Bedrock Aquifers in the Denver Basin, Colorado— A Quantitative Water-Resources Appraisal

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1257

Prepared in cooperation with the
Colorado Department of Natural Resources,
Office of the State Engineer;
Denver Board of Water Commissioners; and
Adams, Arapahoe, Douglas, Elbert, and El Paso Counties

Bedrock Aquifers in the Denver Basin, Colorado— A Quantitative Water-Resources Appraisal

By S. G. ROBSON

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1257

Prepared in cooperation with the
Colorado Department of Natural Resources,
Office of the State Engineer;
Denver Board of Water Commissioners; and
Adams, Arapahoe, Douglas, Elbert, and El Paso Counties

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1987

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, ***Secretary***

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, ***Director***

Library of Congress Cataloging in Publication Data
Robson, Stanley G.
Bedrock aquifers in the Denver basin, Colorado.

(Geological Survey professional paper ; 1257)
"Prepared in cooperation with the Colorado Department of Natural Resources, Office of the State Engineer; Denver Board of Water Commissioners; and Adams, Arapahoe, Douglas, Elbert, and El Paso counties."
Bibliography: p.
Supt. of Docs. no.: I 19.16:1257
1. Aquifers—Colorado—Denver Region. 2. Water, Underground—Colorado—Denver Region—Mathematical models. 3. Water, Underground—Colorado—Denver Region—Data processing. I. Colorado. Office of the State Engineer. II. Title. III. Series.
GB1199.3.C6R63 1987 553.7'9'0978883 84-600228

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center
Box 25425
Denver, CO 80225

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONVERSION FACTORS

Inch-pound units used in this report may be converted to International System of units (SI) by using the following coversion factors:

Multiply	*By*	*To obtain*
acre	4.047×10^{-1}	hectare
acre-foot (acre-ft)	1.233×10^{-3}	cubic hectometer
acre-foot per year (acre-ft/yr)	1.233×10^{-3}	cubic hectometer per year
cubic foot (ft^3)	2.832×10^{-2}	cubic meter
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second
foot (ft)	3.048×10^{-1}	meter
foot per day (ft/d)	3.048×10^{-1}	meter per day
foot per mile (ft/mi)	1.894×10^{-1}	meter per kilometer
foot per year (ft/yr)	3.048×10^{-1}	meter per year
foot squared (ft^2)	9.290×10^{-2}	meter squared
foot squared per day (ft^2/d)	9.290×10^{-2}	meter squared per day
gallon per minute (gal/min)	6.309×10^{-2}	liter per second
gallon per day (gal/d)	3.785	liter per day
inch (in.)	2.540	centimeter
inch per year (in./yr)	2.540	centimeter per year
inch squared per pound ($in.^2/lb$)	1.450×10^{-1}	kilopascal^{-1}
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
temperature, degrees Fahrenheit (°F)	°C=5/9(°F−32)	degrees Celsius

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

BEDROCK AQUIFERS IN THE DENVER BASIN, COLORADO— A QUANTITATIVE WATER-RESOURCES APPRAISAL

By S. G. Robson

ABSTRACT

The Denver metropolitan area is experiencing a rapid population growth which is requiring increasing supplies of potable water to be pumped from bedrock aquifers in order to meet demand. In an effort to determine the ability of the aquifers to continue to meet this demand, the Colorado Department of Natural Resources; the Denver Board of Water Commissioners; and Adams, Arapahoe, Douglas, Elbert, and El Paso Counties joined with the U.S. Geological Survey in undertaking a hydrologic evaluation of the ground-water resources of the basin. This evaluation involved mapping aquifer extent, thickness, structure, hydraulic characteristics, and water-level and water-quality conditions. Ground-water modeling techniques were then used to simulate aquifer response to various pumpage estimates and ground-water development plans.

The Laramie–Fox Hills aquifer (the deepest aquifer) underlies the 6,700-mi^2 study area and is overlain by the more permeable Arapahoe aquifer, the Denver aquifer, and the Dawson aquifer, which crops out in the southern part of the study area. It is estimated that 270×10^6 acre-ft of recoverable ground water is in storage in these four bedrock aquifers. However, less than 0.1 percent of this volume of water is stored under confined conditions. The larger volume of water stored under unconfined conditions will be available for use only when the water levels in the confined aquifers decline below the top of the individual aquifer, allowing water-table conditions to develop.

Annual precipitation on the Denver basin supplies an average of 6,900 ft^3/s of water to the area; about 55 ft^3/s of this recharges the bedrock aquifers, principally through the Dawson Arkose. The direction of ground-water movement is generally from ground-water divides in the southern part of the area northward toward the margins of the aquifers. Pumpage has ranged from about 5 ft^3/s in 1884 to about 41 ft^3/s in 1978. Pumpage exceeds recharge in the metropolitan area and has caused water-level declines (1958–78) to exceed 200 ft in a 135-mi^2 area of the Arapahoe aquifer southeast of Denver.

A quasi-three-dimensional finite-difference model of the aquifer system was constructed and calibrated under steady-state and transient-state conditions. Steady-state calibration indicated that lateral hydraulic conductivity within the aquifers is about 100,000 times larger than vertical hydraulic conductivity between the aquifers. Transient-state calibration indicated that between 1958 and 1978, 374,000 acre-ft of water was pumped from the aquifers, producing a 90,000-acre-ft net decrease in the volume of water in storage in the aquifers. During this time, pumpage also changed the rates of interaquifer flow, induced additional recharge, and caused capture of natural discharge.

Three 1979–2050 pumpage estimates were made for use in simulating the effects of various ground-water development plans. Simulations, using each of these pumpage estimates, indicated that by the year 2050, large water-level declines could occur, particularly in the deeper aquifers. Maximum water-level declines of 410, 1,700, and 1,830 ft were produced, using the small, medium, and large pumping rates.

Four plans for supplementing the Denver water supply include pumping a satellite well field, pumping a municipal well field, pumping to irrigate parks, and injecting water during periods of low demand for later use during periods of peak demand. Model simulation of these plans indicated that the satellite well field will yield twice as much water as the municipal well field but will produce larger and more widespread water-level declines in the four aquifers. The municipal well field would not significantly affect water levels in the Dawson aquifer. Pumping the Arapahoe aquifer to supply irrigation water to selected parks was shown to produce only small water-level declines in the aquifer. Results of simulating injection–pumpage well fields at two locations indicated that injection rates could range from 1.7 to 10 ft^3/s, depending on the choice of site. The volume of water that could be stored in the bedrock aquifer thus is sensitive to the hydrologic characteristics of the chosen site. More study is needed to evaluate water-chemistry compatibility of native and injected water.

INTRODUCTION

Between 1970 and 1980, 238,000 additional housing units were constructed in the Denver metropolitan area in conjunction with a population increase of 353,000 people. This growth produced a 220-percent increase in the number of housing units in Douglas County and a 250- to 400-percent increase in the number of housing units in suburban cities such as Broomfield, Federal Heights, Glendale, Thorton, and Westminster (U.S. Bureau of the Census, 1981).

The growth in housing and population has produced a corresponding increase in demand for potable water. In an effort to provide additional water to meet part of these demands, the Denver Water Department has constructed the Foothills Water Treatment Complex at a cost of about $170,000,000, the first phase of which will provide an additional 125 million gal/d of treated water to the metropolitan area. However, this facility will provide additional water to only about 60 percent of the 1,590,000 people in the metropolitan area. In areas not supplied by the Denver Water Department, additional water must be obtained from surface-water and ground-water sources through numerous smaller water agencies and from private wells.

In rural or suburban areas without access to surface-water supplies, bedrock aquifers commonly are the sole source of water, and water requirements in these areas are met by more than 12,000 municipal, industrial, domestic, and stock wells completed in the bedrock aquifers. Increasing demands for ground water have produced more than 500 ft of water-level decline in local areas and in excess of 200 ft of decline in a 240-mi² area to the north, east, and south of Denver.

The magnitude of present demands, coupled with expected in future demands, has led to concern over the increased ability of the bedrock aquifers to meet future water requirements. In an effort to better understand and manage this vital water supply, the Colorado Department of Natural Resources, Office of the State Engineer; the Denver Board of Water Commissioners; and Adams, Arapahoe, Douglas, Elbert, and El Paso Counties joined with the U.S. Geological Survey in funding a cooperative hydrologic study of the principal bedrock aquifers in the Denver basin. Work on this study began in 1978.

PURPOSE AND SCOPE

The purpose of the study was to provide a broad-scale, comprehensive evaluation of the ground-water resources of the entire Denver ground-water basin. This evaluation involved documenting the past and present hydrologic and geologic conditions in the aquifers. The ultimate objective was to use modeling techniques to evaluate the probable effects of future pumpage on ground-water supplies. Specific elements of this work include:

1. Identification and mapping of the extent, structure, thickness, and depth of the four principal bedrock aquifers in the basin.
2. Determination of the hydraulic characteristics of the water-yielding strata in the four aquifers.
3. Determination of the past and current water-level conditions and rate of water-level change in the aquifers.
4. Estimation of rate and distribution of natural recharge, discharge, and pumpage.
5. Determination of the general water quality in the aquifers and the suitability of the water for potable use.
6. Construction and calibration of a multilayer, mathematical model of the aquifer system for use in estimating the probable effects of future pumpage on the water levels in the aquifers.

LOCATION AND FEATURES OF THE STUDY AREA

The Denver ground-water basin underlies a 6,700-mi² area in Colorado extending from the Front Range of the Rocky Mountains east to near Limon, and from Greeley south near Colorado Springs (fig. 1). The Denver metropolitan area is located on the west-central margin of the basin in a broad valley formed by the South Platte River and its tributaries. Land-surface altitudes in the basin range from 4,500 ft above sea level near Masters on the northeast to as much as 7,500 ft in the mountainous areas north of Colorado Springs. Surface drainage is generally to the north in the area north of El Paso County and to the south or southeast in El Paso County. Alluvial aquifers ranging in thickness from 10 to 150 ft are present in the valleys of the larger streams. These aquifers supply water for irrigation of commercial crops in the northern one-third of the basin and at a few other scattered locations.

The Denver basin has a semiarid continental climate with 50–70 in. of mean annual potential evaporation and only 11–18 in. of mean annual precipitation (fig. 2). About 70 percent of the precipitation falls during the 6-month period from April through September, with areas of higher altitude receiving more precipitation. For example, Greeley, at an altitude of 4,663 ft, receives 11 in. of mean annual precipitation (32 in. of snowfall); Denver, at an altitude of 5,280 ft, receives 14 in. (56 in. of snowfall); and Monument, at an altitude of 6,961 ft, receives 18 in. (83 in. of snowfall). Record high temperatures in the basin range from 100 to 105 °F, and record low temperatures range from −30 to −40 °F. Mean monthly temperatures in Denver range from 70 °F in July and August to 32 °F in December and January (Hansen and others, 1978). A mean annual precipitation rate of 14 in./yr occurs in the Denver basin and produces an average of 5.0 million acre-ft of water per year, equivalent to a continuous flow of 6,900 ft³/s. Most of this volume of water is lost through evaporation, transpiration, and runoff, and less than 1 percent supplies recharge to the bedrock aquifers.

Four bedrock aquifers occur in water-yielding strata of the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, Denver Formation, and Dawson Arkose (fig. 3). The aquifers are termed the Laramie–Fox Hills aquifer, the Arapahoe aquifer, the Denver aquifer, and the Dawson aquifer.

RELATED STUDIES

In 1883, it was discovered that flowing wells could be constructed in the bedrock formations near downtown Denver. This led to a rapid increase in the number of

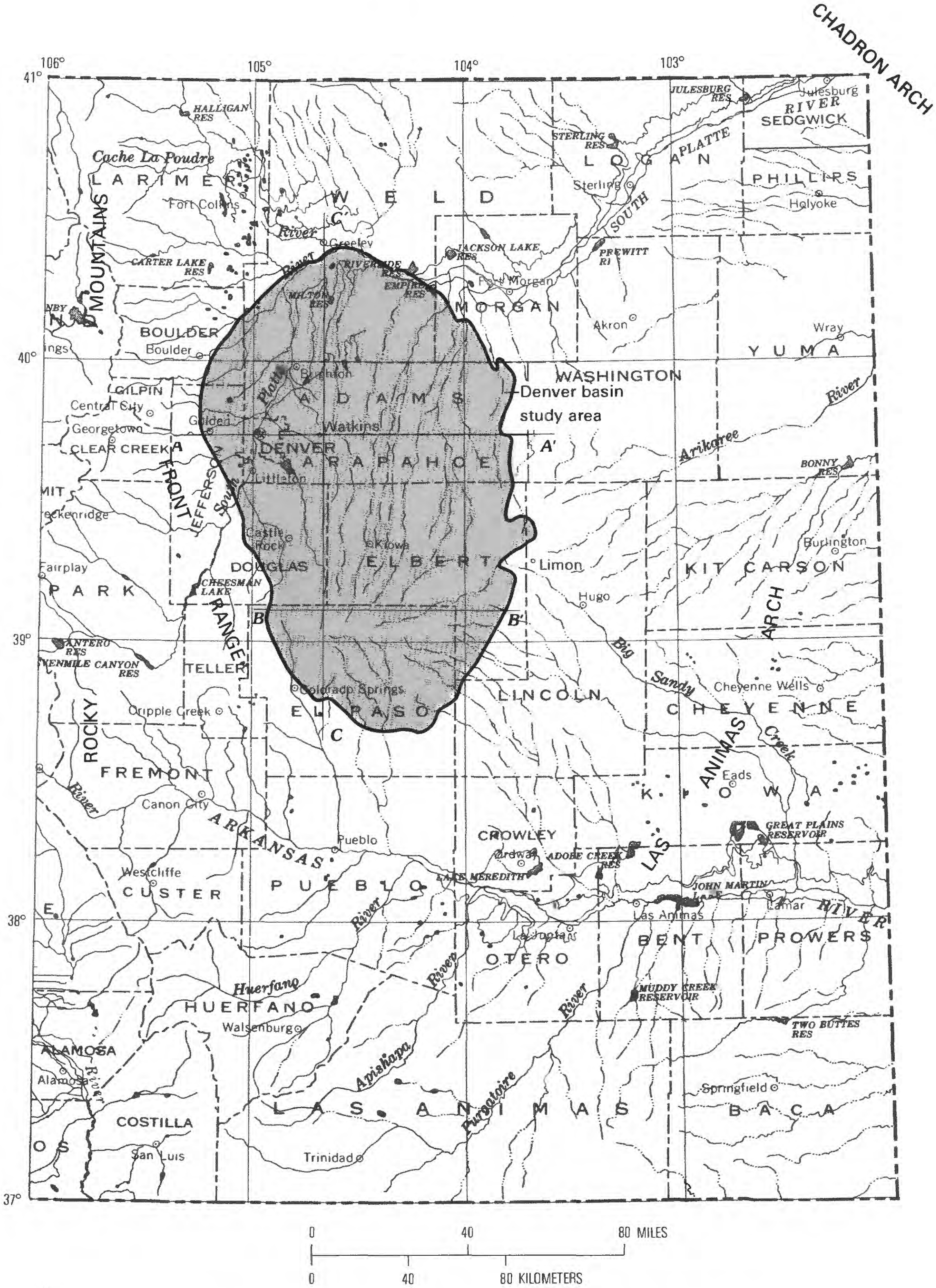


FIGURE 1.—Location of study area and trace of generalized geologic sections.

