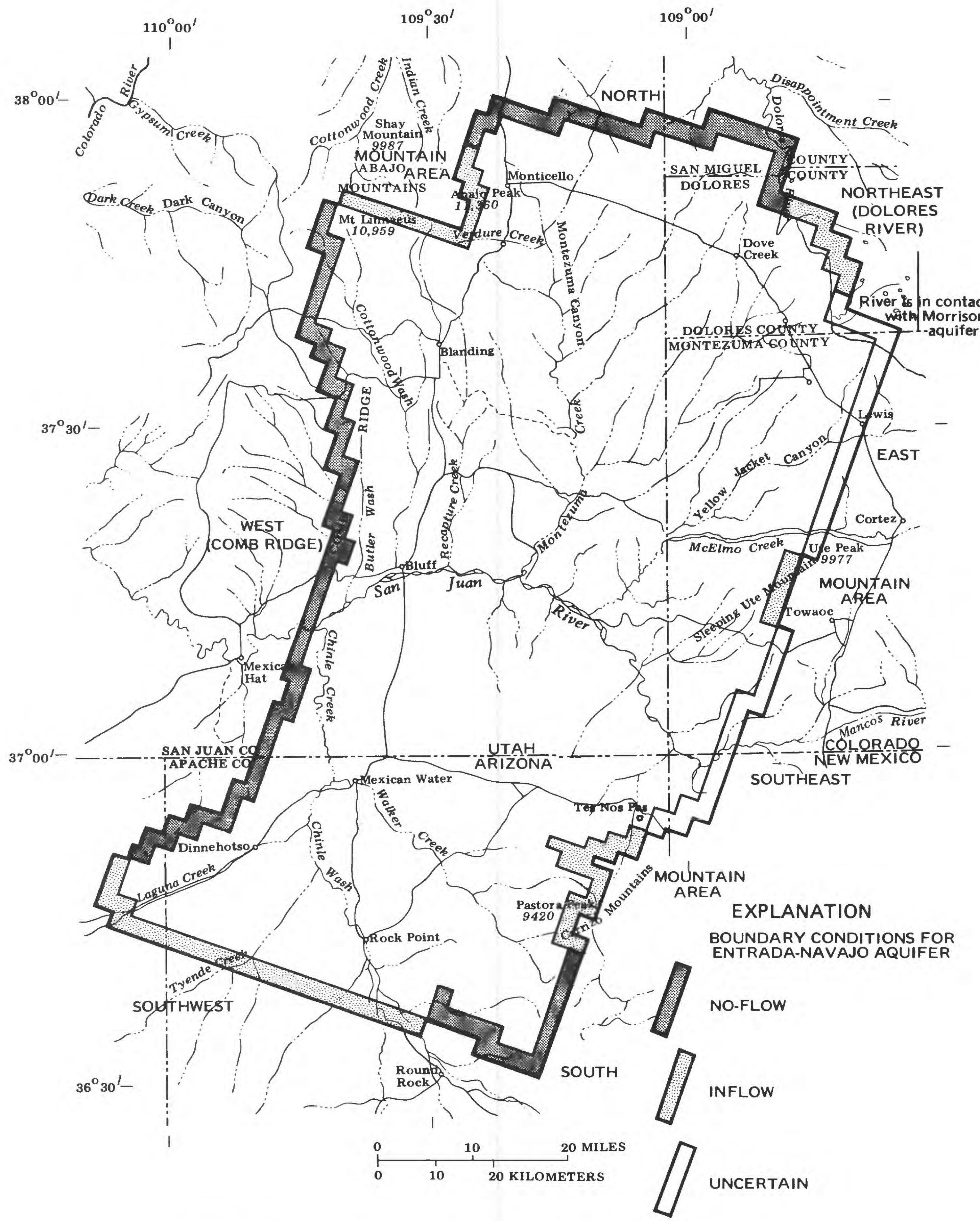


Figure 14.--Labels for segments of the model boundary and generalized boundary conditions for the Entrada-Navajo aquifer.

Table 2.—Lateral ground-water boundary conditions

[Boundary segment: See figure 14 for location of boundary segment. Aquifer: E-N is Entrada-Navajo, M is Morrison, and D is Dakota.]

Boundary segment	Aquifer	Boundary condition	
		Most likely	Possible alternatives
North	E-N,M,D	No-flow	None[1]
Northeast (Dolores River)	E-N	Unsaturated inflow	Saturated inflow
	M	Saturated inflow	Unsaturated inflow
East	E-N	No-flow	Inflow
	M	Small inflow	Substantial inflow
	D	Inflow	None
Southeast	E-N,M	No-flow	Inflow or outflow
	D	No-flow	None
South	E-N	No-flow	None
Southwest	E-N	Inflow	None
West (Comb Ridge)	E-N	No-flow	None
Mountain areas[2] (3 segments)	E-N,M,D	Inflow	None

[1]The flow condition at this boundary segment is well defined, and no alternative conditions are proposed.

[2]Three segments apply to the Entrada-Navajo and Morrison aquifers and two segments apply to the Dakota aquifer.

Digital-Computer Model

A three-dimensional finite-difference numerical model (McDonald and Harbaugh, 1984) was used in this study. In this model, a rectangular grid is superimposed over the horizontal plane of the ground-water system. The vertical dimension of the ground-water system is represented by layers of aquifers. The horizontal grid coordinates extend vertically into all layers, thus, the ground-water system is divided into rectangular blocks, called cells. A cell is an area or volume, and aquifer properties are assumed to be uniform in each cell. The model program uses a node (point) at the center of each cell (block) to represent all characteristics of the cell. Data required for the model include definition of boundary conditions, descriptions of the physical area and thickness of aquifers and confining units, rates of recharge and discharge, hydraulic properties of aquifers and confining units, and initial estimates of the potentiometric surface of each aquifer.

The physical area of each aquifer is defined by the horizontal grid, and thickness of the aquifers is estimated for each cell by specifying the top and bottom altitude of the aquifer. The rates of recharge and discharge for the ground-water system are applied at specified cells in the model. Hydraulic properties and hydraulic heads are estimated for each cell in the model.

The definition of boundary conditions for the model requires that specific "types" of mathematical boundaries be applied to the boundary surface of the ground-water system. The boundary surface is a closed surface that bounds the ground-water system. The types of boundaries used in this study are: constant-head, specified-flux, no-flow, and head-dependent flux.

Application of Model to Ground-Water System

Discretization of Ground-Water System

The finite-difference grid used to simulate the ground-water system is shown in figure 15. The grid has 60 rows and 36 columns and the cells range in width from 1.2 to 2.0 mi. The grid is oriented on a northeast to southwest axis along the principal direction of ground-water movement. Cells are smaller in the recharge areas near the mountains and in the primary area of discharge, the San Juan River.

The ground-water system is divided vertically into three layers representing the Entrada-Navajo, Morrison, and Dakota aquifers. All three aquifers have parts that are unconfined and parts that are confined. The altitude of the top and bottom of each aquifer were entered, and the model simulates a confined or unconfined condition according to the relation between computed hydraulic head and the top of the aquifer. The Wanakah and Brushy Basin confining units were not simulated as separate layers. Horizontal flow in the two confining units is negligible compared to flow in aquifers, therefore, only vertical flow through confining units was simulated. Vertical flow was computed using the head difference between adjacent aquifers and the vertical conductance of the confining units (McDonald and Harbaugh, 1984, p. 138-144).

The Entrada-Navajo, Morrison, and Dakota aquifers each have different physical limits within the study area (fig. 4), thus, the outside boundary of the finite-difference grid is different for each aquifer. The grids and boundary conditions used to simulate each aquifer are shown in figures 15 to 17.

The model boundary adjacent to the mountain areas is located where the ground-water system borders the Abajo Mountains, Sleeping Ute Mountain, and the Carrizo Mountains (figs. 4 and 14). The model boundary is near the 8,000 ft contour at the Abajo Mountains and near the 7,000 ft contour at Sleeping Ute Mountain and the Carrizo Mountains. The location of that boundary is based on a difference in characteristics of infiltration of the areas above and below those altitudes (plateau area versus mountain area)(see page 36). The mountain areas were not simulated because no water-level data are available, hydraulic gradients are probably very steep, and the igneous intrusions in the mountain areas create a complex hydraulic character that would be difficult to simulate.

Initial Water Levels

Initial water levels are required for each node of the model. These initial water levels were estimated from the potentiometric maps of the Entrada-Navajo, Morrison, and Dakota aquifers shown in figures 8, 10, and 12. Water-level data shown on these maps were obtained from Irwin (1966), McGavock and others (1966), Levings and Farrar (1977a, b, c), Avery (1986, table 6), and U.S. Geological Survey ground-water files. The number of measured water levels used in this study is 86 for the Entrada-Navajo aquifer, 28 for the Morrison aquifer, and 46 for the Dakota aquifer.

Boundary Conditions

General boundary conditions of no-flow, inflow, and outflow used for the lateral boundary of the flow system in the calibrated model are listed under the heading "Most Likely Boundary Condition" in table 2. The finite-difference grids and boundaries used to simulate each aquifer are shown in figures 15 to 17.

The boundary conditions shown in the finite-difference grids (figs. 15-17) are the result of adjustments made to an initial simulation of the three-aquifer flow system that included all areas of the aquifers. Results of the simulation of all areas of the aquifers showed that the size of the grid used in this study was too large to simulate narrow and isolated flow systems in the Morrison and Dakota aquifers (figs. 11 and 13). The width of these narrow flow systems was only represented by one or two cells. Two isolated flow systems in the Morrison aquifer in Arizona (fig. 16) and several of the isolated flow systems in the Dakota aquifer (fig. 17), most of which had no water-level data (figs. 10 and 12), were therefore not simulated. These parts of the Morrison and Dakota aquifers that were not simulated were still assumed to contribute flow to the system, and the method of compensating for these deleted areas is explained in the following subsections on boundary conditions for the Entrada-Navajo and Morrison aquifers.

EXPLANATION

NO-FLOW NODE--Entrada-Navajo aquifer simulated as no-flow and unsaturated

AREA OF MORRISON AQUIFER SIMULATED

AREA OF MORRISON AQUIFER SIMULATED AS UNSATURATED--No vertical flow through the Morrison aquifer

INFLOW BOUNDARIES:

SPECIFIED-FLUX NODE--Simulates subsurface inflow

RIVER HEAD-DEPENDENT NODE--Simulates seepage from perennial stream

INFILTRATION OF RAINFALL AND SNOWMELT ON OUTCROP AREA--Simulated as specified flux. A node with a X has 4 times the areal recharge as other nodes

VERTICAL LEAKAGE FROM MORRISON AQUIFER IN AREA WHERE MORRISON AQUIFER NOT SIMULATED--Simulated as specified flux to Entrada-Navajo aquifer

OUTFLOW BOUNDARIES:

RIVER HEAD-DEPENDENT NODE--Simulates seepage to perennial stream

RIVER HEAD-DEPENDENT NODE--Simulates seepage to alluvium in intermittent and ephemeral stream valleys

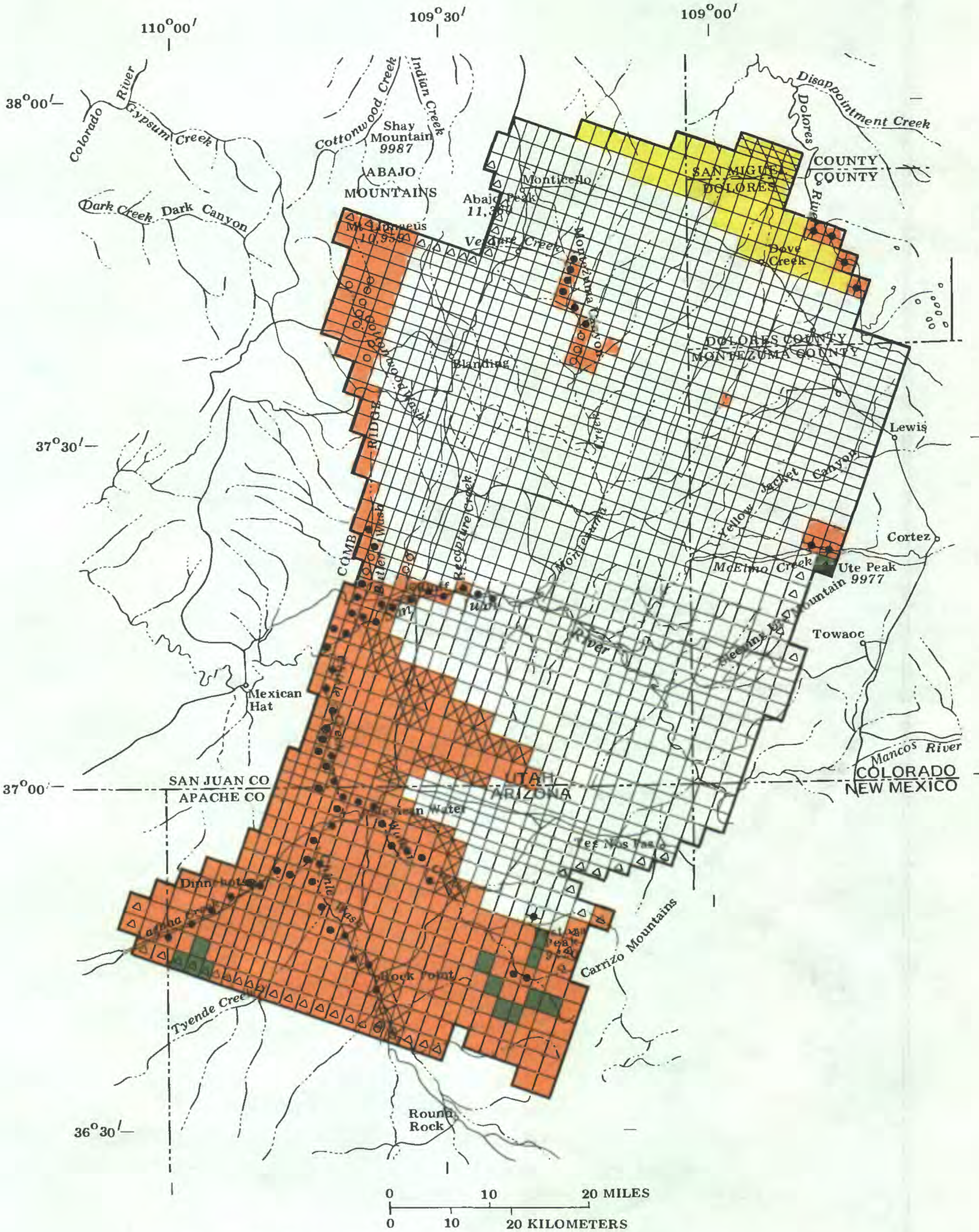


Figure 15.--Finite-difference grid and boundaries used to simulate the Entrada-Navajo aquifer.