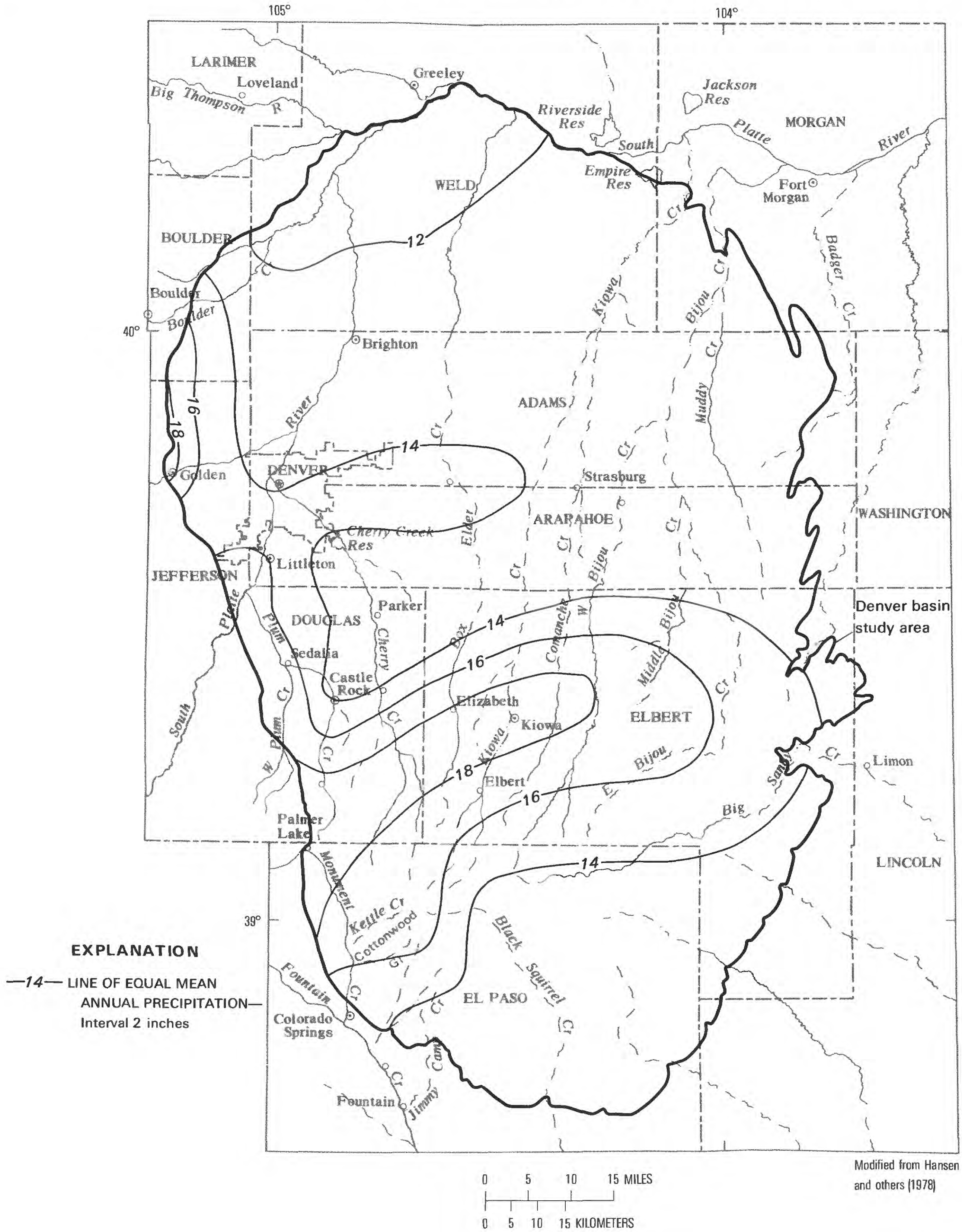


FIGURE 2.—Mean annual precipitation in study area.

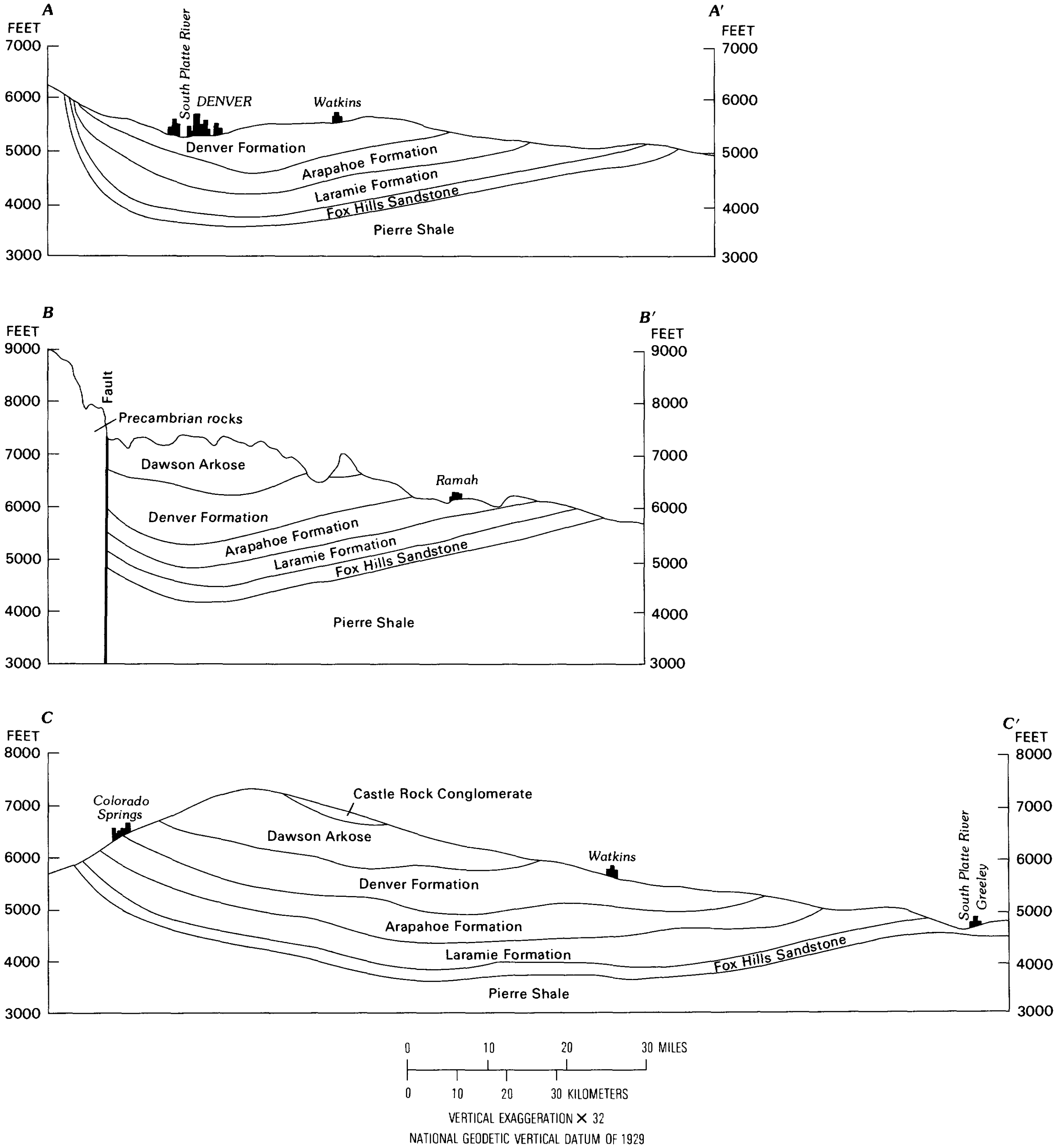


FIGURE 3.—Generalized geologic sections through the Denver Basin. (Line of sections located in fig. 1.)

such wells (from 80 in 1884 to 400 in 1890) and was the subject of the first study of the hydrology of the bedrock aquifers near Denver (Cross and others, 1884). Subsequent work by Emmons and others (1896) provided a more comprehensive evaluation of the geology and hydrology of the formations in the area. Since this early work, numerous authors have studied the geology and hydrology of parts of various geologic units in the basin. Chronic and Chronic (1974), Hampton (1975), Hampton and others (1974), Anna (1975), and Norris and others (1984) provided indexes to more than 1,800 reports dealing with the geology and hydrology of the Denver basin. Therefore, only those reports that have particular relevance to the hydrology of the bedrock aquifers are discussed further in this section. McConaghy and others (1964) and Major and others (1983), for example, presented data for water wells completed in the bedrock aquifers. These data were the bases for several interpretative hydrologic studies. Romero and Hampton (1972) and Romero (1976) were the first of the more recent studies to show structural mapping of bedrock aquifers. Romero (1976) undertook a relatively comprehensive hydrologic investigation of the entire basin which served as the initial framework for this study. Hillier and others (1978) also provided useful hydrologic mapping of part of the Arapahoe aquifer, and Schneider (1980) provided a hydrologic evaluation for part of the Laramie–Fox Hills aquifer in Boulder County.

Results of these studies were reviewed and incorporated with new data to provide a more complete and extensive evaluation of the hydrology of the entire basin. Maps showing geologic structure of the top and base of each aquifer; depth to the base of the aquifer; sandstone thickness in the aquifer; 1958 and 1978 water-level altitudes; water-level change from 1958 to 1978; and concentrations of dissolved solids, dissolved sulfate, and hardness were prepared as part of this study. This information has been presented for the Dawson aquifer (Robson and Romero, 1981a), the Denver aquifer (Robson and Romero, 1981b), the Arapahoe aquifer (Robson and others, 1981a), and the Laramie–Fox Hills aquifer (Robson and others, 1981b). Robson (1983) presented estimates of hydraulic characteristics of the bedrock aquifers, such as hydraulic conductivity, transmissivity, porosity, specific yield, and storage coefficient. Norris and others (1984) provided an overview of the hydrology of the alluvial and bedrock aquifers in the Denver basin, including a more extensive discussion of surface-water relations and the hydrology of the alluvial aquifers than is contained in this report.

ACKNOWLEDGMENTS

This study was conducted as a joint effort of the U.S. Geological Survey and the Colorado Department of Natural Resources, Office of the State Engineer. John Romero, Andrew Wacinski, and Stanley Zawistowski of the State Engineer's Office were an integral part of the team of scientists working on this project; their efforts materially contributed to many of the maps and other results of the study. The basic data collected during this study were provided mainly through the generous cooperation of private well owners, managers of commercial facilities, and private consulting geologists and hydrologists. This cooperation significantly increased the data base for the study and aided in the timely completion of the work. Collection of field data and review of reports and technical procedures were performed by numerous employees of the U.S. Geological Survey and the cooperating agencies. The contributions of all of the above-mentioned individuals is gratefully acknowledged.

THE NATURAL HYDROLOGIC SYSTEM

STRATIGRAPHY

The Denver ground-water basin is part of the larger Denver structural basin that extends from Colorado into western Nebraska, Kansas, and eastern Wyoming. Tectonic movement has produced more than 20,000 ft of structural relief between the Precambrian basement rocks that occur in the Front Range, in the structural depression, and on the Las Animas and Chadron arches in eastern Colorado and western Nebraska (fig. 1). The structural basin is asymmetrical. Low-angle dips occur on the eastern flank of the basin from the Las Animas arch to the synclinal axis in the Denver-Cheyenne area. Steeply dipping to overturned beds occur on the western flank of the basin near the mountain front (fig. 3). Faulting and deformation associated with mountain-building geologic movement beginning in Cretaceous time have created the markedly asymmetrical features of the basin (McCoy, 1953). Faulting along the southwestern edge of the basin has truncated Cretaceous and Tertiary sedimentary rocks and left them in contact with Precambrian rocks on the upthrown fault block (fig. 3). Along the northwestern margin of the basin, faulting has offset and tilted the Cretaceous and older sedimentary rocks and, in Boulder and Jefferson Counties, has produced scenic outcrops with steeply dipping beds (Tweto, 1979). The Flatirons (a local sandstone outcrop) is an example of the results of this structural deformation.

Strata yielding usable quantities of potable water occur in the Fox Hills Sandstone, Laramie Formation, and Arapahoe Formation of Late Cretaceous age; in the Denver Formation of Late Cretaceous and early Tertiary age; and in the Dawson Arkose of Tertiary age. These formations attain a maximum combined thickness of 3,200 ft in an area about 20 mi south of Castle Rock. The Pierre Shale of Late Cretaceous age underlies the Fox Hills Sandstone and is considered to be the base of the water-yielding units because of its thickness, which exceeds 5,000 ft, and minimal permeability. These formations occur in a sequence of layers that form an ellipsoidal, bowl-shaped ground-water basin having structural features similar to those in the underlying structural depression (fig. 3).

The Laramie–Fox Hills aquifer is the deepest and most extensive aquifer in the basin, underlying a 6,700-mi^2 area between Greeley and Colorado Springs. The limit of this aquifer in the area south of the South Platte River also is the limit of the study area (fig. 4). The Laramie–Fox Hills aquifer occurs primarily in the lower sandstone units of the Laramie Formation and the upper sandstone and siltstone units of the underlying Fox Hills Sandstone. However, sandstones in the upper 100–200 ft of the Pierre Shale may form aquifers in the area northwest of Denver and at a few other scattered locations; the uppermost of these sandstones likely are hydraulically connected to those in the Fox Hills Sandstone and are considered in this study to be part of the Laramie–Fox Hills aquifer.

The part of the Laramie–Fox Hills aquifer within the Fox Hills Sandstone is generally 150–200 ft thick and is composed of an overlying bed of very fine grained silty sandstone 40–50 ft thick underlain by 100–150 ft of shaly siltstone and interbedded shale. The part of the Laramie–Fox Hills aquifer within the Laramie Formation is generally 50–100 ft thick and is composed of very fine to medium-grained sandstone with interstitial silt and clay. Locally, the sandstone is separated into upper and lower members by interbedded shale 10–20 ft thick. A shale bed 5–20 ft thick generally separates the Laramie part of the aquifer from the Fox Hills part.

The 400–500 ft of Laramie Formation overlying the Laramie–Fox Hills aquifer form an upper confining layer for the aquifer. Laramie strata above the aquifer are composed of gray to black shale, coal seams, and minor amounts of gray siltstone and sandstone. The lowermost coal seams are useful in identifying the upper limit of the aquifer. The subbituminous to lignitic coal seams range in thickness from a few inches to about 10 ft and are present in several stratigraphic horizons. These seams have been extensively mined along the northwest and southwest margin of the Laramie Formation. The locations of about 300 abandoned or inactive coal mines in these two areas have been shown by Colton and Lowrie (1973) and Kirkham (1978).

The thickness of the Laramie–Fox Hills aquifer ranges from zero at the aquifer boundary to between 200 and 300 ft in the central part of the basin. Altitudes of the base of the aquifer are shown by Robson and others (1981b) to range from 5,700 ft in the area between Limon and Truckton to less than 3,500 ft in the lowest part of the structure near Cherry Creek Reservoir. Depths to the base of the aquifer range from 1,500 to 2,000 ft in most of the Denver metropolitan area, as shown in figure 5*A*. Thickness of water-yielding materials within the aquifer averages about 150 ft and ranges from zero to almost 250 ft (fig. 6*A*).

In the northwest part of the basin, near Boulder County, numerous northeast-trending faults have offset strata in the Fox Hills Sandstone and Laramie Formation. Marked differences in water-level altitudes in wells occur near some of these faults, possibly due to the fault zone funtioning as a barrier to the movement of ground water (Schneider, 1980). The locations of some of these faults have been mapped by Colton and Lowrie (1973) and Tweto (1979) (fig. 7), but the locations of others can only be inferred from features such as the predominantly northeast trending alignment of lower Boulder Creek, lower Saint Vrain Creek, Big Dry Creek, and Coal Creek. Prominent topographic features, such as the mesas 4 mi southeast of Boulder and the west bank of the South Platte River between Brighton and Commerce City, also have a northeast trend.

The Arapahoe aquifer (fig. 4) consists of a 400 to 700-ft-thick series of interbedded conglomerate, sandstone, siltstone, and shale. Shale is more prevalent in the northern one-third of the area where the aquifer can sometimes be subdivided into an upper, middle, and lower part. The upper and lower parts generally consist of 150–200 ft of sandstone and siltstone interbedded with less prevalent zones of shale, whereas the middle part consists of about 100 ft of relatively homogeneous shale. The conglomerates, sandstone, and siltstones are normally light to medium gray with local very light gray and grayish-green beds. These colors are generally darker in the upper 100–200 ft of the formation near its boundary with the overlying Denver Formation. Shales are normally medium gray and silty. The larger proportion of conglomerate and sandstone with respect to shale, the absence of significant carbonaceous beds, and a generally lighter color distinguish the Arapahoe Formation from the underlying Laramie Formation and the overlying Denver Formation. Individual conglomerate and sandstone beds in the Arapahoe Formation are generally lens shaped, moderately consolidated, and range in thickness from a few inches to 30 or 40 ft. The beds may be so closely spaced that they form a single hydrologic unit that is 200–300 ft thick in some areas.

Altitudes of the base of the Arapahoe aquifer have been shown by Robson and others (1981a) to range from more than 6,000 ft near the southern margin of the basin to less than 4,000 ft in the lowest part of the structure near Parker. Depths to the base of the aquifer exceed 2,600 ft near Black Forest, but range from 500 to 1,500 ft in most of the Denver metropolitan area (fig. 5*B*). Although the total thickness of the Arapahoe aquifer commonly ranges from 500 to 700 ft, only 200 to 300 ft of water-yielding material is generally present, as shown in figure 6*B*.

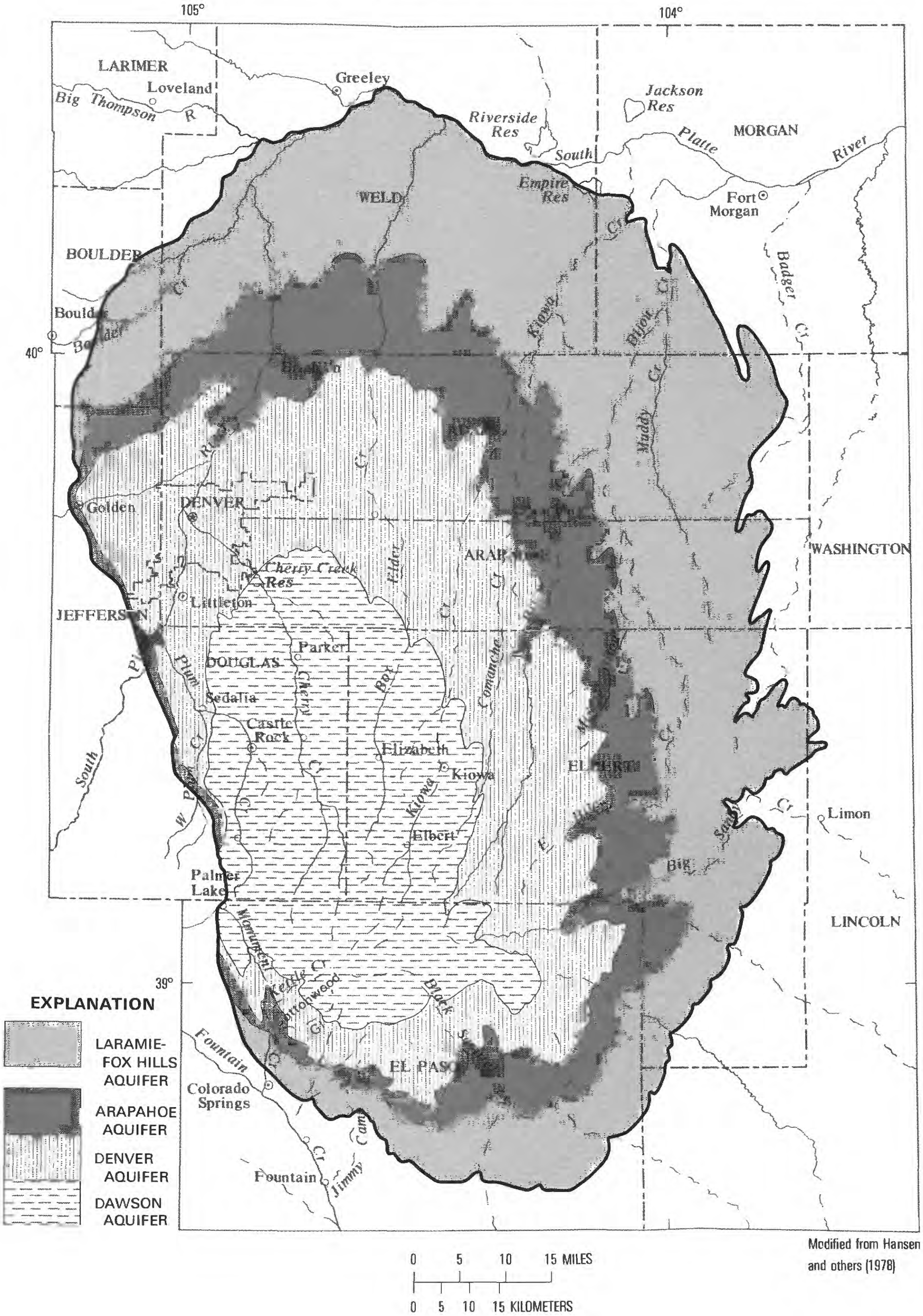


FIGURE 4.—Location and extent of bedrock aquifers.

The Denver aquifer (fig. 4) consists of a 600- to 1,000-ft-thick series of interbedded shale, claystone, siltstone, and sandstone in which coal and fossilized plant remains are common. Distinguishing characteristics of the unit are its olive, green-gray, brown, and tan colors; the presence of coal; and the preponderance of shale and claystone compared to other rock types. The predominant olive and green-gray colors in the formation are due to the presence of iron-rich sediments derived from erosion of basaltic and andesitic lavas. Denver rocks are thus distinguished from the generally lighter colored rocks found in the overlying Dawson Arkose and the underlying Arapahoe Formation. Water-bearing layers of sandstone and siltstone occur in poorly defined, irregular beds that are dispersed within relatively thick sequences of claystone and shale. Individual sandstone and siltstone layers commonly are lens shaped and range from a few inches to as much as 50 ft thick.

Structural mapping by Robson and Romero (1981b) indicates that the altitudes of the base of the Denver aquifer range from more than 6,400 ft in the southern part of the basin to less than 4,600 ft in the lowest part of the structure, extending from Aurora to Parker. Depth to the base of the aquifer exceeds 2,100 ft near Black Forest but is between 100 and 1,000 ft in most of the Denver metropolitan area (fig. 5*C*). Because of the preponderance of shale and claystone in the formation, the thickness of water-yielding materials in the aquifer is proportionally less, generally ranging from 100 to 300 ft, as shown in figure 6*C*.

The sediments that occur in the Dawson aquifer (fig. 4) consist primarily of conglomerate, sandstone, and shale, varying from light gray to yellowish brown, with beds of pale-green shale in some areas. In general, the conglomerates and sandstones are coarse grained and poorly to moderately well consolidated. In most of the aquifer in Arapahoe, Douglas, and Elbert Counties, a layer of shale 100–250 ft thick separates an upper and lower sequence of conglomerate, sandstone, and minor amounts of shale. In the southern part of the aquifer, the intervening shale is absent, and conglomerate, sandstone, and minor amounts of shale occur in a continuous sequence 600 ft or more thick. Individual conglomerate and sandstone beds are usually lens shaped and range from a few inches to as much as 200 ft thick. Conglomerate and sandstone beds that are penetrated by one well may be of a different thickness or may be absent in an adjacent well because of this lens-shaped layering.

Structural altitudes of the base of the Dawson aquifer range from more than 6,600 ft in the southern part of the aquifer to less than 5,300 ft in the center of the structural low near Parker (Robson and Romero, 1981a). Depths to the base of the aquifer exceed 1,000 ft in several areas but range from 300 to 1,000 ft over most of the aquifer, as shown in figure 5*D*. The Dawson aquifer generally ranges from 200 to 900 ft thick and contains 100–400 ft of water-yielding material, as shown in figure 6*D*.

AQUIFER CHARACTERISTICS

The ability of an aquifer to transmit water depends on the thickness and permeability of the water-yielding material. A greater thickness of water-yielding material (or material of greater permeability) allows larger volumes of water to move through the aquifer. Hydraulic conductivity is a common measure of the ability of a unit volume of material to transmit water under a given set of temperature and pressure conditions. Transmissivity is the product of hydraulic conductivity and thickness, and thus incorporates the effects of both thickness and permeability in measuring the ability of an aquifer to transmit water.