EXPLANATION

NO-FLOW NODE--Morrison aquifer simulated as no-flow and unsaturated

AREA OF DAKOTA AQUIFER SIMULATED

AREA OF MORRISON AQUIFER NOT SIMULATED

AREA WHERE MORRISON AQUIFER IS ABSENT

INFLOW BOUNDARIES:

SPECIFIED-FLUX NODE--Simulates subsurface inflow

RIVER HEAD-DEPENDENT NODE--Simulates seepage from perennial stream

INFILTRATION OF RAINFALL AND SNOWMELT ON OUTCROP AREA--Simulated as specified flux. A node with a X has 4 times the areal recharge as other nodes

PERCOLATION OF RAINFALL AND SNOWMELT THROUGH OUTCROP AREA OF BRUSHY BASIN CONFINING UNIT--Simulated as specified flux to Morrison aquifer

VERTICAL LEAKAGE FROM DAKOTA AQUIFER IN AREA WHERE DAKOTA AQUIFER NOT SIMULATED--Simulated as specified flux to Morrison aquifer

OUTFLOW BOUNDARIES:

RIVER HEAD-DEPENDENT NODE--Simulates seepage to perennial stream

RIVER HEAD-DEPENDENT NODE--Simulates seepage to alluvium in intermittent and ephemeral stream valleys

DRAIN HEAD-DEPENDENT NODE--Simulates flow through springs and seeps on canyon walls

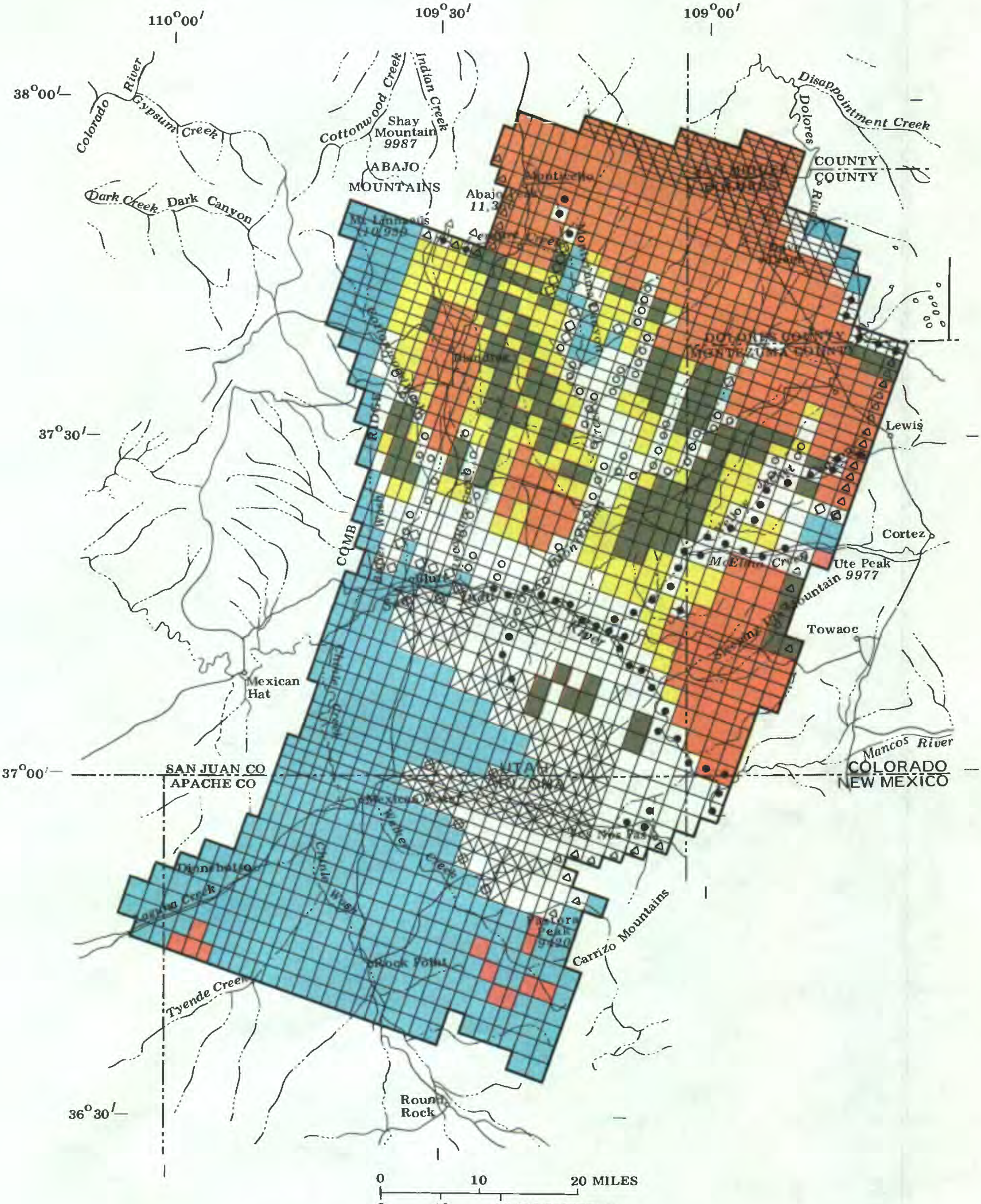


Figure 16.--Finite-difference grid and boundaries used to simulate the Morrison aquifer.

EXPLANATION

NO-FLOW NODE--Area of Dakota aquifer on north side of ground-water divide

AREA OF DAKOTA AQUIFER NOT SIMULATED

AREA WHERE DAKOTA AQUIFER IS ABSENT

INFLOW BOUNDARIES:

SPECIFIED-FLUX NODE--Simulates subsurface inflow

INFILTRATION OF RAINFALL AND SNOWMELT ON OUTCROP AREA--Simulated as specified flux

PERCOLATION OF RAINFALL AND SNOWMELT THROUGH OUTCROP AREA OF MANCOS CONFINING UNIT--Simulated as specified flux to Dakota aquifer

SEEPAGE FROM UNCONSUMED IRRIGATION WATER--Simulated as specified flux in addition to the specified flux simulated for infiltration of rainfall and snowmelt on outcrop area

OUTFLOW BOUNDARIES:

RIVER HEAD-DEPENDENT NODE--Simulates seepage to perennial stream

DRAIN HEAD-DEPENDENT NODE--Simulates flow through springs and seeps on canyon walls

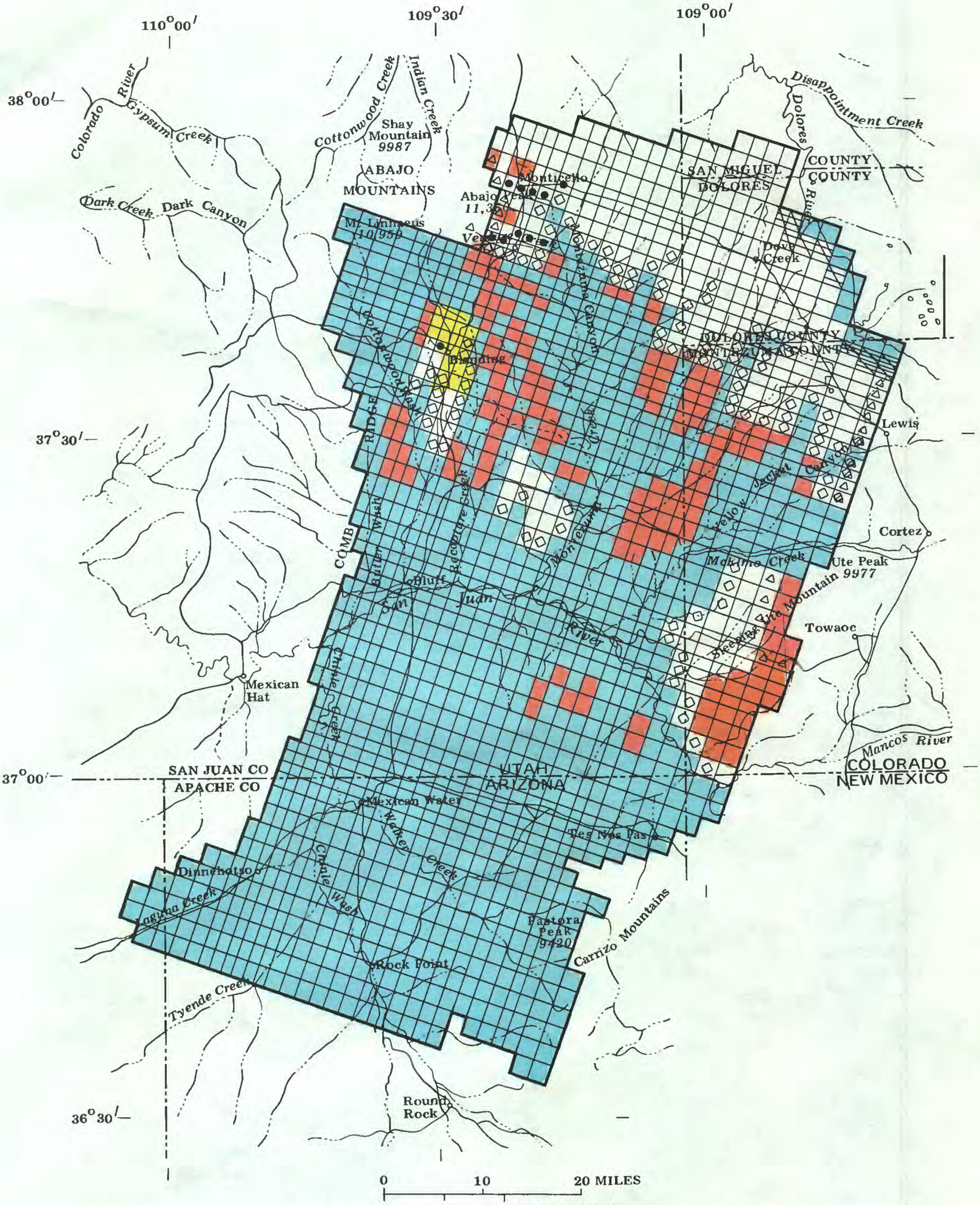


Figure 17.--Finite-difference grid and boundaries used to simulate the Dakota aquifer.

One other adjustment was made to the initial boundary conditions. The position of the north no-flow boundary of the Entrada-Navajo and Morrison aquifers in the initial simulation was along the north edge of the finite-difference grids shown in figures 15 and 16. That north edge of the grid was along a ground-water divide for the Dakota aquifer described by Avery (1986, p. 49 and fig. 19) and the assumed ground-water divides for the Entrada-Navajo and Morrison aquifers. No water-level data were available for the Entrada-Navajo or Morrison aquifers in that area, but concepts based on sources of recharge make it feasible for either aquifer to be unsaturated in the area. Initial simulations showed that the north parts of the Entrada-Navajo and Morrison aquifers could be unsaturated. Therefore, the north no-flow boundary was moved southward the appropriate distance assuming that the aquifers were unsaturated north of the adjusted boundary position and saturated south of the adjusted boundary position.

The lower boundary for vertical flow in the ground-water system is the base of the Entrada-Navajo aquifer, and it was simulated as a no-flow boundary. The upper boundary for each aquifer was simulated as the altitude of the water table in unconfined areas, and as the altitude of the top of the aquifer in confined areas.

Vertical flow between aquifers is computed across the Wanakah and Brushy Basin confining units, which were treated as head-dependent flux boundaries. Flow is computed two different ways depending on the confined or unconfined condition of buried aquifers. Where the lower aquifer is confined, vertical flow can be upward or downward, and flow is a function of the head difference between the adjacent aquifers and the vertical conductance between the adjacent aquifers. The Morrison and Dakota aquifers have several areas of perched conditions. In these areas, the model computes a constant flow rate from the perched aquifer down to the underlying unconfined aquifer. The flow rate is a function of the vertical conductance between adjacent aquifers, and the difference between the head in the perched aquifer and the altitude of the bottom of the confining unit (McDonald and Harbaugh, 1984, p. 138-147).

Entrada-Navajo aquifer

The finite-difference grid and boundaries used to simulate the Entrada-Navajo aquifer are shown in figure 15. No-flow boundaries were placed at the physical limit of the aquifer where it has been removed by erosion. Such locations are the west (Comb Ridge) boundary, most of the south boundary, and a small area of older-rock outcrop in the Dolores River canyon (figs. 9, 14, and 15). No-flow boundaries also were placed at the north boundary and the east part of the south boundary where ground-water divides exist (Avery, 1986, fig. 14).

Recharge to the Entrada-Navajo aquifer was simulated with specified-flux nodes for: (1) infiltration of rainfall and snowmelt on outcrops, (2) subsurface inflow from the mountain areas, and (3) subsurface inflow through the southwest boundary. Recharge by seepage from perennial streams was simulated with the river head-dependent boundary. In the areas where the Morrison aquifer was not simulated (fig. 15), it was assumed that vertical leakage moved from the Morrison to Entrada-Navajo aquifer. This was simulated with specified flux directly applied to the Entrada-Navajo aquifer.