The hydraulic conductivity of the water-yielding materials in the bedrock aquifers was estimated through use of aquifer tests, specific-capacity tests, and laboratory analyses of undisturbed rock samples. Robson (1983) showed that hydraulic-conductivity values in the Laramie–Fox Hills aquifer range from more than 6 ft/d near Littleton to less than 0.05 ft/d along the northwest margin of the aquifer. The largest hydraulic conductivity (7 ft/d) in the study area occurs in the Arapahoe aquifer south of Littleton; however, values less than 0.5 ft/d occur in the central part of the Arapahoe aquifer. Hydraulic conductivity in the Denver aquifer ranges from 0.5 to 1.5 ft/d; in the Dawson aquifer hydraulic conductivity ranges from 0.2 to 3.0 ft/d.

The transmissivity of the aquifers was also mapped by Robson (1983). Transmissivity ranges from zero at the edge of each of the aquifers to over 1,000 ft^2/d in the Laramie–Fox Hills aquifer, 2,100 ft^2/d in the Arapahoe aquifer, 400 ft^2/d in the Denver aquifer, and 1,200 ft^2/d in the Dawson aquifer (fig. 8). By comparison, the transmissivity of the alluvial aquifer along the South Platte River between Brighton and Platteville averages about 13,000 ft^2/d (Hurr and Schneider, 1972). The

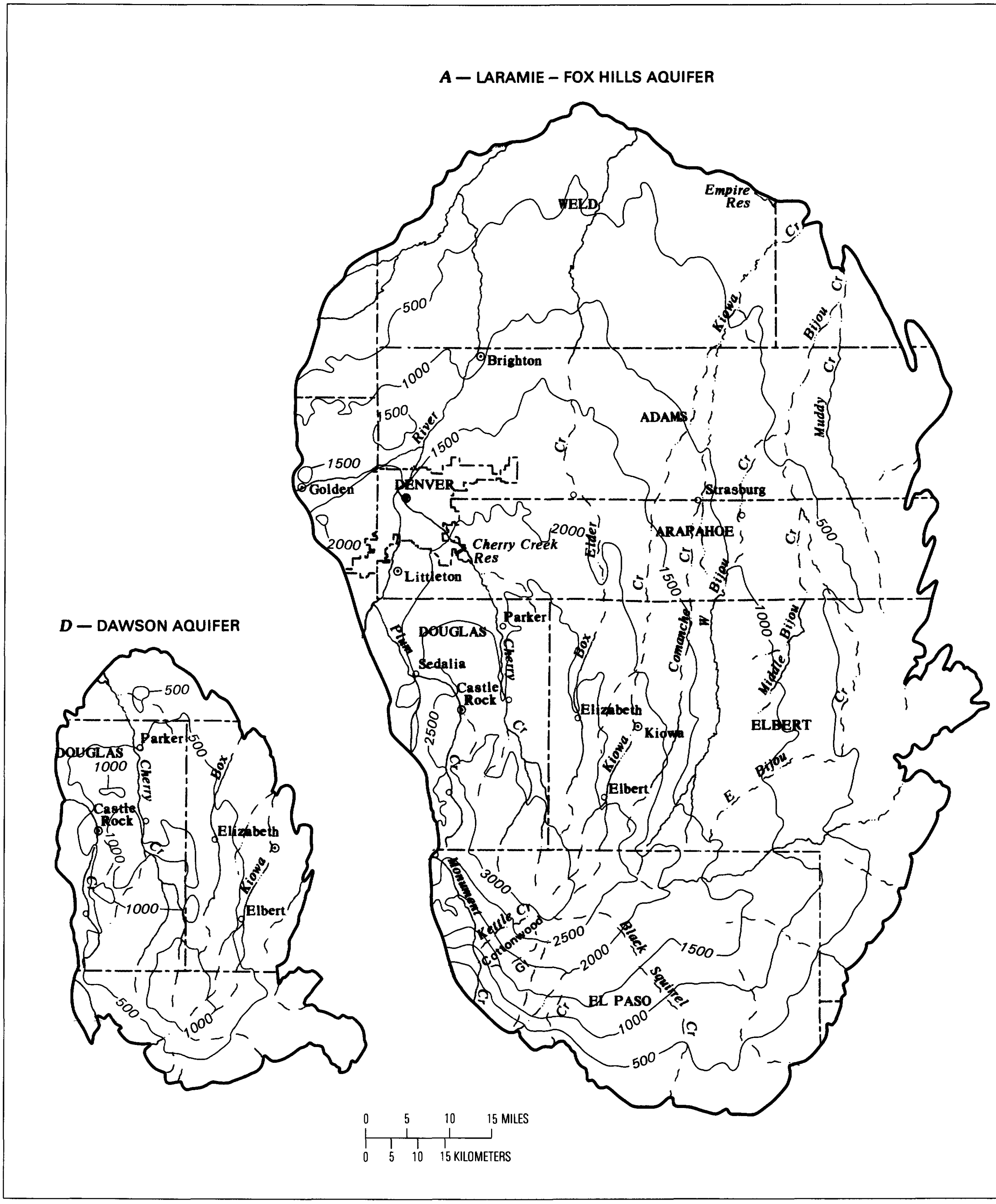


FIGURE 5.—Depth to the base of the bedrock aquifers. *A*, Laramie–Fox Hills aquifer; *B*, Arapahoe aquifer; *C*, Denver aquifer; *D*, Dawson aquifer. (See fig. 4 for geographic location of aquifers.)

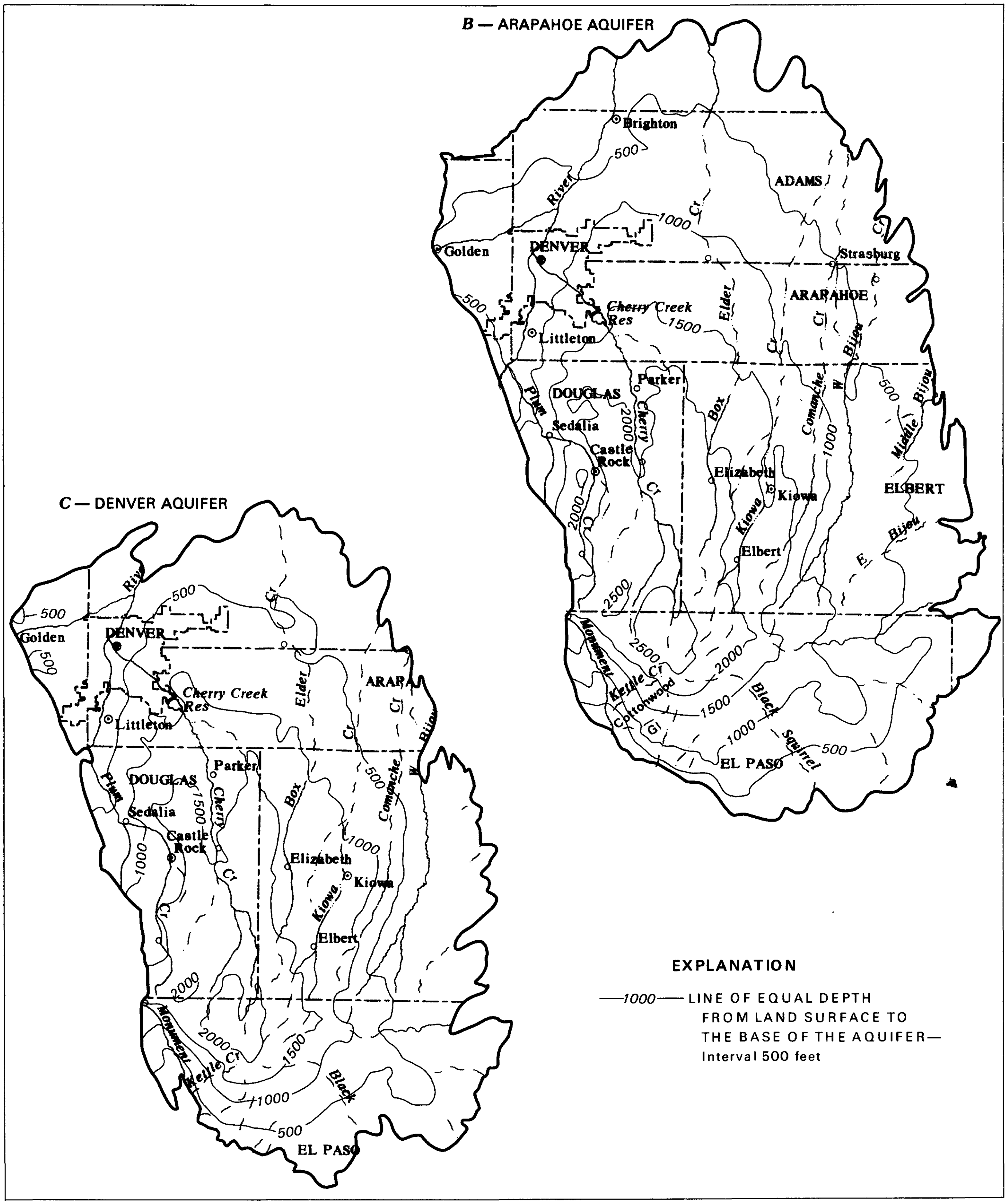


FIGURE 5.—Continued.

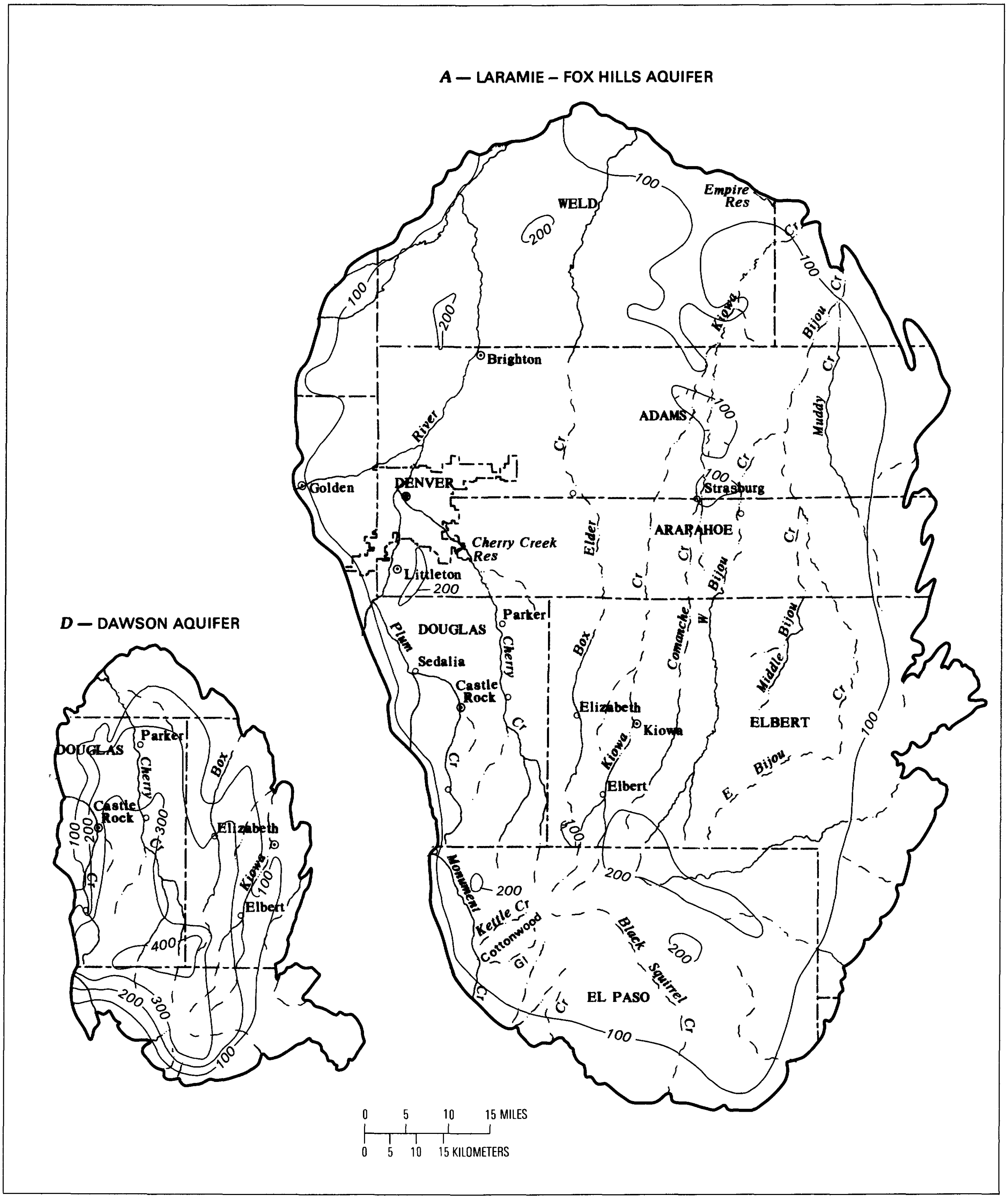


FIGURE 6.—Total thickness of water-yielding material in the bedrock aquifers. *A*, Laramie–Fox Hills aquifer; *B*, Arapahoe aquifer; *C*, Denver aquifer; *D*, Dawson aquifer. (See fig. 4 for geographic location of aquifers.)