Ground-water discharge by seepage to perennial streams and seepage to alluvium in intermittent and ephemeral stream valleys was simulated with the river head-dependent boundary (fig. 15). This boundary was selected to simulate seepage to alluvium (and eventual evapotranspiration in intermittent and ephemeral stream valleys) instead of the evapotranspiration subroutine in the model because: (1) there was uncertainty regarding evapotranspiration rates, (2) many of the sites that were simulated are areas of spring and seep discharge, and (3) interaction of ground water in alluvium and in bedrock prevents accurate estimation of discharge from the bedrock aquifers. The river head-dependent boundary was considered reasonable as long as the computed discharges were within a reasonable range. Discharge from springs and seeps in the Entrada-Navajo aquifer is included with the simulation of seepage to perennial streams and to alluvium.

Uncertain flow conditions for the Entrada-Navajo aquifer are at the northeast (Dolores River), east, and southeast boundaries (fig. 14). A most likely flow condition for each of these boundaries, based on field information, was selected to calibrate the model (table 2).

The Entrada-Navajo aquifer is in contact with part of the Dolores River, therefore, recharge occurs as seepage from the river to the aquifer. Water-level data are too meager in this area to indicate whether the seepage flows directly from the river to the saturated aquifer, or whether the seepage flows through unsaturated material before reaching the water table of the Entrada-Navajo aquifer. The river head-dependent boundary was used to simulate the Dolores River because it will limit the flow from the river if the aquifer material becomes unsaturated.

The Entrada-Navajo aquifer extends beyond the east and southeast boundaries of the model, and flow conditions are uncertain at these two model boundaries because of meager water-level data. The most likely condition for the east boundary is no-flow, and the alternative is inflow. The most likely condition for the southeast boundary is also no-flow, with alternatives of inflow or outflow. Therefore, the east and southeast boundaries were simulated as no-flow during calibration.

Morrison aquifer

The finite-difference grid and boundaries used to simulate the Morrison aquifer are shown in figure 16. No-flow boundaries were placed at the physical limit of the aquifer where it has been removed by erosion and where the potentiometric surface (fig. 10) shows ground-water flow away from or parallel to those physical limits. Such locations are along the west side of the physical limit north of the San Juan River, along the southwest side of the physical limit south of the San Juan River in Utah, and along the extreme south side of the physical limit in Arizona (figs. 11 and 16). A no-flow boundary was placed at the north boundary (fig. 14) where a ground-water divide was assumed.

Recharge to the Morrison aquifer was simulated with specified-flux nodes for: (1) infiltration of rainfall and snowmelt on outcrops, (2) subsurface inflow from the mountain areas, (3) subsurface inflow through the east boundary, and (4) percolation of rainfall and snowmelt through outcrops of the Brushy Basin confining unit. In the areas where the Dakota aquifer was not simulated (fig. 16), it was assumed that vertical leakage moved from the Dakota to Morrison aquifer. This was simulated with specified flux directly applied to the Morrison aquifer. Recharge by seepage from perennial streams was simulated with the river head-dependent boundary. Ground-water discharge by seepage to perennial streams and seepage to alluvium in intermittent and ephemeral stream valleys was simulated with the river head-dependent boundary.

Discharge from springs and seeps was separated into springs and seeps on canyon walls and springs and seeps in stream valleys. The springs and seeps on canyon walls were simulated with the drain head-dependent boundary (fig. 16). Discharge from the springs and seeps in stream valleys is included with the simulation of seepage to perennial streams and to alluvium.

Uncertain flow conditions for the Morrison aquifer are at the northeast (Dolores River), east, and southeast boundaries (fig. 14). A most likely flow condition for each of these boundaries, based on field information, was selected to calibrate the model (table 2).

The Morrison aquifer is in contact with part of the Dolores River, therefore, recharge occurs as seepage from the river to the aquifer. Water-level data are too meager in this area to indicate whether the seepage flows directly from the river to the saturated aquifer, or whether the seepage flows through unsaturated material before reaching the water table of the Morrison aquifer. The river head-dependent boundary was used to simulate the Dolores River because it will limit the flow from the river if the aquifer material becomes unsaturated.

The Morrison aquifer extends beyond the east and southeast boundaries, and flow conditions are uncertain because of meager water-level data. The most likely flow condition for the east boundary is a small quantity of inflow, and the alternative is a large quantity of inflow. The most likely flow condition for the southeast boundary is no-flow, with alternatives of inflow or outflow. Therefore, the east boundary was simulated with specified-flux nodes and the southeast boundary was simulated as no-flow during calibration.

Dakota aquifer

The finite-difference grid and boundaries used to simulate the Dakota aquifer are shown in figure 17. No-flow boundaries were placed at the physical limit of the aquifer where it has been removed by erosion and where the potentiometric surface (fig. 12) shows ground-water flow away from or parallel to those physical limits. Such locations are along the northwest, north, and northeast sides of the physical limits. A no-flow boundary was placed along the southeast boundary of the model (fig. 14) based on ground-water flow parallel to the model boundary (fig. 12). No-flow boundaries were placed along the north and northeast model boundaries along ground-water divides described by Avery (1986, p. 49 and fig. 19).

Recharge to the Dakota aquifer was simulated with specified-flux nodes for: (1) infiltration of rainfall and snowmelt on outcrops, (2) subsurface inflow from the mountain areas, (3) subsurface inflow through the east boundary, (4) percolation of rainfall and snowmelt through outcrops of the Mancos confining unit, and (5) seepage from unconsumed irrigation water. The seepage from unconsumed irrigation water was applied at nodes in the northeast part of the mesa near Blanding where canals and irrigated fields are located. Recharge by seepage from perennial streams was simulated with the river head-dependent boundary. Discharge from the aquifer by seepage to perennial streams was simulated with the river head-dependent boundary, and discharge from springs and seeps on canyon walls was simulated with the drain head-dependent boundary (fig. 17).

Calibration Procedure

The calibration of a ground-water model is a trial-and-error procedure wherein values of hydraulic properties and rates of recharge and discharge are adjusted within prescribed limits until a reasonable match is achieved between simulated and measured water levels, and simulated and estimated discharge to streams. The prescribed limits of hydraulic properties, recharge, and discharge are given in the following section entitled "Conceptual Limits for Hydrologic Parameters".

The hydraulic conductivity of the aquifers and vertical leakance of the confining units were adjusted, but values were kept uniform across the corresponding layer of the model. All the recharge to the system was simulated with specified-flux nodes, except a small quantity of recharge by seepage from perennial streams, which was simulated with the river head-dependent boundary. Recharge through the lateral boundaries of the model was adjusted by changing values of specified flux, and recharge by infiltration of rainfall and snowmelt was adjusted by uniformly changing the percentage of mean annual precipitation that was applied on the outcrop areas. All the discharge was simulated with either the river or drain head-dependent boundaries. The quantity of discharge was adjusted by changing the conductance values of the head-dependent boundaries.

Conceptual Limits for Hydrologic Parameters

This section provides a summary of the independent estimates for hydraulic properties, recharge, and discharge of the ground-water system. These estimates were made using field data and results of previous investigations, and the methods and sources of these estimates were explained in the previous section entitled "Ground-Water System". The values cited in this section were used during the calibration of the model.

Hydraulic properties of aquifers and confining units

Values of hydraulic conductivity and the top and bottom altitudes of each aquifer were entered in the model. The model computes transmissivity from saturated thickness times hydraulic conductivity. The confining units were simulated using the vertical leakance of the confining units. During calibration, the hydraulic conductivity for each aquifer and vertical leakance for each confining unit were kept a uniform value for every cell in the corresponding model layer. The allowable range for hydraulic conductivity of the three aquifers was 0.1 to 1.0 ft/d. The range for vertical leakance of the confining units was 10^{-10} to 10^{-7} (ft/d)/ft.

The top and bottom altitudes of the Entrada-Navajo, Morrison, and Dakota aquifers were estimated using published maps (Strobell, 1956; Haynes and others, 1972; Huff and Lesure, 1965; O'Sullivan and Beikman, 1963; and Avery, 1986), and data obtained from U.S. Geological Survey files and petroleum test-hole records. Values of altitude for each cell could be adjusted during calibration by plus or minus 50 ft in areas with a reasonable quantity of data, and by plus or minus 200 ft in areas with meager or no data. Adjustments to top and bottom altitudes could not result in changing the initial estimated thickness of an aquifer by more than 20 percent.

Recharge

Recharge by infiltration of rainfall and snowmelt occurs on the model area (plateau area) and the mountain areas. For the model area, an array of mean annual precipitation values was prepared for the outcrop area of each aquifer and the outcrop areas of the Brushy Basin and Mancos confining units. A percentage of the mean annual precipitation on each outcrop area was applied as areal recharge. The infiltration and percolation through a confining unit was applied as recharge to the underlying aquifer. The range for percentage of mean annual precipitation was 1 to 3 percent for aquifer outcrops and 0 to 2 percent for the confining-unit outcrops. The range for recharge from this source to the entire model area was 1 to 3 percent of mean annual precipitation or 23,000 to 68,000 acre-ft/yr.

Several parts of the Morrison and Dakota aquifers were not simulated in the model (see page 45 and figs. 16 and 17). Some compensation had to be made for this deletion. The loss to the system is vertical leakage from the overlying to underlying aquifer. To compensate for this loss, a specified flux was applied to the Morrison or Entrada-Navajo aquifer in these areas. The range of flow directly applied to the underlying aquifer was 10 to 50 percent of the estimated areal recharge for the overlying aquifer.

Infiltration of rainfall and snowmelt on the mountain areas moves as subsurface inflow into the model area. The range for recharge from the mountain areas was 5 to 15 percent of the mean annual precipitation, which was 4,150 to 12,500 acre-ft/yr from the Abajo Mountains, 1,550 to 4,650 acre-ft/yr from Sleeping Ute Mountain, and 2,550 to 7,650 acre-ft/yr from the Carrizo Mountains. The recharge was spread evenly along the lateral boundary for each aquifer adjacent to the mountain areas. The vertical distribution of the subsurface inflow to the 3 aquifers is unknown, but is related to the depth and thickness of the aquifers and quantity of fractures in the aquifers in the mountain areas. The initial estimate for distributing recharge within a vertical column was 20 percent to the Entrada-Navajo aquifer, 40 percent to the Morrison aquifer, and 40 percent to the Dakota aquifer.

The estimate for subsurface inflow from an adjoining area was 1,500 acre-ft/yr through the southwest boundary to the Entrada-Navajo aquifer. Estimates of inflow through the east boundary to the Morrison and Dakota aquifers were not made because of meager data.

An estimate for recharge by seepage from streams to the Entrada-Navajo aquifer was 2,200 acre-ft/yr from middle Montezuma Creek. Recharge to the Morrison aquifer was estimated to be 550 acre-ft/yr from upper Cottonwood Wash and 2,200 acre-ft/yr from middle Montezuma Creek.

Seepage from streams was simulated with the river head-dependent boundary. The quantity of seepage to or from a river node is based on the altitude of water in the stream, the simulated water level in the aquifer for that node, and the vertical conductance for the node. The range for altitude of water in the streams was between 1 and 4 ft above the altitude of the streambed. Flow between an aquifer and a stream was adjusted during the simulations by changing the values of vertical conductance.

The conductance of river nodes was estimated using the equation, $C=KA/L$. A wide range for values of conductance (C) was used because the thickness (L) and hydraulic conductivity (K) of the streambeds are not measured and are difficult to estimate. The remaining factor in conductance is the area (A) through which water moves between the aquifer and the stream. The area of a stream was, therefore, used to determine relative differences in conductance for the streams. The San Juan and Dolores Rivers are the largest streams in the area, therefore, their conductance values were assigned values one order of magnitude larger than all other streams. The other perennial streams were assumed to have conductance values within two orders of magnitude of each other. Thus, a three order of magnitude difference for conductance was assigned between nodes simulating perennial streams. Absolute limits for conductance were 10 to 50,000 ft^2/d, based on measured areas of streams, thickness of streambeds of 1 to 10 ft, and hydraulic conductivity of streambeds of 0.01 to 1.0 ft/d.

Recharge of unconsumed irrigation water (primarily supplied by imported surface water) to the Dakota aquifer was simulated with specified-flux nodes in about 17,000 acres in the Blanding area. The initial estimate used in the model was 500 acre-ft/yr applied uniformly over the irrigated area.

Discharge

Seepage to perennial streams was simulated with the river head-dependent boundary. The range for values of vertical conductance of the river nodes was explained in the previous subsection on recharge. Estimates for discharge by seepage to perennial streams from the Entrada-Navajo aquifer were 5,000 acre-ft/yr to the San Juan River, 2,900 acre-ft/yr to Chinle Wash and Laguna Creek, and 190 acre-ft/yr to upper Cottonwood Wash (intermittent stream). Discharge to McElmo Creek from the Morrison aquifer was estimated to be 1,500 acre-ft/yr. Discharge from the Morrison and Dakota aquifers to upper Montezuma Creek was estimated to be 2,800 acre-ft/yr.

Seepage to stream-valley alluvium (and eventual evapotranspiration) was simulated with the river head-dependent boundary. The discharge by evapotranspiration in perennial stream valleys is included in the simulation of seepage to perennial streams. Thus, the total simulated ground-water discharge in the areas of perennial streams may need to be slightly larger than discharge estimates based on measured gains in streamflow during base-flow periods. A quantitative estimate of evapotranspiration in perennial stream valleys was not made, because the movement of water between the stream and alluvium and to evapotranspiration is highly interactive. A rough estimate for total simulated discharge to perennial streams was, therefore, 0 to 20 percent larger than the estimates given for seepage to perennial streams.

Estimates for seepage to alluvium in intermittent and ephemeral stream valleys were made based on areas of stream valleys and assumed rates of evapotranspiration. The estimate for the Entrada-Navajo aquifer was 470 to 1,400 acre-ft/yr. The estimate for the Morrison aquifer was 1,700 to 5,000 acre-ft/yr. The values for vertical conductance of river nodes simulating seepage to alluvium in intermittent and ephemeral stream valleys were only limited so simulated discharge was within the specified ranges.