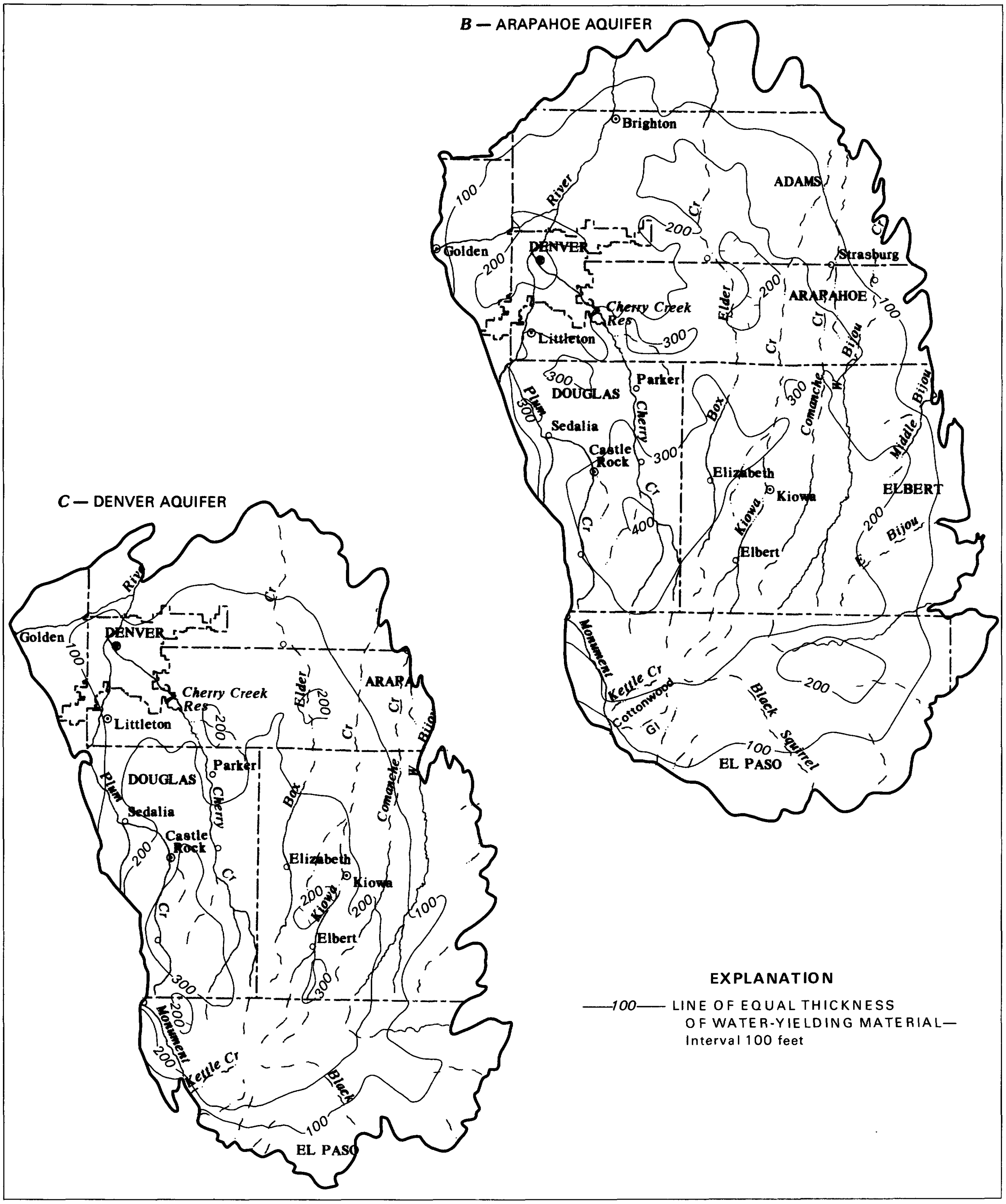
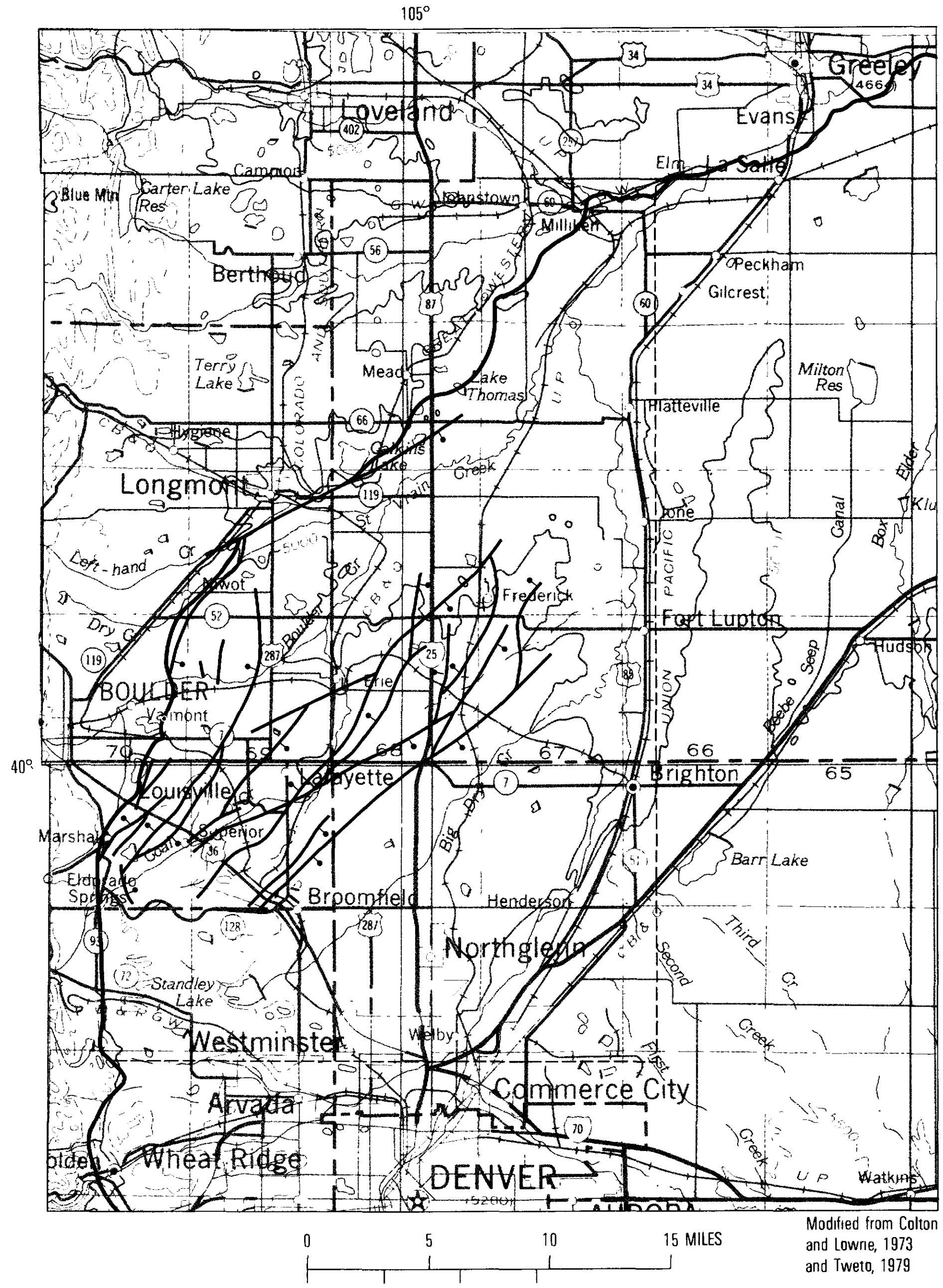


FIGURE 6.—Continued.



EXPLANATION

LIMIT OF LARAMIE FOX HILLS AQUIFER

FAULT—Bar and Ball on downthrown side

LIMIT OF AREA WHERE GROUND-WATER MOVEMENT MAY BE AFFECTED BY FAULTING

FIGURE 7.—Location of faults in the Laramie–Fox Hills aquifer north of Denver.

TABLE 1.—*Porosity and specific-yield statistics for water-yielding materials*

[Data, with exception of number of samples, in percentage]

Aquifer	Porosity data based on: Laboratory analysis of samples — Mean	Range	Number of samples	Standard deviation	Porosity data based on: Interpretation of geophysical logs — Mean	Range	Number of samples	Standard deviation	Specific yield data based on laboratory analysis of samples — Mean	Range	Number of samples	Standard deviation
Dawson	32	18–46	20	6.7	(1)	25–30	5	(1)	18	3.6–34	18	8.4
Denver	31	15–44	24	6.0	29	24–34	19	2.9	14	.2–29	11	9.7
Arapahoe	30	12–46	33	7.3	30	22–35	52	3.8	18	3.3–33	25	8.4
Laramie-Fox Hills	32	21–44	42	6.1	32	24–36	21	2.5	20	4.8–38	29	9.1

[1]Insufficient data

bedrock aquifers are thus only about one-tenth as transmissive as this alluvial aquifer. This fact accounts for the smaller well yields normally encountered in bedrock wells and affects the water budget and potential yield of the entire basin.

The ability of an aquifer to store water depends on the thickness and porosity of the water-yielding material and, to a lesser extent, on the compressibility of the water and rock. If the void space in a porous rock is physically drained of water, as occurs during a decline in the water table, the volume of water released from storage may be expressed as a percent of the rock volume. This ratio is called specific yield. The volume of water that will not drain from the rock adheres to the rock structure. The ratio of this volume of water to the volume of rock is called specific retention. Porosity, which is a measure of the pore volume of the rock, is mathematically equal to specific yield plus specific retention.

The mean porosity of the water-yielding materials in the bedrock aquifers was estimated by Robson (1983) to range from 29 to 32 percent, and the mean specific yield was estimated to range from 14 to 20 percent, as shown in table 1. Estimates of specific retention ranged from about 12 to 17 percent. Thus, a cubic foot of water-yielding material typically would contain about 0.3 ft^3 of water in the void space of the rock (porosity = 30 percent), and, by drainage, would yield about 0.15 ft^3 of water to a well (specific yield = 15 percent), and would retain about 0.15 ft^3 of water in permanent storage in the rock structure (specific retention = 15 percent).

The porosity data shown in table 1 are based on either laboratory analyses of undisturbed rock samples or on interpretation of neutron-density geophysical logs (Robson, 1983). Laboratory porosity determinations were made on about 120 undisturbed bedrock samples, taken mainly from excavations or outcrops. The samples were chosen to represent the general character of the water-yielding materials in each aquifer. Neutron-density geophysical logs were interpreted to provide a second determination of porosity of these water-yielding materials. Porosity determinations from 97 siltstone, sandstone, and conglomerate intervals shown on 50 logs indicate that the mean in situ porosity of these intervals is in good agreement with the mean porosity based on laboratory analyses from other locations (table 1).

Laboratory specific-yield determinations were made on about 60 samples of the water-yielding materials. Results of this work and data from McConaghy and others (1964) indicate that the specific yield of individual samples may range from about 1 to 38 percent. This large range is due to the variable composition of the aquifer materials, clay content being a principal factor. A moderately consolidated sandstone with minimal clay content generally will have a relatively large porosity and corresponding large specific yield. A clayey sandstone, by contrast, can have a relatively large porosity but a small specific yield due to the presence of the clay (Todd, 1967). Because of the variable composition of the permeable materials, specific yield can be expected to vary considerably from one water-yielding bed to another and from one area to another in the basin.

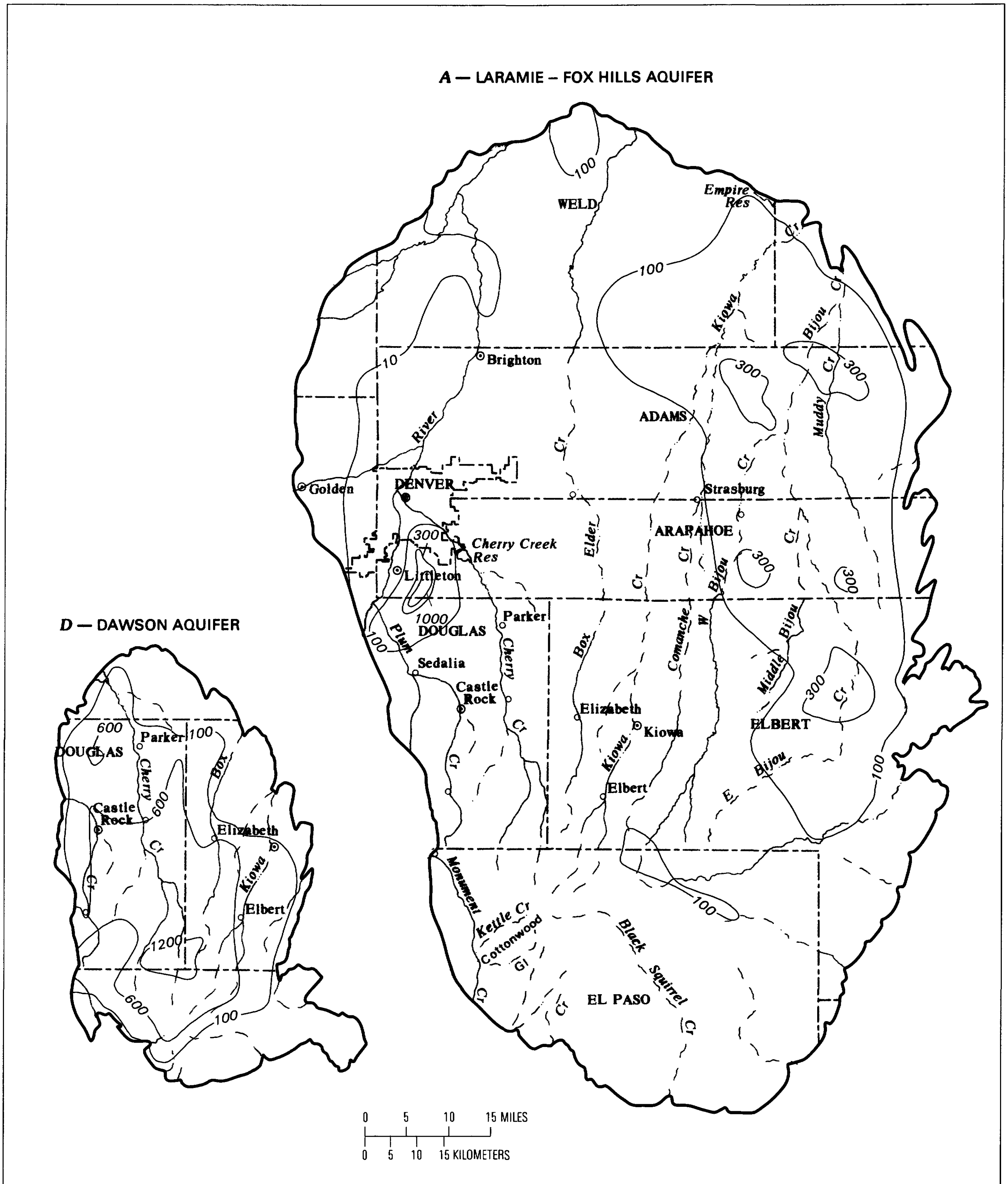


FIGURE 8.—Transmissivity of the bedrock aquifers. *A*, Laramie-Fox Hills aquifer; *B*, Arapahoe aquifer; *C*, Denver aquifer; *D*, Dawson aquifer. (See fig. 4 for geographic location of aquifers.)

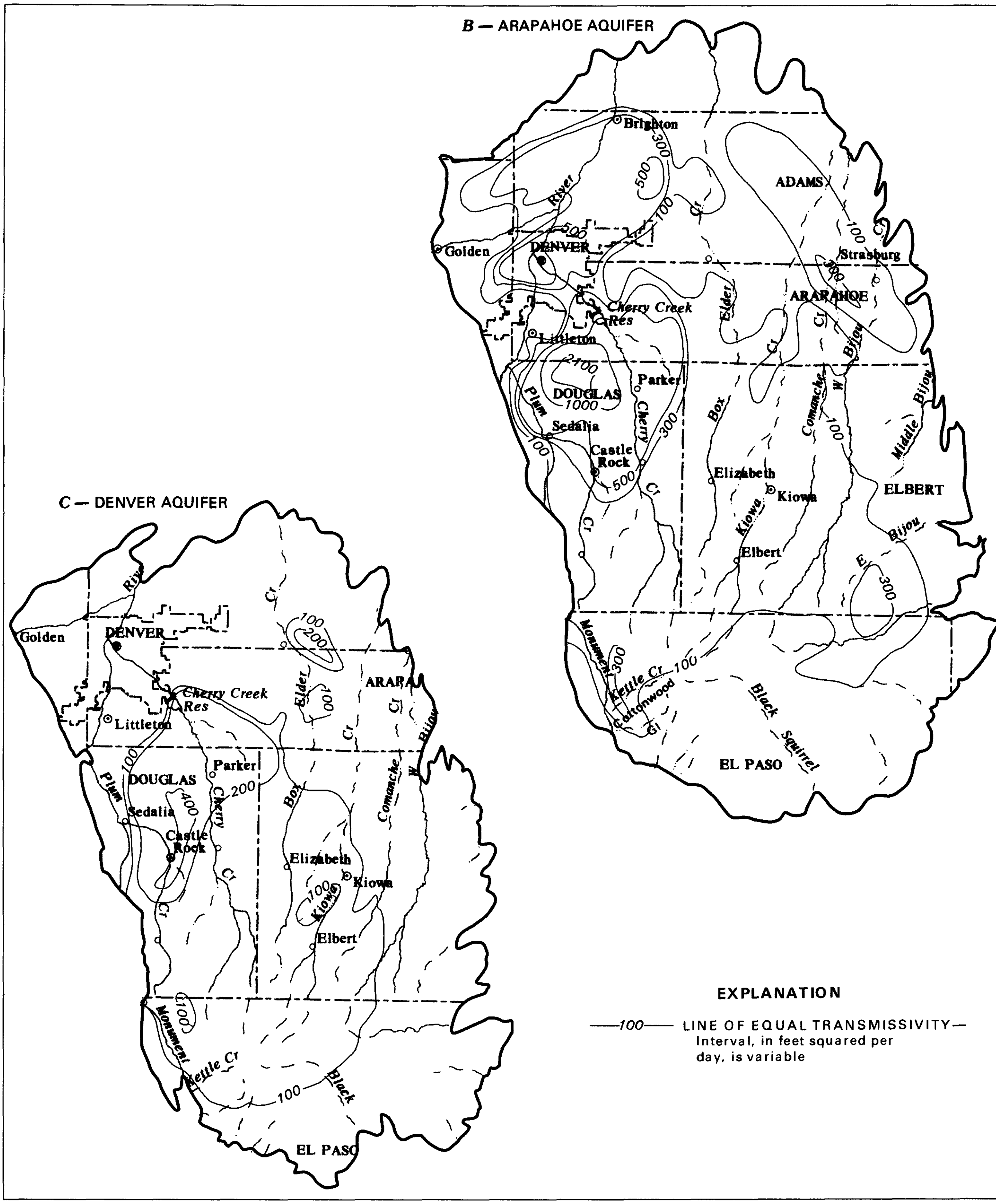


FIGURE 8.—Continued.

Water also may be released from storage in an aquifer without physically draining water from the void space in the rock. This occurs as a result of the elastic properties of water and rock, and is measured by an aquifer characteristic called the confined storage coefficient. Fatt (1958) and Clark (1966) presented data indicating that rocks similar to those in the Denver basin have a compressibility ranging from 7×10^{-7} to 7×10^{-6} in.²/lb. These and other data were used by Robson (1983) to estimate confined storage coefficients ranging from less than 2×10^{-4} to more than 8×10^{-4} (fig. 9). Although a cubic foot of water-yielding material typically would contain about 0.3 ft³ of water in storage, it would yield only about 2×10^{-6} ft³ of water (about 1 drop) as a result of the compressibility of the water and rock. The volume of water released from storage (or taken into storage) in the aquifers is thus drastically different, depending on whether gravity drainage of rock void space occurs under water-table conditions, or whether compressive release of water from storage occurs under confined conditions. The specific yield and confined storage coefficient have an important effect on water-level changes in the aquifers and will be discussed further in the section "The Transient-State Model." The location of water-table and confined conditions in the bedrock aquifers is shown in figure 9. The lateral extent of these areas may be altered by changes in water levels in the aquifer; thus, figure 9 represents approximate conditions as of 1978. As indicated in figure 9, water-table conditions generally are present in the near-surface parts of an aquifer, and confined conditions occur at greater depth in the aquifer and in underlying aquifers.

About 470×10^{6} acre-ft of water is in storage in the bedrock aquifers in the Denver basin. Of this amount, about 270×10^{6} acre-ft is estimated to be theoretically recoverable by gravity drainage of the aquifers. Aquifers generally cannot be completely drained by wells, so this volume of recoverable water represents a theoretical upper limit on yield, not a pratical limit. The distribution of total and recoverable water by aquifers is shown in table 2.

TABLE 2.—*Estimated total and recoverable ground water in storage in the Denver basin*

[Storage in millions of acre-feet]

Aquifer	Total water in storage	Recoverable water in storage
Dawson	48	27
Denver	89	42
Arapahoe	150	90
Laramie-Fox Hills	180	110
Total	467	269

By comparison, the Denver Water Department has a water-storage capacity of about 0.25×10^{6} acre-ft in a principal mountain reservoir (Dillon Reservoir), and the Denver metropolitan area annually uses about 0.31 $\times10^{6}$ acre-ft of water (A. Udin, Engineering Science, oral commun., 1983). The recoverable water in storage in the Denver basin is thus about 1,000 times the volume of Dillon Reservoir and would constitute slightly less than a 1,000-yr supply for the metropolitan area if such massive use of the ground water were feasible.

As shown in figure 9, confined conditions occur in most of the area of the bedrock aquifers. In spite of the large area of confined conditions, the volume of water in confined storage in these areas is only about 0.3×10^{6} acre-ft. This is the volume of water that would be released from storage in the aquifers as water levels in confined areas decline to the point where water-table conditions first develop in each aquifer. This volume constitutes less than 0.1 percent of the total volume of ground water in storage in the basin. These figures indicate that if ground-water development is to use the large volume of water in storage, water levels ultimately must be lowered such that water-table conditions develop in larger areas of the basin. Only under water-table conditions does gravity drainage of the aquifer allow large volumes of water to be removed from ground-water storage.

WATER LEVELS

The water-table conditions shown in figure 9 are present in the near-surface parts of the aquifers in the outcrop areas. A water table is present when the water level in a well lies below the top of the water-yielding zone. However, water in the bedrock aquifers generally is confined by overlying and underlying shale and clay strata of low hydraulic conductivity. As a result, the water level in a well may be considerably above the top of the water-yielding strata (a confined aquifer). Near Aurora, for example, the top of the Laramie-Fox Hills aquifer occurs at a depth of 1,500 ft, but the depth to water in wells completed in the aquifer is only about 250 ft. Depths to water in wells completed in the confined aquifers thus reflect the varying fluid pressures encountered in strata of different depths at different times. These pressures are expressed in terms of altitude of water level in a well (head) in feet above mean sea level. A map showing lines of equal head is referred to as a potentiometric surface map.

Prior to about 1885, heads in the Denver, Arapahoe, and Laramie-Fox Hills aquifers were large enough to cause bedrock wells in the valley of the South Platte River near Denver to flow with considerable pressure at the land surface (Emmons and others, 1896). The subsequent rapid decline in head in one of these wells, completed in the Arapahoe aquifer, is shown in figure 10. The head in this well has ranged from about 60 ft above land surface in 1883 to as much as 340 ft below land surface in 1960. Since 1960, heads have risen, probably as a result of a decrease in pumpage in the downtown area. In other parts of the basin, depths to water in 1978 have ranged from near zero in some low-lying undeveloped areas to more than 1,000 ft in other areas.

In 1978, the measured altitude of the potentiometric surface in the Dawson aquifer ranged from a high of 7,500 ft in the area near Black Forest to a low of 5,500 ft near Englewood, as shown on plate 1. A ridge in the potentiometric surface is located near a line from Palmer Lake to Rattlesnake Butte and forms a ground-water divide. Ground water north of the divide moves in a northerly direction; ground water south of the divide moves in a southerly direction. The altitude of the potentiometric surface and the direction of water movement are controlled primarily by the altitude of the stream channels in the area, the aquifer characteristics, and the magnitude and distribution of precipitation. This occurs because the rate of precipitation recharge to the Dawson aquifer generally exceeds the ability of the aquifer to transmit water over long distances. The excess ground water is discharged to nearby streams, allowing the altitude of the stream channels to affect the altitude of the potentiometric surface and the direction of the ground-water movement. As a result of this condition, the areas with the highest land-surface altitude (near the Black Forest, for example) also have the highest potentiometric surface altitude. In addition, more water is available for recharge in these high areas because of greater precipitation at the higher altitudes (fig. 2).

Vertical as well as lateral movement of water occurs in the Dawson aquifer. Lower potentiometric surface altitudes in the underlying Denver aquifer allow water to move down through the Dawson aquifer into the Denver aquifer. This vertical component of flow is small in comparison to the lateral component of flow but constitutes an important source of recharge for the underlying aquifers.

In most of the northwestern part of the Dawson aquifer, water-level changes have ranged from less than 50 ft of rise to less than 50 ft of decline during the 20-year period from 1958 to 1978. However, water-level declines near Castle Rock have exceeded 100 ft, and declines near Parker have exceeded 50 ft, as shown in figure 11*D*. The 1958–78 water-level change data from wells at a few scattered locations in other parts of the Dawson aquifer generally show water-level rises or declines of less than 30 ft, with no consistent pattern in these areas.

In 1978, the measured part of the potentiometric surface in the Denver aquifer ranged from a high of 6,800 ft in the southern part of the aquifer to a low of 5,000 ft near Commerce City (pl. 1). In the central part of the aquifer, water-level data are unavailable, and the potentiometric surface cannot be defined. In the northern, eastern, and southern parts of the aquifer, water generally is moving from the south-central part of the area toward the margins of the aquifer. Relatively sharp bends in the potentiometric contours occur near some small streams as a result of water moving from the aquifer into the stream valleys. Near the western edge of the aquifer, water is moving either approximately parallel to the aquifer limit or east from the aquifer limit toward the South Platte River. Ground water flows into a major trough in the potentiometric surface extending along Plum Creek and the South Platte River to the area northeast of Commerce City. The trough originally was shallower, being formed by the natural discharge of ground water into the South Platte River and its tributaries, but it has been deepened during the past hundred years by flowing wells and pumpage in the Denver metropolitan area.

Between 1958 and 1978, water-level declines in the Denver aquifer have exceeded 200 ft in an area east of Denver, and declines exceeding 50 ft have occured in large areas along the eastern and southern edges of the metropolitan area (fig. 11*C*). Near Cherry Creek Reservoir, the water level in the uppermost part of the Denver aquifer rose more than 50 ft between 1958 and 1978, probably as a result of recharge from the reservoir. The water-level change data from wells at a few scattered locations in other parts of the Denver aquifer usually show water-level rises or declines of less than 50 ft, with no consistent pattern in these areas.