Ground-water discharge through springs and seeps was separated into springs and seeps in stream valleys and springs and seeps on canyon walls. Flow from springs and seeps in stream valleys is included in the simulation of seepage to perennial streams and seepage to alluvium in intermittent and ephemeral stream valleys. The flow from springs and seeps on canyon walls was simulated with the drain head-dependent boundary. Estimates for a minimum rate of flow from springs and seeps on canyon walls were 280 acre-ft/yr from the Morrison aquifer and 160 acre-ft/yr from the Dakota aquifer.

The nodes simulated as drains are in the Morrison and Dakota aquifers and are shown on figures 16 and 17. The altitude of the bottom of the aquifer was used for the elevation of the drain. The range for values of drain conductance was calculated using the equation, $C=KA/L$. Area (A) was used to make the conductance for all drain nodes proportional to the length of the side of the cell where water is discharging from the aquifer onto a canyon wall. A cell that is 1.2 mi wide had a conductance value 60 percent of the value of a cell 2 mi wide. Area (A) is length of the cell times height, and height was assumed to be 1 ft for all cells. Length (L) was assumed to be 1 ft for all cells. For several cells where the Dakota aquifer was locally absent due to canyon cutting, conductance values were assigned that were proportional to twice the cell width. During all simulations, these cells were checked to make sure all flow leaving the cells either went to vertical leakage or drain discharge.

The hydraulic conductivity (K) of the drain nodes was assumed to be several orders of magnitude smaller than the hydraulic conductivity of the Morrison or Dakota aquifers, because flow through the drain nodes was assumed to include some flow through unsaturated material as the water flowed from the aquifer to the canyon wall. The transition from saturated to unsaturated conditions generally entails a steep drop of several orders of magnitude in values of hydraulic conductivity (Hillel, 1971, p. 105). A range of hydraulic conductivity of 0.0001 to 0.1 ft/d was, therefore, used to estimate a range for conductance for the drain nodes of 1 to 1,000 ft^2/d.

Results of Calibration

Calibration of the model resulted in a reasonable representation of the ground-water system. Simulated potentiometric surfaces for the Entrada-Navajo, Morrison, and Dakota aquifers are shown in figures 18 to 20. The known areas of recharge, discharge, and vertical head gradients were reproduced in the model.

The accuracy of a simulation can be expressed in terms of the residuals, which are the differences between measured water levels and simulated water levels. The measured water levels used in this study are shown in figures 8, 10, and 12. Some statistics were computed for the residuals to express the

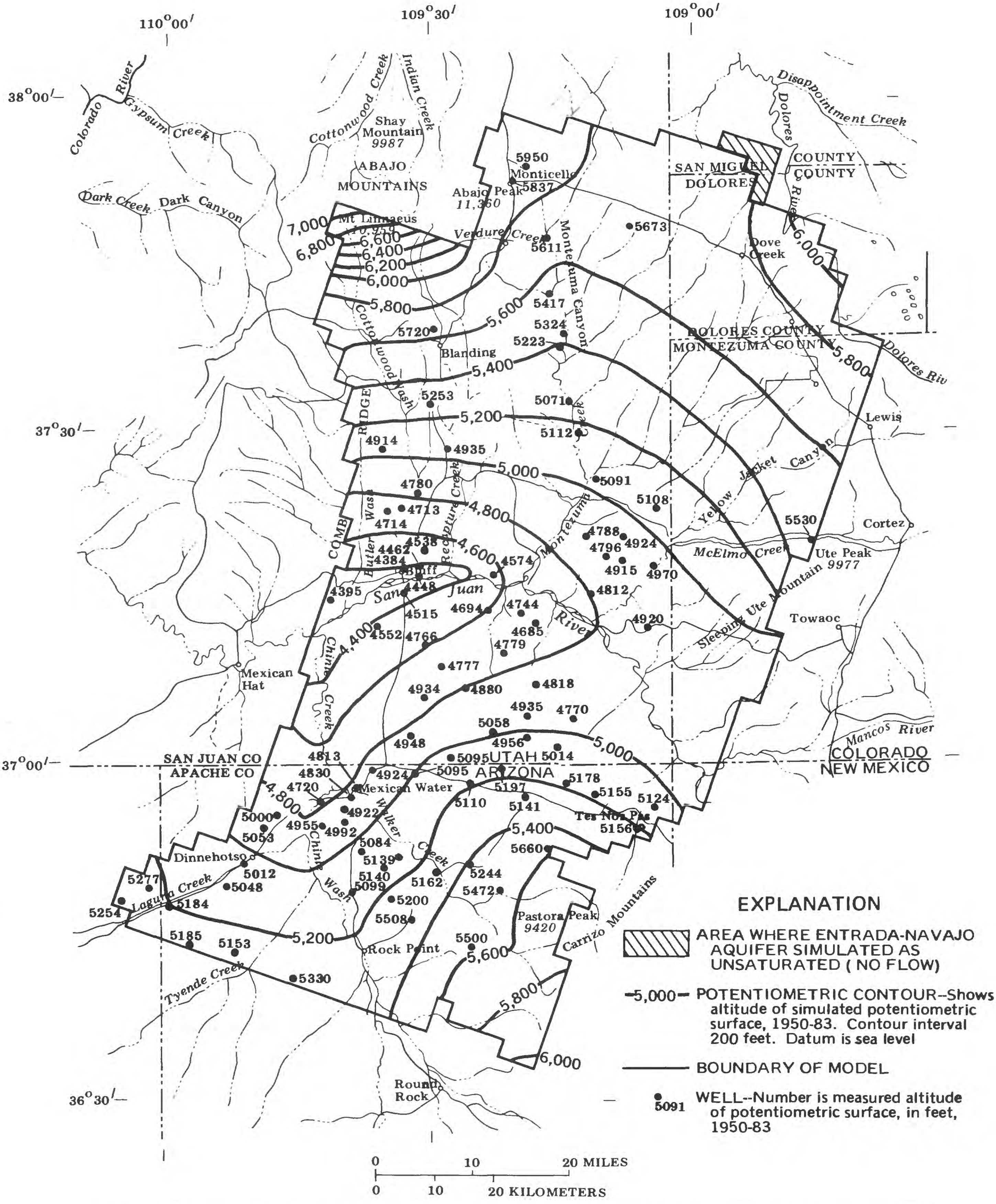


Figure 18.--Simulated steady-state potentiometric surface of the Entrada-Navajo aquifer, 1950-83.

EXPLANATION

AREA WHERE MORRISON AQUIFER SIMULATED AS UNSATURATED (NO FLOW)

AREA WHERE MORRISON AQUIFER NOT SIMULATED

AREA WHERE MORRISON AQUIFER IS ABSENT

—5000— POTENTIOMETRIC CONTOUR--Shows altitude of simulated potentiometric surface, 1950-83. Contour interval 200 feet. Datum is sea level

BOUNDARY OF MODEL

● 5039 WELL--Number is measured altitude of potentiometric surface, in feet, 1950-83

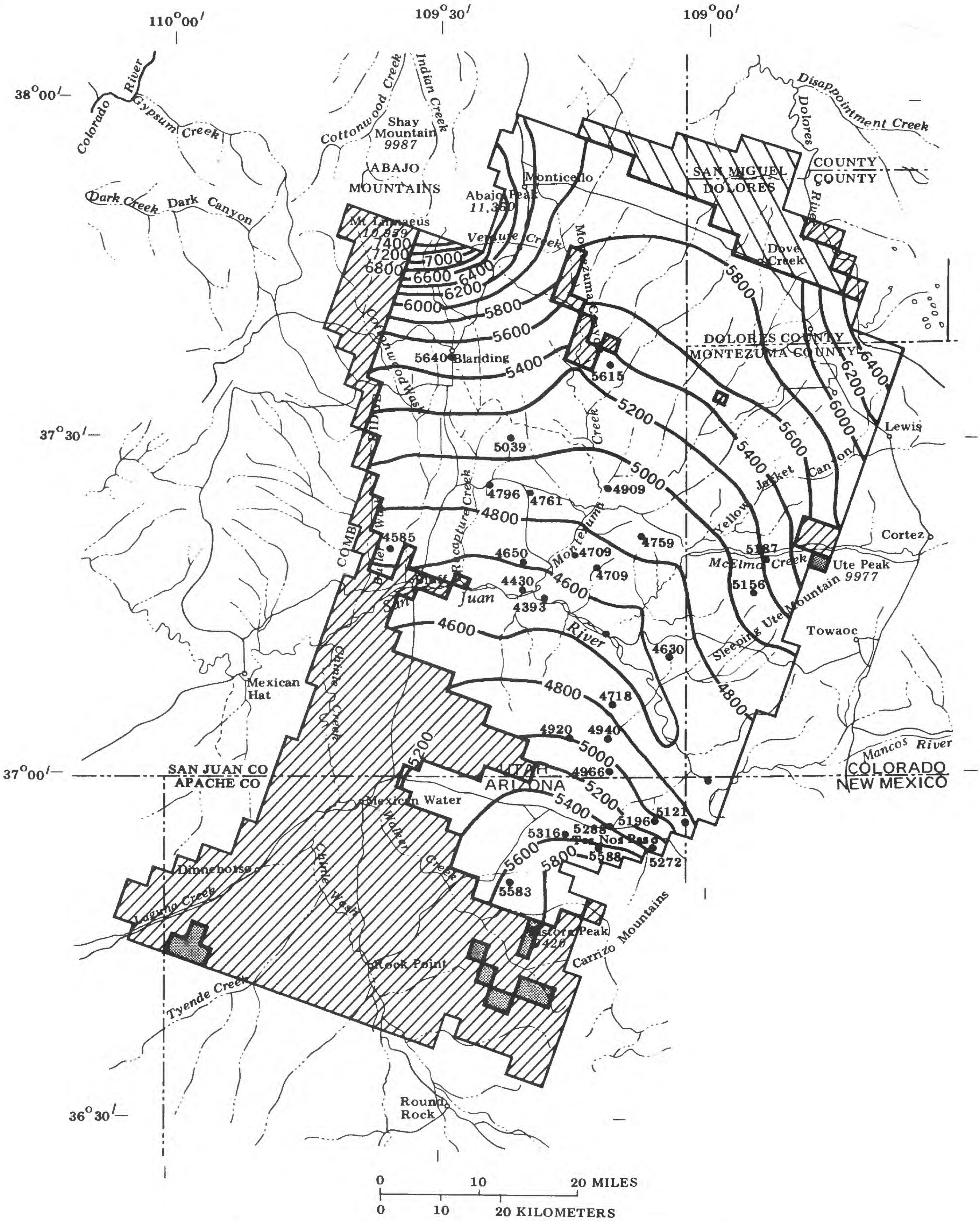


Figure 19.--Simulated steady-state potentiometric surface of the Morrison aquifer, 1950-83.

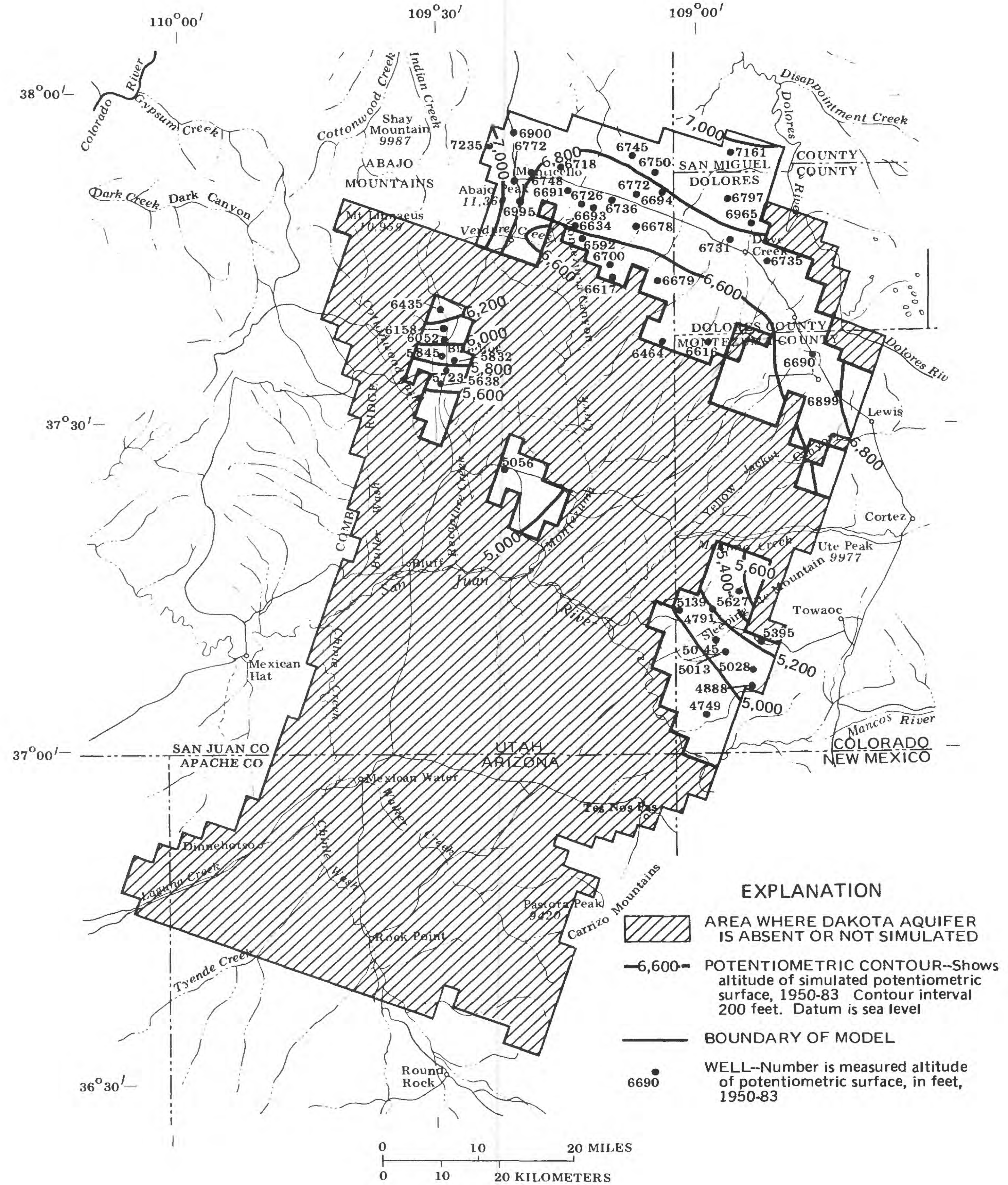


Figure 20.--Simulated steady-state potentiometric surface of the Dakota aquifer, 1950-83.

accuracy of a simulation. The mean of the residuals was computed to show the bias in the distribution of positive or negative values. A large positive mean residual indicates more positive values than negative ones. A small mean residual indicates nearly equal quantities of positive and negative residuals; however, it does not necessarily indicate that the simulation can reproduce each measured water level. The absolute value of each residual was also determined and mean values of these numbers were computed. The absolute value of a residual is henceforth called the error.