In the Arapahoe aquifer, the measured part of the 1978 potentiometric surface ranged in altitude from a high of 6,500 ft in the southern part of the aquifer to a low of 4,900 ft near Brighton (pl. 1). In the central part of the aquifer, reliable water-level data for the Arapahoe aquifer are unavailable, and the potentiometric surface cannot be accurately defined. In the northern, eastern, and southern parts of the aquifer, water generally is moving from the south-central part of the area toward the margins of the aquifer. Near the western edge of the aquifer, water is moving either approximately parallel to the aquifer limit or is moving east from the aquifer limit toward the South Platte River. Ground water flows from the west, northwest, and southeast into a major trough in the potentiometric surface extending along the South Platte River to an area northeast of

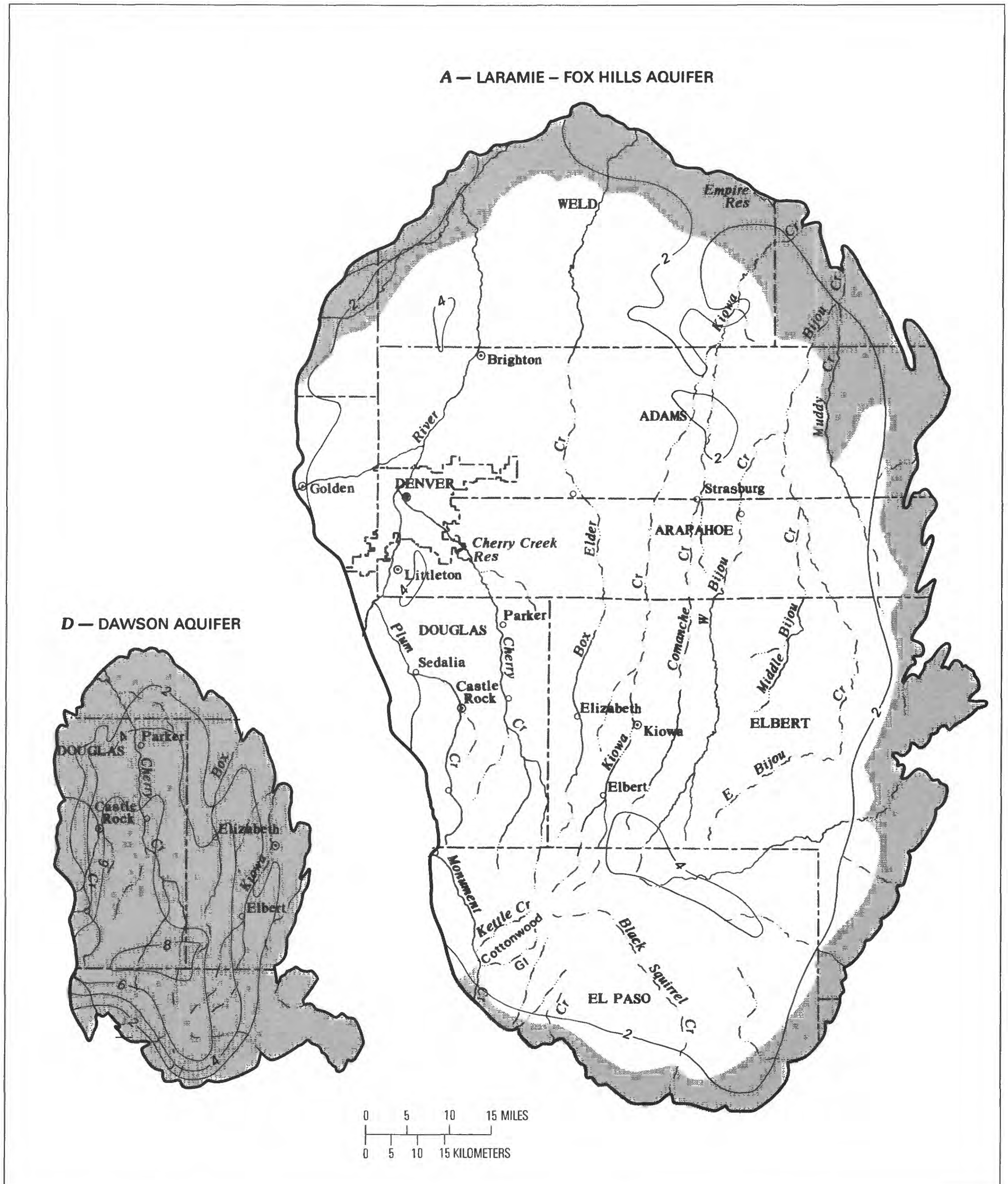


FIGURE 9.—Confined storage coefficient of the bedrock aquifers and location of water-table and confined conditions. *A*, Laramie–Fox Hills aquifer; *B*, Arapahoe aquifer; *C*, Denver aquifer; *D*, Dawson aquifer. (See fig. 4 for geographic location of aquifers.)

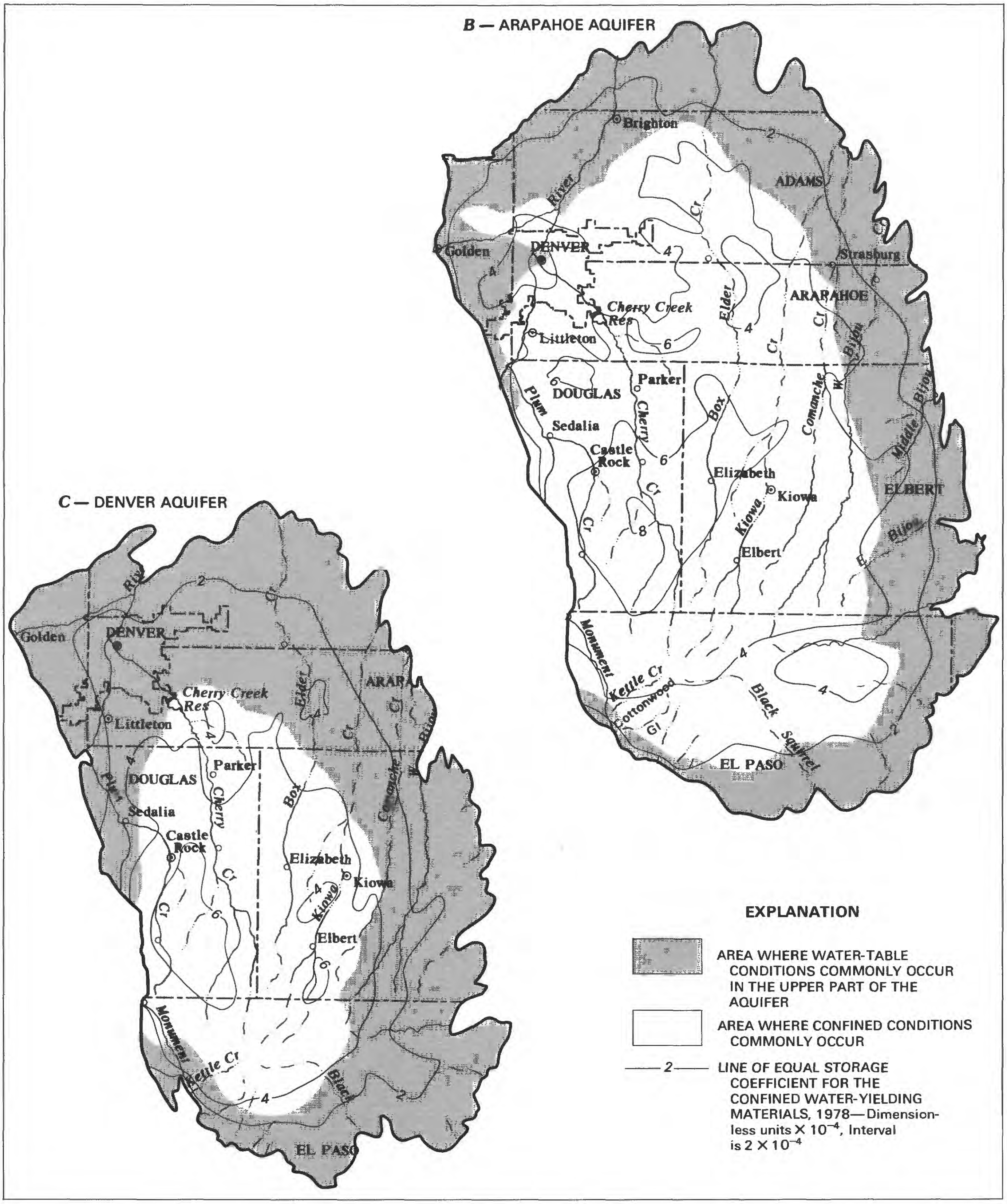


FIGURE 9.—Continued.

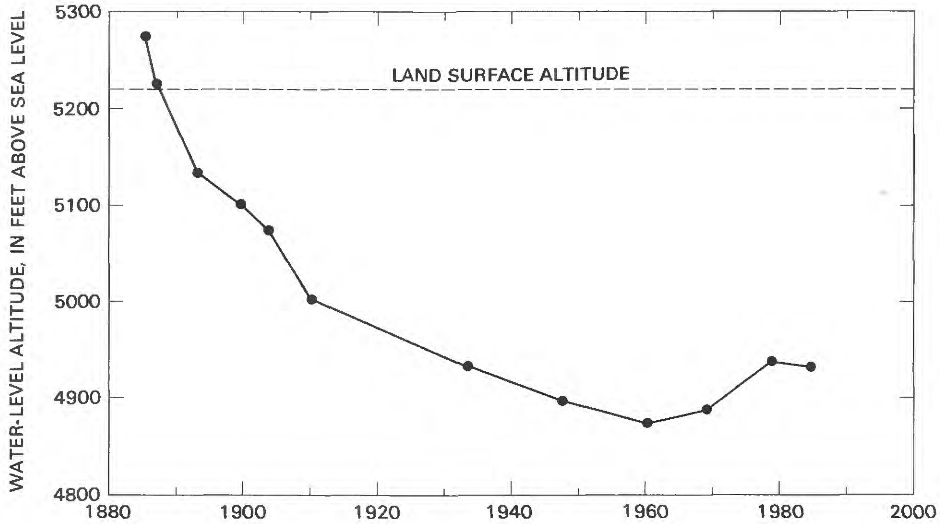


FIGURE 10.—Water-level hydrograph for the Arapahoe aquifer near the Colorado State Capitol.

Brighton. The trough originally was shallower prior to well drilling in the area and has been deepened and expanded during the past hundred years by flowing wells and pumpage.

Water-level declines in the Arapahoe aquifer have exceeded 200 ft in a 135-mi^2 area southeast of Denver, and have exceeded 50 ft in a much larger, but less well defined, area (fig. 11*B*). Water-level rises have exceeded 100 ft in a 60-mi^2 area under the north-central part of the Denver metropolitan area; in other parts of this area, only moderate water-level changes have occured. This pattern of water-level change is the likely result of recharge and a decrease in the rate of pumping in the metropolitan area, coupled with an increase in pumping in the surrounding suburban areas. The 1958–78 water-level change data for wells at a few scattered locations and other parts of the Arapahoe aquifer generally show water-level rises or declines of less than 50 ft.

The 1978 altitude of the measured potentiometric surface in the Laramie–Fox Hills aquifer is highest (6,300 ft) in the southern part of the aquifer and lowest (4,600 ft) near the northeast margin of the aquifer where ground water discharges to the alluvium of the South Platte River and its tributaries (pl. 1). In the central part of the aquifer, reliable water-level data for the Laramie–Fox Hills aquifer are unavailable, and the potentiometric surface cannot be accurately defined. North of El Paso County, water typically is moving to the north or northeast; south of the El Paso–Douglas County line, water generally is moving to the south or southeast. In and near Boulder County, local faulting appears to have segmented the aquifer and allowed markedly different water levels to occur in adjacent segments. The resulting potentiometric surface is distorted near these segments, and the direction of water movement in this area is complex. Schneider (1980) provided more detailed maps of the potentiometric surface and additional discussion of the hydrology in this area. In the northwestern part of the Denver basin, ground water in the Laramie–Fox Hills aquifer moves toward a major trough in the potentiometric surface. This trough extends from Littleton through Northglenn and Brighton and northeast toward Masters. A similar, but less extensive, trough has been shown to have been present in this area in 1970 (Romero, 1976). The trough has been formed by pumpage from wells in the area and has expanded and deepened as withdrawals have increased.

In an 80-mi^2 area near Brighton, water levels in the Laramie–Fox Hills aquifer declined more than 200 ft between 1958 and 1978. Declines in excess of 100 ft have occurred in an area extending from north of Denver to northeast of Brighton, and in the area northeast of Littleton, as shown in figure 11*A*. Water-level changes measured in wells at a few scattered locations in other parts of the aquifer usually indicate water-level rises or declines of less than 50 ft.

In spite of their outward appearance, bedrock formations have elastic properties and are compressible when subjected to stress such as that created by large water-level declines (Mayuga and Allen, 1970). For example, land-surface subsidence due to elastic compression of the bedrock aquifers in the Denver metropolitan area is estimated to range from 0.07 to 0.7 in. per 100 ft of water-level decline in the Laramie–Fox Hills aquifer and to range from 0.2 to 2.0 in. per 100 ft of water-level decline in the Arapahoe aquifer. The 400 ft of water-level decline in the Arapahoe aquifer between 1883 and

1960 (fig. 10) thus may have produced between 0.8 and 8.0 in. of land-surface subsidence in the metropolitan area. Resurvey of bench-mark altitudes on first-order level lines would provide a means of checking the accuracy of these subsidence estimates; however, this needed resurvey is not scheduled for completion before late 1984 (R. Cohen, National Geodetic Survey, oral commun., 1984). Lacking corroboration, these subsidence estimates based on rock-compressibility data from other areas (Fatt, 1958; Clark, 1966) must be considered as approximations.