The means of the residuals and errors were determined for five sets of measured water levels: (1) Entrada-Navajo aquifer, north of the San Juan River, (2) Entrada-Navajo aquifer, south of the San Juan River, (3) Morrison aquifer, north of the San Juan River, (4) Morrison aquifer, south of the San Juan River, and (5) Dakota aquifer. Data for the Entrada-Navajo and Morrison aquifers were separated by the San Juan River, which is the regional sink of the flow system.

The match of measured to simulated water levels is summarized in table 3, and the residuals (measured - simulated water level) for each aquifer are shown in figures 21 to 23. The mean error (mean absolute value of residual) is 70 ft for the Entrada-Navajo aquifer, 67 ft for the Morrison aquifer, and 79 ft for the Dakota aquifer.

The range of residuals for the Entrada-Navajo, Morrison, and Dakota aquifers was -181 to 179 ft, -244 to 236 ft, and -209 to 217 ft, respectively. The adjustment of hydraulic properties and rates of recharge and discharge within prescribed limits did not decrease the range in residuals. The goal, during calibration, was to minimize the errors and to obtain an even areal distribution of positive and negative values of residuals. This goal was generally achieved, but the areal distribution of residuals is slightly biased for the Entrada-Navajo aquifer. North of the San Juan River, most of the residuals were negative (simulated water levels are higher than measured); and south of the San Juan River, most of the residuals were positive.

The hydraulic-property values (hydraulic conductivity of aquifers, vertical leakance of confining units, and conductance for river and drain nodes) used in the model were within the prescribed limits. The hydraulic conductivity was 0.46 ft/d for the Entrada-Navajo aquifer, 0.47 ft/d for the Morrison aquifer, and 0.38 ft/d for the Dakota aquifer. The vertical leakance for the confining units was 1.8×10^{-7} (ft/d)/ft for the Wanakah confining unit and 4.1×10^{-8} (ft/d)/ft for the Brushy Basin confining unit. These values of hydraulic properties were uniform for the entire model layer. The vertical conductance for river nodes simulating perennial streams was 8,600 ft^2/d for the San Juan River, 3,500 ft^2/d for the Dolores River, and a range of 90 to 5,200 ft^2/d for all other perennial streams. The vertical conductance for the river nodes simulating seepage to alluvium in intermittent and ephemeral stream valleys ranged from 7 to 90 ft^2/d. The conductance for drain nodes ranged from 10 to 35 ft^2/d.

Table 3.—Statistics of differences between measured and simulated water levels

[Residual: Measured water level - simulated water level. Error: Absolute value of residual]

Aquifer and area	Number of measured water levels	Residual, in feet			Error, in feet	
		Mean	Maximum	Minimum	Mean	Standard deviation
Dakota aquifer	46	14	217	-209	79	65
Morrison aquifer	28	-11	236	-244	67	68
North of San Juan River	17	-7	216	-118	59	56
South of San Juan River	11	-17	236	-244	79	84
Entrada-Navajo aquifer	86	3	179	-181	70	48
North of San Juan River	29	-34	94	-173	65	50
South of San Juan River	57	23	179	-181	73	48

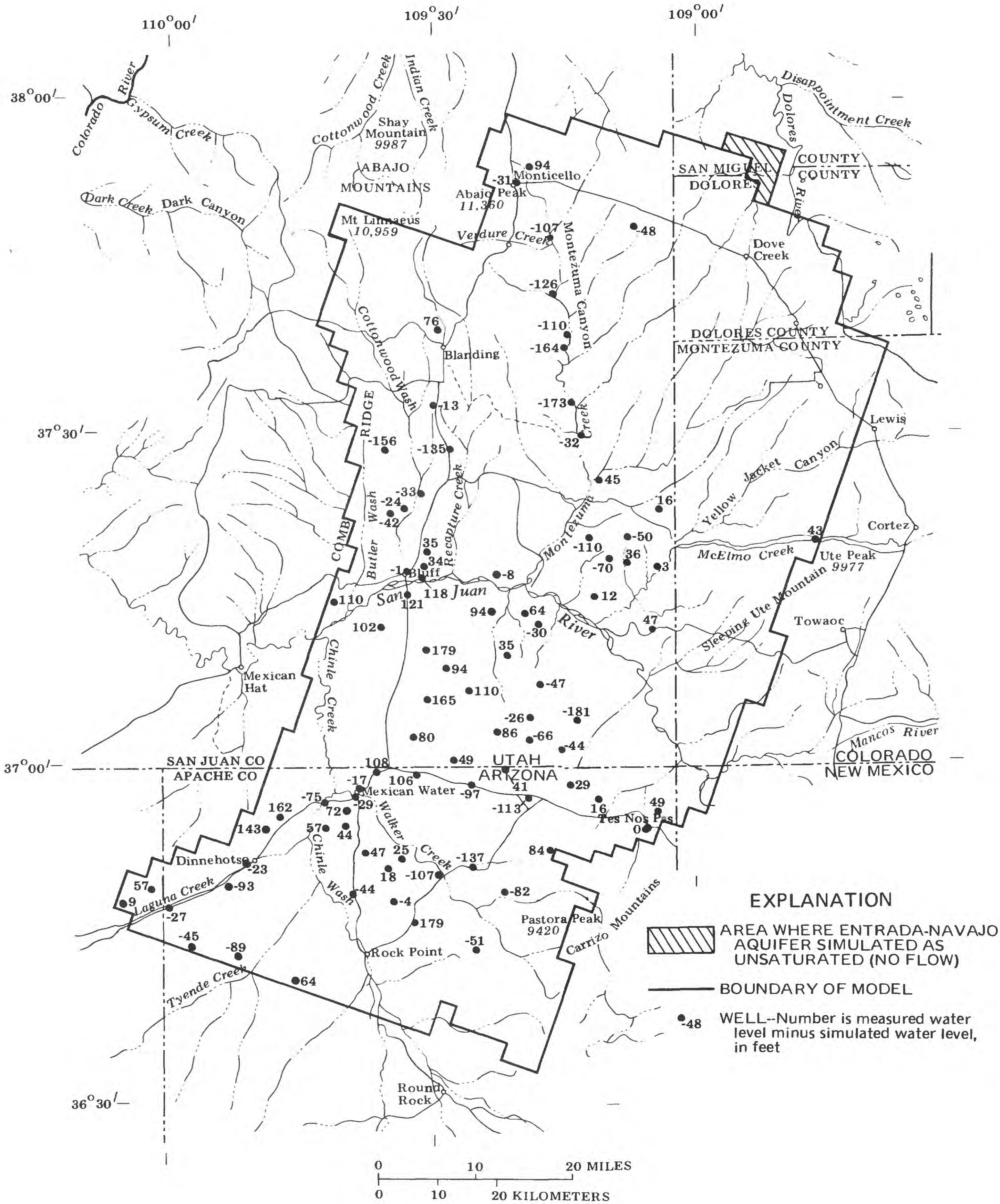


Figure 21.--Differences between measured and simulated water levels for the Entrada-Navajo aquifer.

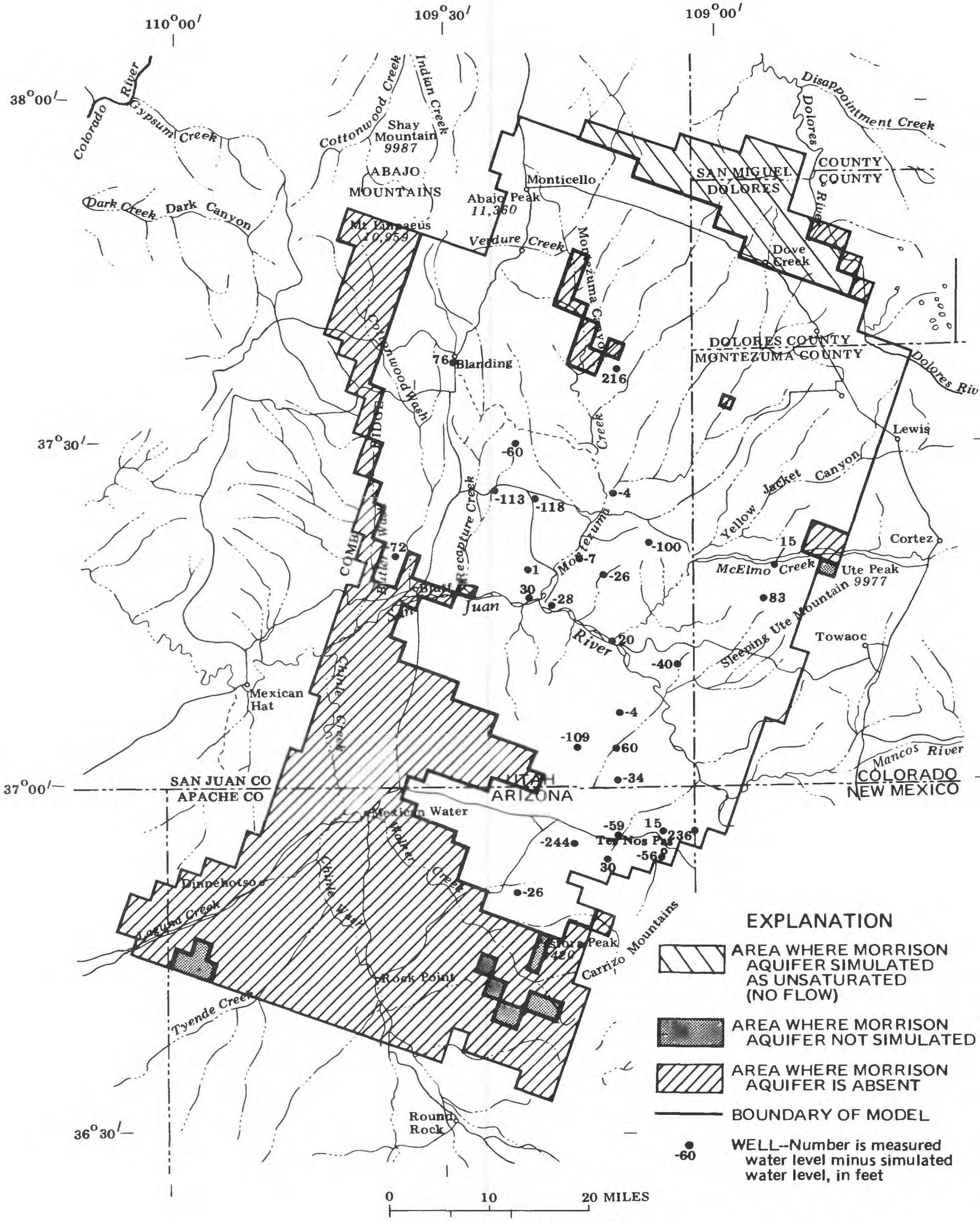


Figure 22.--Differences between measured and simulated water levels for the Morrison aquifer.

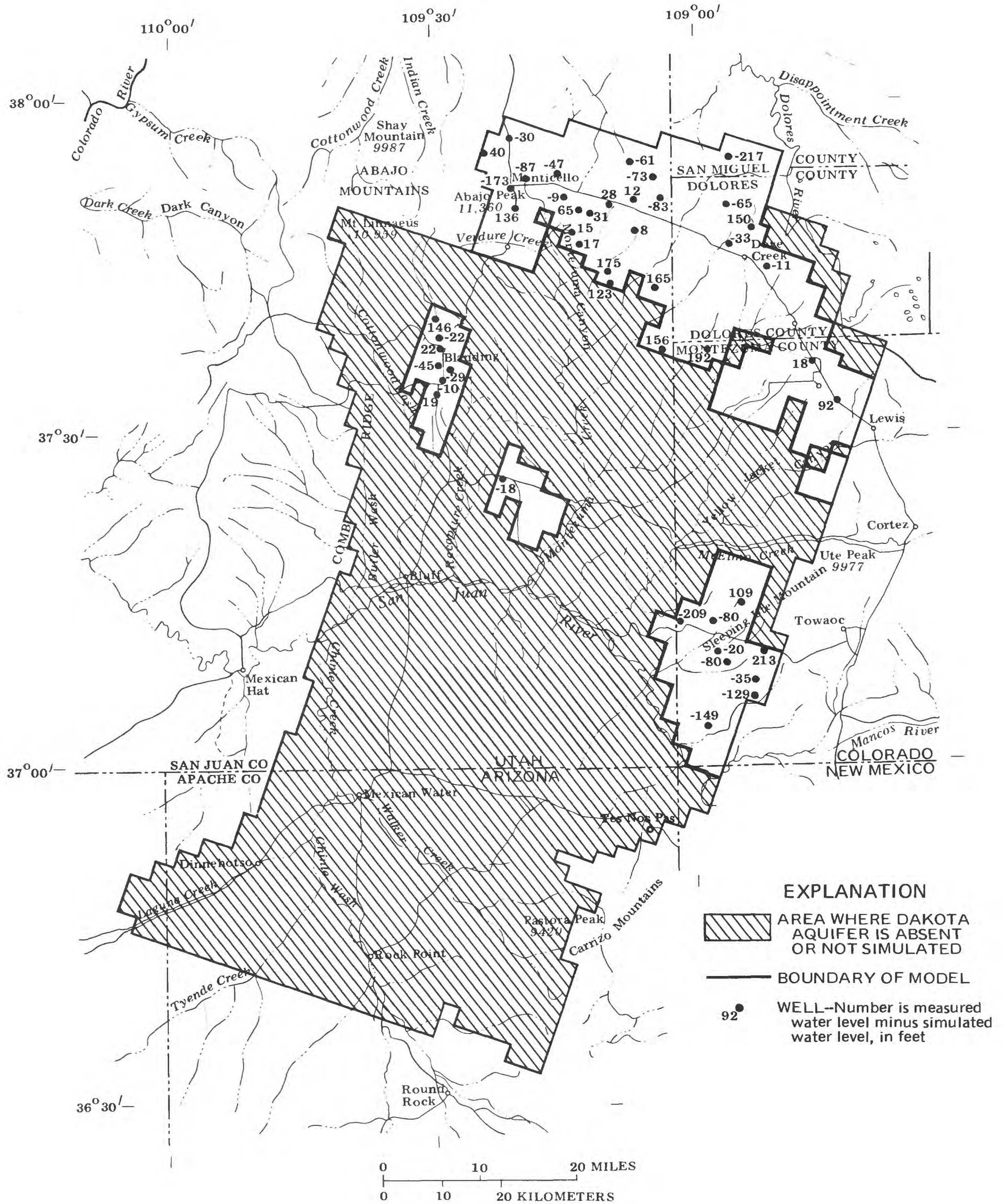


Figure 23.--Differences between measured and simulated water levels for the Dakota aquifer.

The small values of conductance for drain nodes (10-35 ft^2/d) are justified based on the concept that the flow through springs and seeps on canyon walls includes some flow through unsaturated material with its associated small values of hydraulic conductivity. The hydraulic conductivity used in calculating conductance for the drain nodes was about 0.001 ft/d. The hydraulic conductivity used in calculating vertical conductance of river nodes simulating perennial streams ranged from about 0.01 to 0.5 ft/d.

The simulated ground-water budget (table 4) is only an approximation; however, the quantities and distribution of water were consistent with most of the estimated discharges. Total inflow to the ground-water system was 30,390 acre-ft/yr as compared to the previously estimated inflow of about 40,000 to 100,000 acre-ft/yr. The discrepancy between simulated inflow and estimated inflow by other investigators is due to the estimates of infiltration of precipitation on the plateau area. The 5 percent estimate by Avery (1986) seems to be high. If the estimated inflows exclude Avery's estimate, then the estimated inflow is between 25,000 and 40,000 acre-ft/yr, which is closely correlated with the simulated inflow. Annual inflow to each aquifer, excluding vertical leakage, was 14,370 acre-ft to the Entrada-Navajo aquifer, 11,560 acre-ft to the Morrison aquifer, and 4,460 acre-ft to the Dakota aquifer. Simulated annual vertical flow was 2,560 acre-ft from the Dakota to Morrison aquifer, 7,270 acre-ft from the Morrison to Entrada-Navajo aquifer, and 6,120 acre-ft from the Entrada-Navajo to Morrison aquifer. The areas and quantities of simulated vertical flow between the Entrada-Navajo and Morrison aquifers are shown in figure 24. Simulated annual vertical flow from the Dakota to Morrison aquifer was 1,880 acre-ft in the northeast area, 220 acre-ft near Blanding, 60 acre-ft in the area near lower Montezuma Creek, and 400 acre-ft southwest of Sleeping Ute Mountain (fig. 20).

Vertical leakage between aquifers is a significant part of the simulated water budget. Vertical leakage from the Dakota to Morrison aquifer was 57 percent of the total inflow to the Dakota aquifer. Vertical leakage from the Morrison to Entrada-Navajo aquifer was 36 percent of the total inflow to the Morrison aquifer and vertical leakage from the Entrada-Navajo to Morrison aquifer was 28 percent of the total inflow to the Entrada-Navajo aquifer.

The simulated recharge from infiltration of rainfall and snowmelt on the plateau area (model area) was 14,560 acre-ft/yr, which is 48 percent of the total inflow. The distribution of this recharge is 7,520 acre-ft to the Entrada-Navajo aquifer, 4,510 acre-ft to the Morrison aquifer, and 2,530 acre-ft to the Dakota aquifer. The areal recharge of 2,530 acre-ft/yr for the Dakota aquifer is not representative of the whole Dakota aquifer in the study area, because about 20 percent of the areal extent of the Dakota aquifer was not simulated. Those parts of the Dakota aquifer were not simulated, because they are narrow, isolated mesas that are too small compared to the model grid size. The recharge in the mesas was simulated as vertical leakage to the underlying aquifers.

Table 4.—Simulated steady-state ground-water budget

[Values are in acre-feet per year. Values in parentheses are independent estimates based on field data. For explanation of independent methods, see "Ground-Water System" section of text.]

Budget element	Dakota aquifer	Morrison aquifer	Entrada-Navajo aquifer
Inflow:			
Infiltration of rainfall and snowmelt			
Plateau area (model area)			
Outcrop areas of aquifers[1]	2,500	4,050	7,340
Outcrop areas of confining units			
Mancos	30	—	—
Brushy Basin	—	270	—
Specified flux[2]	—	190	180
Total	2,530	4,510	7,520
Mountain areas			
Abajo Mountains	620	3,380	3,270
Sleeping Ute Mountain	590	880	470
Carrizo Mountains	—	1,770	1,640
Total	1,210	6,030	5,380
Subsurface inflow from adjoining areas			
East boundary	380	430	0
Southwest boundary	—	—	950 (1,500)
Seepage from streams			
Dolores River	—	530	460
Middle Montezuma Creek	—	0 (2,200)	0 (2,200)
Upper Cottonwood Wash	—	0 (550)	0
Other streams	50	60	60
Total	50	590	520
Seepage from unconsumed irrigation water	290	0	0
Total inflow—excluding vertical leakage	4,460	11,560	14,370
Vertical leakage			
From Dakota aquifer	—	2,560	—
From Morrison aquifer	0	—	7,270
From Entrada-Navajo aquifer	—	6,120	—

Table 4.—Simulated steady-state ground-water budget—Continued

Budget element	Dakota aquifer	Morrison aquifer	Entrada-Navajo aquifer
Outflow:			
Seepage to perennial streams (includes evapotranspiration in stream valleys)			
San Juan River	--	6,450	7,110 (5,000)
Upper Montezuma Creek	260	100	1,790
	——(2,800)——		(0)
Chinle Wash and Laguna Creek (above Mexican Water)	--	--	2,910 (2,900)
McElmo Creek (Utah-Colorado stateline to confluence with San Juan River)	--	1,530 (1,500)	--
Other perennial streams	210	1,000	2,700
Total	470	9,080	14,510
Flow through springs and seeps on canyon walls	1,430	350	0
Seepage to alluvium in intermittent and ephemeral stream valleys (includes evapotranspiration)	0	3,540 (1,700-5,000)	1,010 (470-1,400)
Total outflow—excluding vertical leakage	1,900	12,970	15,520
Vertical leakage			
To Dakota aquifer	--	0	--
To Morrison aquifer	2,560	--	6,120
To Entrada-Navajo aquifer	--	7,270	--

[1]The outcrop area of the Wanakah confining unit is small, and infiltration through the Wanakah outcrop is included in the quantity for the Entrada-Navajo aquifer.

[2]Specified flux represents vertical leakage from Dakota to Morrison aquifer and from Morrison to Entrada-Navajo aquifer in areas where the Morrison and Dakota aquifers are not simulated in the model.

The percentage of mean annual precipitation applied to bare-rock outcrop areas was 1 percent to the Entrada-Navajo aquifer (includes outcrop of Entrada-Navajo aquifer and Wanakah confining unit), 0.4 percent to the Morrison aquifer, 0.1 percent to the Brushy Basin confining unit (applied to Morrison aquifer in the model), 0.4 percent to the Dakota aquifer, and 0.1 percent to the Mancos confining unit (applied to Dakota aquifer in the model). The recharge rates from infiltration of rainfall and snowmelt for the Entrada-Navajo (7,250 acre-ft/yr) and Morrison aquifers (4,510 acre-ft/yr) include simulated vertical leakage from areas of the Morrison and Dakota aquifers that were not simulated as active nodes (table 4 and figs. 15 and 16). The simulated vertical leakage to the Morrison aquifer from inactive Dakota-aquifer nodes was equal to 0.1 percent of the mean annual precipitation on the corresponding area of Dakota-aquifer outcrop. The simulated vertical leakage to the Entrada-Navajo aquifer from inactive Morrison-aquifer nodes was equal to 0.2 percent of the mean annual precipitation on the corresponding area of Morrison-aquifer outcrop.

The percentages of mean annual precipitation applied as areal recharge were modified for the outcrops of the Entrada-Navajo and Morrison aquifers in the areas that are covered with alluvial or eolian deposits (figs. 15 and 16). The modification was 4 times the 1 and 0.4 percent values applied to the outcrop areas of bare rock. This increase in recharge was done as part of the calibration process, because it gave a better fit to measured water levels and the increase is hydrologically reasonable.

The simulated subsurface inflow from the mountain areas was 12,620 acre-ft/yr, which is 42 percent of the total inflow (table 4). The inflow is 9 percent of the mean annual precipitation for the Abajo Mountains, 6 percent for Sleeping Ute Mountain, and 7 percent for the Carrizo Mountains.

The specified flux applied to each aquifer at the mountain-area boundaries was spread evenly across the boundary based on the width of each cell. The quantity of inflow to each aquifer and the percentage of inflow applied to each aquifer within a vertical column was adjusted to match nearby measured water levels. The range in this percentage of inflow distributed within a vertical column was between 6 and 20 percent for the Entrada-Navajo aquifer, 38 and 41 percent for the Morrison aquifer, and 40 and 56 percent for the Dakota aquifer. For the areas where the Dakota aquifer is absent, the percentage of inflow was varied between 38 and 47 percent for the Entrada-Navajo aquifer and 53 and 62 percent for the Morrison aquifer.

The simulated recharge from infiltration of rainfall and snowmelt averaged 0.65 percent of mean annual precipitation on the plateau area. The small simulated recharge rate in this low-altitude area (below an altitude of 7,000 ft) is similar to recharge estimates for similar areas by Whitfield and others (1983, p. 30) who estimated no recharge in areas below 6,900 ft, and Eychaner (1983, p. 10) who estimated recharge of 1 percent of mean annual precipitation in areas below 6,500 ft. In contrast, the simulated recharge from infiltration in the high-altitude mountain areas is a fairly large average of 7.6 percent of mean annual precipitation. This simulated recharge is also reasonable when compared to the estimated range of 5 to 15 percent of mean annual precipitation and a measured infiltration rate for a similar area of 14 percent of precipitation during July-September 1977 (Danielson and Hood, 1984, p. 18).

EXPLANATION

- 220 — AREA OF DOWNWARD FLOW FROM MORRISON TO ENTRADA-NAVAJO AQUIFER--Number in outlined area is quantity in acre-feet per year
- 1110 — AREA OF UPWARD FLOW FROM ENTRADA-NAVAJO TO MORRISON AQUIFER--Number in outlined area is quantity in acre-feet per year
- AREA WHERE MORRISON AQUIFER SIMULATED AS UNSATURATED (NO FLOW)
- AREA WHERE MORRISON AQUIFER NOT SIMULATED
- AREA WHERE MORRISON AQUIFER IS ABSENT
- BOUNDARY OF MODEL

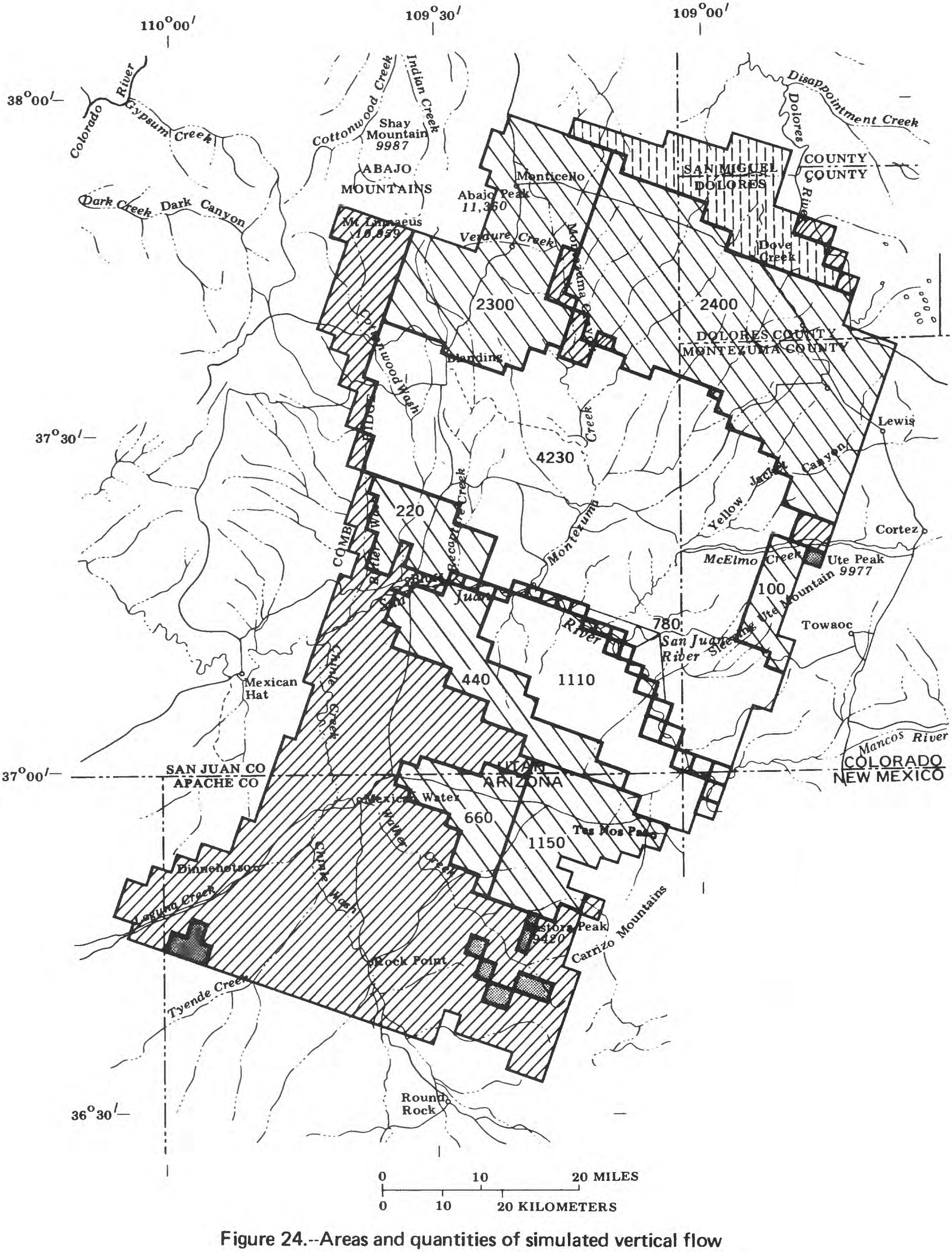


Figure 24.--Areas and quantities of simulated vertical flow between the Entrada-Navajo and the Morrison aquifers.

The distribution of simulated outflow from the ground-water system is 79 percent to perennial streams, 6 percent to flow through springs and seeps on canyon walls, and 15 percent to seepage to alluvium in intermittent and ephemeral stream valleys. The distribution of total outflow (including vertical leakage) from the Entrada-Navajo aquifer is 67 percent to perennial streams, 5 percent to seepage to alluvium in intermittent and ephemeral stream valleys, and 28 percent to the Morrison aquifer. The distribution of total outflow (including vertical leakage) from the Morrison aquifer is 45 percent to perennial streams, 2 percent to flow through springs and seeps on canyon walls, 17 percent to seepage to alluvium in intermittent and ephemeral stream valleys, and 36 percent to the Entrada-Navajo aquifer. The distribution of total outflow (including vertical leakage) from the Dakota aquifer is 11 percent to perennial streams, 32 percent to flow through springs and seeps on canyon walls, and 57 percent to the Morrison aquifer.

The simulated water budget has a fair correspondence with independent estimates of the water budget (table 4). The numbers enclosed in parentheses in table 4 are independently estimated values of recharge or discharge. The match of simulated to estimated budget elements is good for discharge from the Entrada-Navajo aquifer to the San Juan River and Chinle Wash and Laguna Creek, discharge from the Morrison aquifer to McElmo Creek, and discharge from the Entrada-Navajo and Morrison aquifers by seepage to alluvium in intermittent and ephemeral stream valleys. Another comparison, not shown in table 4, is estimated discharge of 190 acre-ft/yr from the Entrada-Navajo aquifer to part of upper Cottonwood Wash and simulated discharge of 180 acre-ft/yr to the same reach.

The simulation did not accurately reproduce estimates of aquifer recharge and discharge in middle and upper Montezuma Creek (table 4). This discrepency was not considered crucial in the simulation, because the purpose and scope of the study was to determine regional characteristics of the ground-water system, and the model was calibrated to obtain a reasonable match between simulated and estimated values for the entire model area. Also, the estimates of ground-water recharge and discharge from streamflow gains and losses in Montezuma Creek were uncertain because of (1) streamflow measurement errors, (2) interaction of streamflow loss or gain with ground water in alluvium, and (3) an uncertain quantity of effluent into Montezuma Creek from a sewage treatment plant near Monticello, Utah (Avery, C., U.S. Geological Survey, Salt Lake City, Utah, oral commun., 1985). In addition, the large size of the finite-difference cells (1.44 to 4.0 mi^2) and the simplification of 12 formations into 3 aquifers precluded a precise representation of a complex stream-aquifer interaction in a 22-mile reach of the stream.

The overall accuracy of the simulation is fair using the indicators of accuracy such as residuals (measured water levels minus simulated water levels) and the match of simulated to estimated budget elements. The residuals for the Entrada-Navajo aquifer have an areal bias where residuals are mostly negative north of the San Juan River (simulated water levels are too high), and residuals are mostly positive south of the San Juan River. The following sources of errors contribute to the inaccuracy of the simulation or to the areal bias of residuals for the Entrada-Navajo aquifer.

1. A complex system is simplified into rectangular blocks for the finite-difference model. A single characteristic is required for each cell,

which range in horizontal length from 1.2 to 2.0 mi, and vertical length ranges from 150 to 1,200 ft.

2. Grouping 12 sedimentary formations into only three aquifers is a major simplification of the system. In recharge and discharge areas, vertical gradients of water levels within the Entrada-Navajo and Morrison aquifers have been measured. The model does not account for these vertical differences in water levels within one aquifer.

3. The assumption of uniform hydraulic properties for each model layer is probably incorrect. This assumption could be one cause of the areal bias in residuals for the Entrada-Navajo aquifer, because the hydraulic conductivity of the Entrada-Navajo aquifer may be consistently different north and south of the San Juan River. It also may contribute to the poor matches between simulated and estimated stream seepage in Montezuma Creek.

4. The assumption that the base of the system (Chinle Formation) is a no-flow boundary may be incorrect. Vertical leakage upward or downward through the Chinle Formation could be a cause of the areal bias of residuals for the Entrada-Navajo aquifer.

5. Measurements of water levels in wells may be incorrect. Many of the larger negative residuals in the Entrada-Navajo aquifer north of the San Juan River are computed from measured pressures that are from flowing wells. The measured pressure may not reflect the true static head in the well because of recent unmeasured discharge of water.

6. Residuals compare a water level measured at a point (well) to a simulated water level that is an average level for a model block.

7. Some stresses and areas of transient-state conditions may not have been identified, and the model is a steady-state simulation.

Simulations of Alternative Boundary Conditions

The purpose of these simulations was to examine some reasonable alternatives to the boundary conditions used in the calibrated model. Four alternative conditions were simulated for the lateral boundary of the model and two alternatives were simulated for the two confining units. The lateral boundary conditions of the Dakota aquifer are defined by adequate data, thus all the lateral boundary alternatives are for the Entrada-Navajo and Morrison aquifers.

The lateral boundary of the model was divided into 10 segments (fig. 14). The flow conditions at three boundary segments are uncertain because there are few or no water-level data near those boundaries. The other seven segments have a sufficient quantity of nearby data or conclusive geologic evidence, therefore, they were not altered. All boundary segments and their alternative flow conditions are shown in table 2.

The alternatives for the three uncertain boundary segments (northeast (Dolores River), east, and southeast) are no-flow, inflow, or outflow. The framework for testing the alternative boundary conditions is shown in table 5.

Table 5.--Alternative flow conditions for lateral boundaries

[Capitalized flow condition is one used in the calibrated model.
Alternative: See section entitled "Simulations of Alternative Boundary Conditions" for explanation of each alternative.
E-N aquifer is Entrada-Navajo aquifer and M aquifer is Morrison aquifer]

Alternative	Boundary Segment				
	Northeast (Dolores River)	East		Southeast	
	M and E-N aquifers	M aquifer	E-N aquifer	M aquifer	E-N aquifer
Calibrated Model	INFLOW (head-dependent)	INFLOW[1]	NO-FLOW	NO-FLOW	NO-FLOW
1. Northeast (Dolores River) boundary--Constant-head	inflow (constant-head)	Do.	do.	do.	do.
2a. East boundary--inflow to M aquifer	INFLOW (head-dependent)	inflow	do.	do.	do.
2b. East boundary--inflow to E-N aquifer	Do.	INFLOW	inflow	do.	do.
3a. Southeast boundary--inflow to M aquifer	Do.	do.	NO-FLOW	inflow	do.
3b. Southeast boundary--inflow to E-N aquifer	Do.	do.	do.	NO-FLOW	inflow
4a. Southeast boundary--outflow from M aquifer	Do.	do.	do.	outflow	NO-FLOW
4b. Southeast boundary--outflow from E-N aquifer	Do.	do.	do.	NO-FLOW	outflow

[1]The calibrated boundary condition for the Morrison aquifer at the east boundary is a small quantity of inflow, and alternative number 2 is a substantial quantity of inflow.

Alternatives 1-4 are set up so one boundary segment is changed and the other two are kept at the condition used in the calibrated model. Alternatives 2-4 are subdivided into two parts where (a) is changing flow conditions for the Morrison aquifer at the boundary and (b) is changing flow conditions for the Entrada-Navajo aquifer. All values of hydraulic properties, recharge, and discharge used in the calibrated model were used in the alternative simulations. Many other combinations of boundary conditions exist, however, it was impractical to evaluate all combinations.

The simulations of alternative boundary conditions were evaluated by comparing the results of the alternative simulations with the results of the calibrated model. The changes in: (1) residuals (measured - simulated water levels), (2) simulated water levels along the boundary, and (3) simulated discharge to the San Juan River were examined. The comparisons are shown in tables 6 and 7.

The northeast (Dolores River) boundary was simulated with the river head-dependent boundary in the calibrated model. The alternative was simulated with a constant-head boundary to examine the effects of a different simulated inflow condition.

Simulated inflow from the northeast (Dolores River) boundary in the calibrated model was 460 acre-ft/yr to the Entrada-Navajo aquifer and 530 acre-ft/yr to the Morrison aquifer. These combined rates are about 4 percent of the total inflow to the Entrada-Navajo and Morrison aquifers.

Simulated inflow from the northeast (Dolores River) boundary in the alternative simulation was 1,450 acre-ft/yr to the Entrada-Navajo aquifer and 720 acre-ft/yr to the Morrison aquifer. These combined rates are about 8 percent of the total inflow to the Entrada-Navajo and Morrison aquifers. Thus, inflow was about doubled, but the residuals used for evaluation of this model changed only slightly (table 6). Therefore, the two simulations show that feasible inflow from the northeast (Dolores River) boundary may range from about 1,000 to 2,200 acre-ft/yr or 4 to 8 percent of the total inflow to the Entrada-Navajo and Morrison aquifers.

The east boundary was simulated as no-flow for the Entrada-Navajo aquifer and as inflow for the Morrison aquifer in the calibrated model. The inflow to the Morrison aquifer was the minimum quantity needed to keep the aquifer saturated at the boundary. The alternative for both aquifers is that the quantity of inflow is substantial and is equal to 25 percent of the total inflow determined for each aquifer in the calibrated model. A specified flux was applied to the boundary at a rate of 3,590 acre-ft/yr for the Entrada-Navajo aquifer and 2,890 acre-ft/yr for the Morrison aquifer.

The southeast boundary was simulated as no-flow for the Entrada-Navajo and Morrison aquifers in the calibrated model. The alternatives are inflow or outflow (table 5) which were simulated using the 25 percent flows specified for the east-boundary alternatives.

The mean residual and mean error for the calibrated model and alternatives for the east and southeast boundaries (alternatives 2-4) are shown in table 6. The mean residual and mean error changed only slightly for the Dakota aquifer in all alternatives. Comparing the statistics for the

Table 6.--Statistics of differences between measured and simulated water levels for simulations of alternative boundary conditions

[Alternative: See section entitled "Simulations of Alternative Boundary Conditions" for explanation of each alternative. Alternatives 2-4 have specified flux for the east or southeast boundaries of 3,590 acre-feet per year for the Entrada-Navajo aquifer and 2,890 acre-feet per year for the Morrison aquifer.
Residual: Measured water level - simulated water level.
Error: Absolute value of residual.]

Alternative	Dakota aquifer		Morrison aquifer				Entrada-Navajo aquifer			
			North of San Juan River		South of San Juan River		North of San Juan River		South of San Juan River	
	Mean residual (feet)	Mean error (feet)	Mean residual (feet)	Mean error (feet)	Mean residual (feet)	Mean error (feet)	Mean residual (feet)	Mean error (feet)	Mean residual (feet)	Mean error (feet)
Calibrated model	14	79	-7	59	-17	79	-34	65	23	73
1. Northeast (Dolores River) boundary--Constant-head	20	80	-11	60	-18	79	-44	68	22	73
2a. East boundary--inflow to Morrison aquifer	15	79	-11	60	-18	80	-43	66	22	73
2b. East boundary--inflow to Entrada-Navajo aquifer	19	81	-16	61	-19	80	-56	74	21	73
3a. Southeast boundary--inflow to Morrison aquifer	5	85	-11	59	-36	69	-38	64	19	72
3b. Southeast boundary--inflow to Entrada-Navajo aquifer	7	84	-15	60	-55	90	-48	68	-6	84
4a. Southeast boundary--outflow from Morrison aquifer	23	75	-3	59	-8	86	-30	66	25	73
4b. Southeast boundary--outflow from Entrada-Navajo aquifer	20	76	1	59	25	81	-19	70	52	86
5. No vertical flow through both confining units	-129	148	3	61	-155	200	-47	131	7	86
6. No vertical flow through Brushy Basin confining unit	-129	148	6	59	-16	79	-1	65	24	73

Table 7.—Comparison of water levels and discharge for calibrated model and simulations of alternative boundary conditions

[Alternative: See section entitled "Simulations of Alternative Boundary Conditions" for explanation of each alternative. Alternative 1 has 2,170 acre-feet per year of inflow through the northeast-Dolores River boundary versus 990 acre-feet per year of inflow in the calibrated model. Alternatives 2-4 have specified flux for the east or southeast boundaries of 3,590 acre-feet per year for the Entrada-Navajo aquifer and 2,890 acre-feet per year for the Morrison aquifer.
Change in average water level along boundary: Equals average water level for alternative simulation minus average water level for calibrated model.
Change in ground-water discharge to San Juan River: Equals discharge in the alternative simulation minus discharge in the calibrated model. In the calibrated model, 13,560 acre-feet per year of ground water is discharged to the San Juan River.]

Alternative	Change in average water level along boundary (feet)		Change in ground-water discharge to San Juan River (acre-feet per year)		
	Morrison aquifer	Entrada-Navajo aquifer	Downstream from confluence with Montezuma Creek	Upstream from confluence with Montezuma Creek	Total
Calibrated model	0	0	0	0	0
1. Northeast (Dolores River) boundary—constant-head	25	211	40	40	80
2a. East boundary—inflow to Morrison aquifer	233	127	50	50	100
2b. East boundary—inflow to Entrada-Navajo aquifer	58	417	100	120	220
3a. Southeast boundary—inflow to Morrison aquifer	144	50	50	2,320	2,370
3b. Southeast boundary—inflow to Entrada-Navajo aquifer	66	390	230	2,000	2,230

Table 7.—Comparison of water levels and discharge for calibrated model and simulations of alternative boundary conditions—Continued

Alternative	Change in average water level along boundary (feet)		Change in ground-water discharge to San Juan River (acre-feet per year)		
	Morrison aquifer	Entrada-Navajo aquifer	Downstream from confluence with Montezuma Creek	Upstream from confluence with Montezuma Creek	Total
4a. Southeast boundary—outflow from Morrison aquifer	-148	-46	-30	-1,490	-1,520
4b. Southeast boundary—outflow from Entrada-Navajo aquifer	-71	-395	-230	-2,040	-2,270
5. No vertical flow through both confining units	—	—	430	-1,820	-1,390
6. No vertical flow through Brushy Basin confining unit	—	—	-140	-290	-430

Entrada-Navajo and Morrison aquifers, the accuracy of alternatives 2-4 was either similar to the calibrated model or worse in all the simulations.

Simulated water levels and discharge to the San Juan River for the calibrated model and alternatives 2-4 are compared in table 7. Average water-level changes on the boundaries due to changes in boundary conditions ranged from -395 to 417 ft. Discharge to the San Juan River was changed slightly in the alternative simulations for the east boundary. Discharge to the upper reach of the San Juan River in alternative simulations 3 and 4 changed significantly because the boundary is close to the river, and few other discharge areas are available.

These results show that the available data and this model configuration are not adequate to determine the flow conditions at the east and southeast boundaries. The simulated water levels along the boundaries changed significantly, but the measured water levels that are used for evaluation of the simulations are too far from the boundaries. Water levels in the aquifers near the wells are more affected by streams such as the San Juan River, Montezuma Creek, and McElmo Creek than by the flow conditions of the east and southeast boundaries. The small hydraulic conductivity (0.38 to 0.47 ft/d) of the aquifers used in the simulations is another characteristic that causes large water-level changes at the boundaries and small water-level changes several miles inside the boundary where the wells are located.

The calibrated model has the best match to measured water levels and discharge to the San Juan River, but the results of the alternative simulations for the lateral boundaries are not significantly different than the results of the calibrated model. Full adjustments of hydraulic properties, recharge, and discharge in the alternatives probably could result in a similar match to measured water levels. However, the calibrated model probably is a better representation of the ground-water system than alternatives 1-4, because it is the best estimate based on the available field information.

The flow conditions through the confining units are also uncertain, and two alternatives were tested. Alternative 5 specified no vertical flow through both confining units. Alternative 6 specified no vertical flow through the Brushy Basin confining unit. These alternatives were simulated by setting the appropriate vertical conductance equal to zero for the condition of no vertical flow. All other hydraulic conditions were kept the same as those used in the calibrated model.

The simulation of alternative 5 has mean residuals and mean errors for water levels that are much worse than the calibrated model, with differences in mean error ranging from 2 to 121 ft (table 6). An important difference between alternative 5 and the calibrated model is the difference of the residuals for the Entrada-Navajo and Morrison aquifers in the recharge and discharge areas. The mean residual for six nodes in the Entrada-Navajo aquifer within 15 mi of the Abajo Mountains is -24 ft for the calibrated model and 170 ft for alternative 5. The mean error for the same nodes is 80 ft for the calibrated model and 182 ft for alternative 5. Near the San Juan River, alternative 5 has negative values of residuals for the Entrada-Navajo aquifer that are over 150 ft smaller than the residuals in the calibrated model. To compensate for simulated water levels in the Entrada-Navajo aquifer being too low in recharge areas, and too high in discharge areas; recharge from the mountain areas and discharge to the San Juan River would have to be increased. Because increased recharge from the mountain areas to the Entrada-Navajo aquifer can not be justified with existing data, and increased discharge to the San Juan River would make the match between estimated discharge (table 4) and simulated discharge worse, these changes were considered unreasonable and were not simulated with the model.

In the calibrated model, vertical leakage between the Entrada-Navajo and Morrison aquifers was about 30 percent of the total inflow to those aquifers. Therefore, comparison of the calibrated model with the simulation of alternative 5 shows that vertical flow between the Entrada-Navajo and Morrison aquifers is needed to develop a reasonable representation of the system, and the quantity of vertical flow may be a significant part of the total budget.

Alternative 6 specified no vertical flow through the Brushy Basin confining unit. Results of this alternative simulation show that the agreement between measured and simulated water levels in the Entrada-Navajo and Morrison aquifers is similar to or better than the calibrated model (table 6). Simulated water levels in the Dakota aquifer in alternative 6 are too high, but the match could be made reasonable by adjustments to areal recharge, discharge, or both. Therefore, alternative 6 (no vertical flow between the Morrison and Dakota aquifers) and the calibrated model are both feasible representations of the ground-water system.

ADDITIONAL DATA AND STUDY NEEDS

Additional data are needed for a better understanding of the ground-water system in the Four Corners area. Aquifer tests are needed to determine values and areal differences in hydraulic conductivity of aquifers and confining units. More water-level data are needed to: (1) define ground-water flow conditions at the northeast, east, and southeast boundaries of the study area, (2) determine water-level gradients between aquifers below the Chinle Formation and the Entrada-Navajo aquifer, and (3) provide a better definition of the potentiometric surface of each aquifer. Water-level data are needed for all aquifers near the mountain areas. Other areas where water-level data are needed are: the entire study area for the aquifers below the Chinle Formation; the northeast and east parts of the study area for the Entrada-Navajo aquifer; the north, northeast, and east parts of the study area, and in stream valleys north of San Juan River for the Morrison aquifer; and the east part of the study area for the Dakota aquifer.

The ground-water budget is difficult to estimate. Measurements of: streamflow during base-flow periods, water levels in the alluvium in stream valleys, and water levels in bedrock aquifers are needed to determine the relationship between water in bedrock, water in alluvium, and streamflow. Measurements of flow from the numerous springs in the study area are also needed to estimate discharge from aquifers. Detailed studies of infiltration of rainfall and snowmelt can improve estimates of recharge from this source. An inventory of pumpage from the Dakota aquifer is needed to define the water budget of that aquifer.

Future simulations need to consider the following changes to the concepts used in this study:

1. The Entrada-Navajo and Morrison aquifers need to be subdivided into additional aquifers. For example, the Entrada-Navajo aquifer could be subdivided into two or three aquifers. The two-aquifer subdivision would define the Carmel Formation as a confining unit and make the Wingate and Navajo Sandstones an aquifer and the Entrada Sandstone another aquifer. The Morrison aquifer could be subdivided into at least two permeable zones, with the Bluff Sandstone Member of the Morrison Formation separated from the other sandstones of the Morrison.

2. The aquifers below the Chinle Formation need to be simulated along with the Mesozoic sandstones to determine vertical leakage across the Chinle Formation.

3. Areal differences in hydraulic conductivity for the aquifers and confining units need to be simulated.

4. A smaller grid size is needed for the entire Dakota aquifer, and for the lower aquifers near the mountain areas and near streams that are discharge areas.

5. Since 1950, some changes in water levels in all three aquifers have been measured in several areas. Simulation of these measured transient conditions could improve the understanding of the system and estimate effects of development. Stresses on the Entrada-Navajo aquifer are discharges from flowing wells and pumpage from wells used for industry, irrigation, and public supply. Stresses on the Dakota aquifer that need to be considered are discharges from irrigation wells, and the infiltration of unconsumed irrigation water in the Blanding area.

SUMMARY AND CONCLUSIONS

The steady-state ground-water system in Mesozoic rocks in the Four Corners area, Utah, Colorado, Arizona, and New Mexico was simulated with a finite-difference digital-computer model to improve the understanding of the system. The simulated area is approximately 4,100 mi^2, and it includes 12 sedimentary formations, which are grouped into three aquifers. The Entrada-Navajo aquifer is composed of the Wingate Sandstone, Kayenta Formation, Navajo Sandstone, Carmel Formation, and Entrada Sandstone of Triassic and Jurassic age. The Morrison aquifer is composed of the Junction Creek Sandstone, and the Bluff Sandstone, Recapture, Westwater Canyon, and Salt Wash Members of the Morrison Formation of Jurassic age. The Dakota aquifer is composed of the Burro Canyon Formation and the Dakota Sandstone of Cretaceous age.

Objectives of this study were to improve the definition of hydraulic boundary conditions, to improve the estimate of the ground-water budget, and to gain a better understanding of vertical flow between aquifers. A ground-water flow model was calibrated on the basis of field information from previous investigations. Results of the calibrated model were used to estimate the steady-state ground-water budget and rates of vertical flow between the three aquifers. Six alternative conditions were also simulated to evaluate potential boundary conditions other than those used in the calibrated model.

Eighty-one percent of the lateral boundary of the model area can be defined with available information. Meager data exists near the other 19 percent of the boundary, therefore, the assigned flow conditions are uncertain. The base of the aquifer system, the Chinle Formation, was assumed to be a no-flow boundary. Analysis of aquifer tests and core samples in previous studies resulted in a range of hydraulic conductivity of 0.02 to 2.1 ft/d for the Entrada-Navajo aquifer, 0.01 to 2.7 ft/d for the Morrison aquifer, and 0.09 to 3.3 ft/d for the Dakota aquifer. For this study, the hydraulic conductivity of all three aquifers was assumed to range from 0.1 to 1.0 ft/d, and the hydraulic conductivity was assumed to be uniformly distributed. The maximum and average thickness of each aquifer is: 1,250 and 900 ft for the Entrada-Navajo aquifer, 800 and 400 ft for the Morrison aquifer, and 360 and 250 ft for the Dakota aquifer. Estimates of recharge to the ground-water system made independently of the simulations ranged from 40,000 to 100,000 acre-ft/yr.

The calibrated model provided a reasonable representation of the ground-water system for steady-state conditions. The simulation had a mean error (error is absolute value of measured minus simulated water level) of 70 ft for the Entrada-Navajo aquifer, 67 ft for the Morrison aquifer, and 79 ft for the Dakota aquifer. The hydraulic-conductivity values used in the simulation were: 0.46 ft/d for the Entrada-Navajo aquifer, 0.47 ft/d for the Morrison aquifer, and 0.38 ft/d for the Dakota aquifer. A uniform vertical leakance was used for each confining unit with values of 1.8×10^{-7} (ft/d)/ft for the Wanakah confining unit and 4.1×10^{-8} (ft/d)/ft for the Brushy Basin confining unit.

Total inflow derived from the calibrated model was 30,390 acre-ft/yr. Annual inflow to each aquifer, excluding vertical leakage, was 14,370 acre-ft to the Entrada-Navajo aquifer, 11,560 acre-ft to the Morrison aquifer, and 4,460 acre-ft to the Dakota aquifer. The simulated recharge to the Dakota aquifer probably is too small because recharge in the areas of small mesas was not simulated. The integrated area of the small mesas is about 20 percent of the Dakota aquifer. Simulated annual vertical flow was 2,560 acre-ft from the Dakota to Morrison aquifer, 7,270 acre-ft from the Morrison to Entrada-Navajo aquifer, and 6,120 acre-ft from the Entrada-Navajo to Morrison aquifer.

Forty-eight percent of the simulated inflow to the ground-water system is from infiltration of rainfall and snowmelt within the model area and 42 percent of the inflow is from infiltration on the three mountain areas that border the model area. The remaining 10 percent is mostly inflow at the model boundaries and seepage from streams. The recharge from infiltration averaged 0.65 percent of the mean annual precipitation within the model area and 7.6 percent within the mountain areas. The distribution of simulated outflow is 79 percent to perennial streams, 6 percent to springs and seeps on canyon walls, and 15 percent to seepage to alluvium in intermittent and ephemeral stream valleys.

The accuracy of the calibrated model is only fair using the indicators of accuracy such as residuals of water levels and the match of simulated to estimated water-budget elements. The important assumptions and possible errors that contribute to the poor fit of simulated to measured or estimated data are (1) 12 sedimentary formations that were simulated as three aquifers probably is too much of a simplification of the aquifer system, (2) the error in the assumption of uniform hydraulic properties for each aquifer and confining unit, and (3) the error in the assumption of no flow through the base of the ground-water system (Chinle Formation).

Simulations of alternative lateral-boundary conditions were mostly inconclusive. Comparison of measured and simulated water levels for simulations of two different inflow conditions at the northeast (Dolores River) boundary showed that either simulation is reasonable, therefore, inflow to the Entrada-Navajo and Morrison aquifers from that boundary could range from 4 to 8 percent of the total inflow to those aquifers. The uncertainty about flow conditions at the east and southeast boundaries could not be resolved because the available hydrologic data are located too far from the boundaries. Nonetheless, the flow conditions for the east and southeast boundaries used in the calibrated model are considered to be the most likely because those flow conditions were the best estimate based on available field information.

Vertical flow through the ground-water system was examined by comparing results of the calibrated model with simulations of two alternative conditions about flow through the confining units. The alternative simulations were done with (1) no vertical flow between all three aquifers, and (2) no flow between the Morrison and Dakota aquifers. Results of these simulations showed that flow between the Morrison and Dakota aquifers is not important to the overall system, but flow between the Entrada-Navajo and Morrison aquifers is needed for a reasonable simulation, and the quantity of vertical flow is a significant part of the total budget.

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