Land-surface subsidence also may occur in suburban areas where more recent water-level declines have occured. Subsidence in these areas is likely smaller than in central Denver due to smaller water-level declines. Subsidence due to the elastic compression of the formations is partly reversible, and large water-level rises may produce some recovery in the land-surface altitude. Subsidence due to inelastic compaction of formation materials generally is not reversible. However, the consolidated nature of the formations indicates that inelastic compaction probably is not a major contribution to subsidence in the Denver basin.

If future development of the ground-water resources produces large water-level declines in the aquifer, several feet of land-surface subsidence might occur. Results of subsidence due to water-level declines in Arizona, California, Idaho, Nevada, and Texas were shown by Bull (1975) and Holzer (1977) to include damage to well casings, disruption to surface drainages and ditches, development of surface fissures, and disruption to gravity-flow sewage lines. The severity of these conditions is affected by the magnitude and distribution of subsidence.

The rate of ground-water movement is controlled by the hydraulic conductivity, porosity, and gradient of the potentiometric surface in the aquifer. These factors vary from one area to another in the basin but, in general, produce rates of movement that are much slower than those commonly found in surface streams. The average rate of movement in the Dawson or Arapahoe aquifers, for example, may range from 5 to 200 ft/yr. The Denver or Laramie–Fox Hills aquifers have rates of movement ranging from about 1 to 100 ft/yr. These figures represent average rates of movement in the aquifers and do not consider the larger rates of movement that occur near pumping wells. If porosity and hydraulic conductivity are similar in two areas, the area with the more closely spaced potentiometric contours (steeper gradient) will have a greater rate of ground-water movement; thus, the potentiometric-surface maps shown on plate 1 provide an indication of the relative rates of ground-water movement in the basin.

RECHARGE AND DISCHARGE

The mean annual precipitation in the basin supplies an average of 6,900 ft^3/s of water to the area. However, almost all of this water is lost through surface runoff, evaporation, and transpiration by vegetation, allowing only a small part of the precipitation to replenish the bedrock aquifers. In the outcrop area of the formations, recharge occurs as deep infiltration of precipitation in the highland areas between stream channels or as infiltration of water from alluvial aquifers located above the water level in the bedrock aquifers. In the central part of the basin, downward movement of water from overlying bedrock aquifers is an important source of recharge to most of the underlying aquifers. Although the rate of vertical movement is small in comparison to the rate of lateral movement, the large areas involved allow significant volumes of water to move between aquifers. In the case of the Laramie–Fox Hills aquifer, however, vertical movement of water through the thick shales of the Laramie Formation is probably insignificant.

Most water moves laterally through the permeable sandstone strata from areas of recharge toward areas of discharge. This can occur on both a local and regional scale. On a local scale, water moves from the highland recharge areas in the outcrop through the upper part of the aquifer, or through perched aquifers, to the discharge areas in nearby stream valleys. On a regional scale, water moves from outcrop recharge areas, or the central part of the study area where recharge occurs from overlying aquifers, into deeper parts of the aquifer and ultimately discharges in more remote stream valleys. In these stream valleys, water from the bedrock discharges into the streams or into the alluvial aquifers along the stream channels, or it is consumed by vegetation growing in the valleys.

In addition to these long-standing processes of natural recharge and discharge, relatively recent discharge is occurring from pumping wells. In areas where pumping has caused significant water-level declines, natural discharge may no longer occur, and pumpage may be the only form of ground-water discharge. In these areas, the interaquifer movement of water may be enhanced, halted, or reversed, depending on the relation of the heads in adjacent aquifers.

The Denver basin has a long history of water use from the bedrock aquifers. In 1883, a well drilled for coal exploration in sec. 29, T. 3 S., R. 68 W., was abandoned because of the large, uncontrollable flow of water encountered. By 1884, about 80 wells had been drilled into the Denver and Arapahoe aquifers in an approximately 4-mi^2 area near secs. 22, 27, 28, 32, 33, and 34 of T. 3 S., R. 68 W. Cross and others (1884) estimated that in 1884,

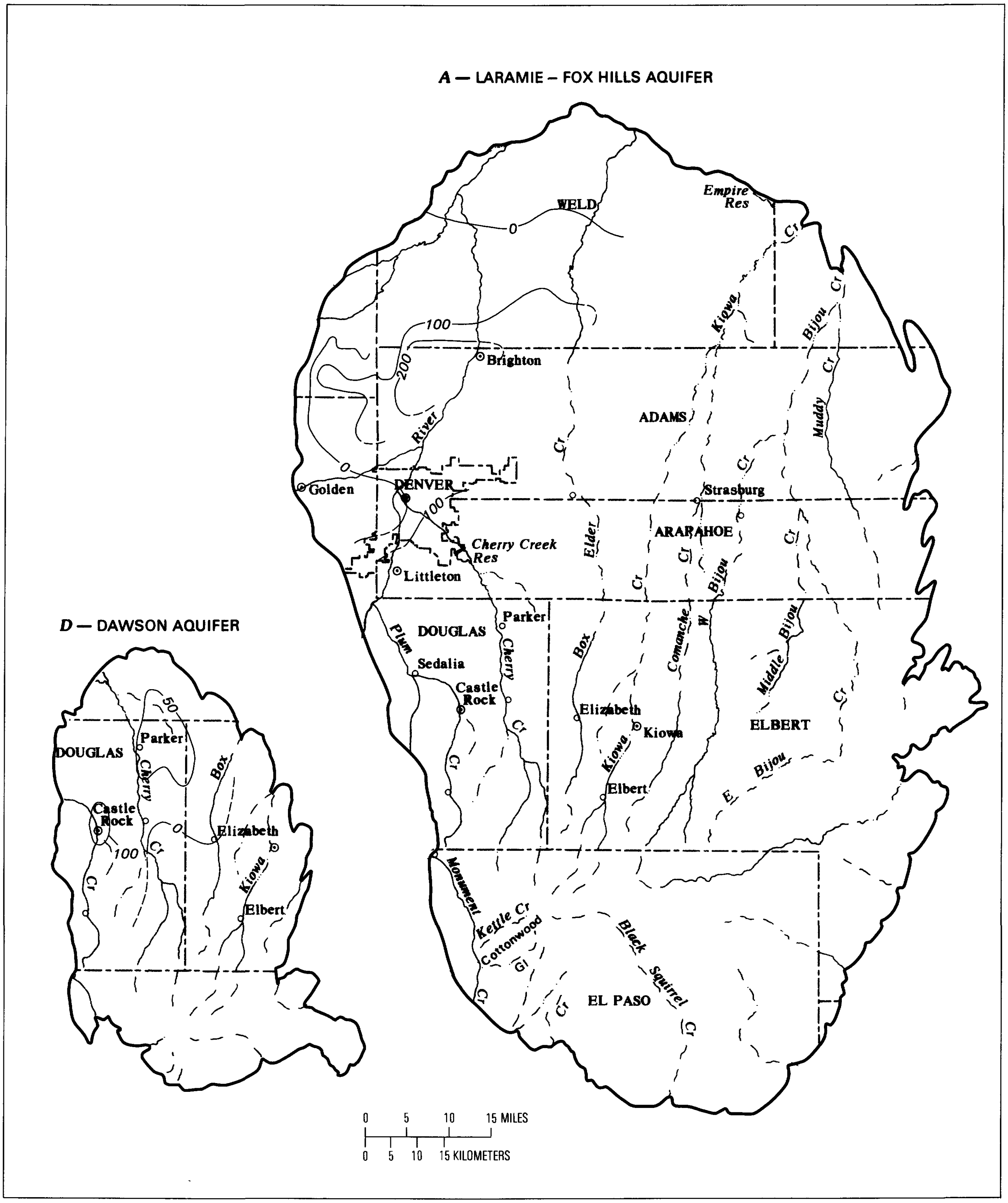


FIGURE 11.—Measured water-level changes in the aquifers between 1958 and 1978. *A*, Laramie–Fox Hills aquifer; *B*, Arapahoe aquifer; *C*, Denver aquifer; *D*, Dawson aquifer. (See fig. 4 for goegraphic location of aquifers.)

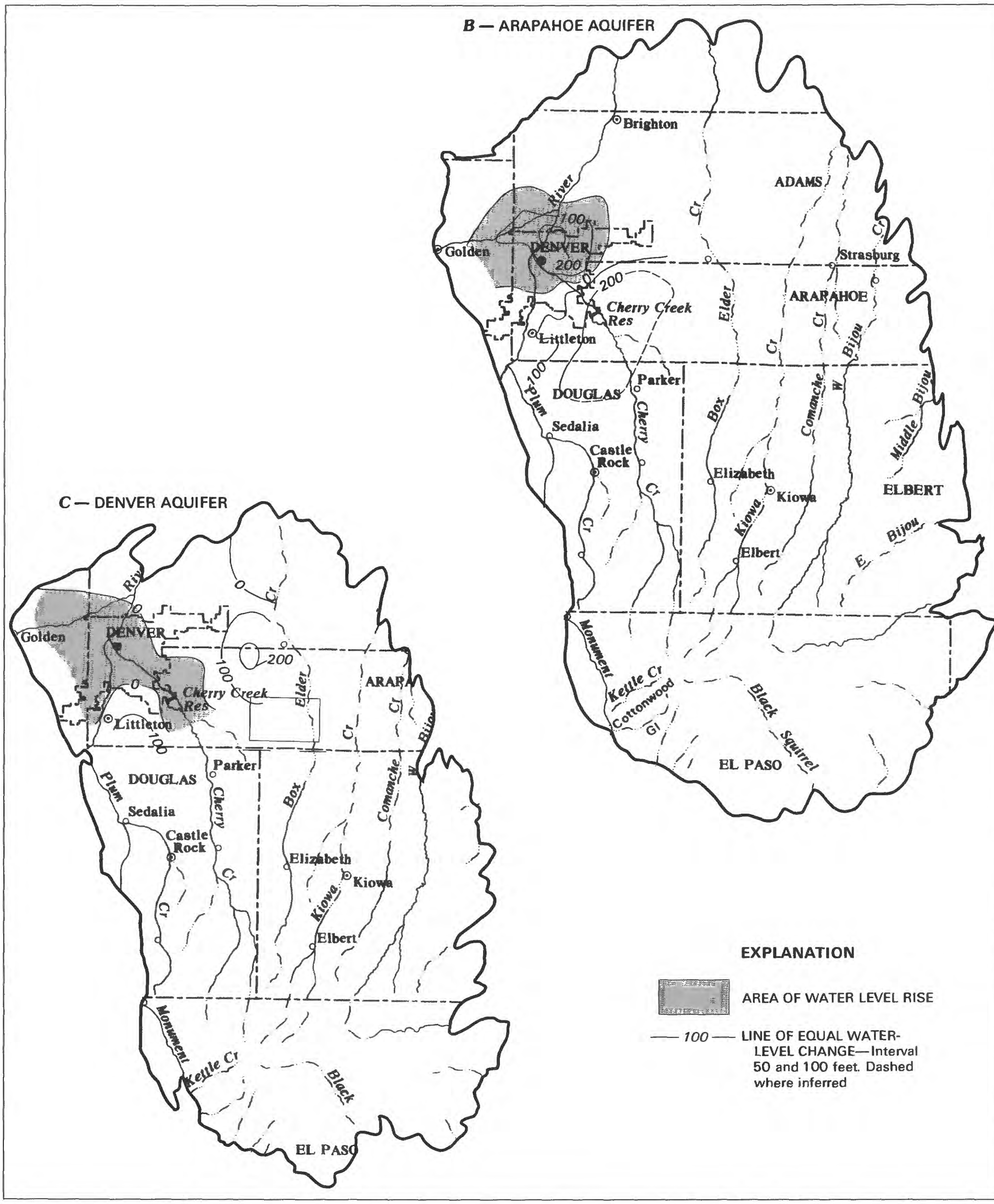


FIGURE 11.—Continued.

uncapped flowing wells produced about 4.5 ft^3/s of discharge from the aquifers. Emmons and others (1896) estimated that 400 bedrock wells had been drilled by 1890, but that decreasing heads in the aquifers had caused the discharge to decreased to about 2.3 ft^3/s. Darton (1905) reported that heads in the Denver and Arapahoe aquifers were 50 to 200 ft below land surface in the Denver area by 1905, requiring that water be pumped to the surface in most areas. In 1963, the U.S. Geological Survey compiled a preliminary tabulation of bedrock pumpage in the basin. This work included municipal, commercial, and industrial pumpage from most wells in the basin and indicated a pumping rate of 12.5 ft^3/s. Work by Romero (1976) contain the only other known pumpage estimate for the bedrock aquifers, but it is not usable for this work because it is an estimate of the maximum pumpage allowed under Colorado statutes rather than actual pumpage.

Because of limited data, it was necessary to estimate the total bedrock pumpage in the Denver basin for the model period 1958–78. Data were adequate to make annual estimates of municipal pumpage during this period, total pumpage for the years 1960, 1974, and 1977 also could be estimated. These estimates and results of ground-water modeling indicated that total pumpage was 3.0 to 4.5 times the municipal pumpage. This relation and the annual municipal pumpage were used to estimate the annual total pumpage for the entire 1958–78 period. Further discussion of the procedure used to estimate pumpage is contained in the "Supplemental Information" section at the end of this paper.

Estimates of total pumpage for wells completed in the bedrock aquifers ranged from 15 ft^3/s in 1958 to as much as 41 ft^3/s in 1978. As shown in figure 12, a gradual increase in pumpage occurred between 1958 and 1962, with little change between 1962 and 1975, followed by a

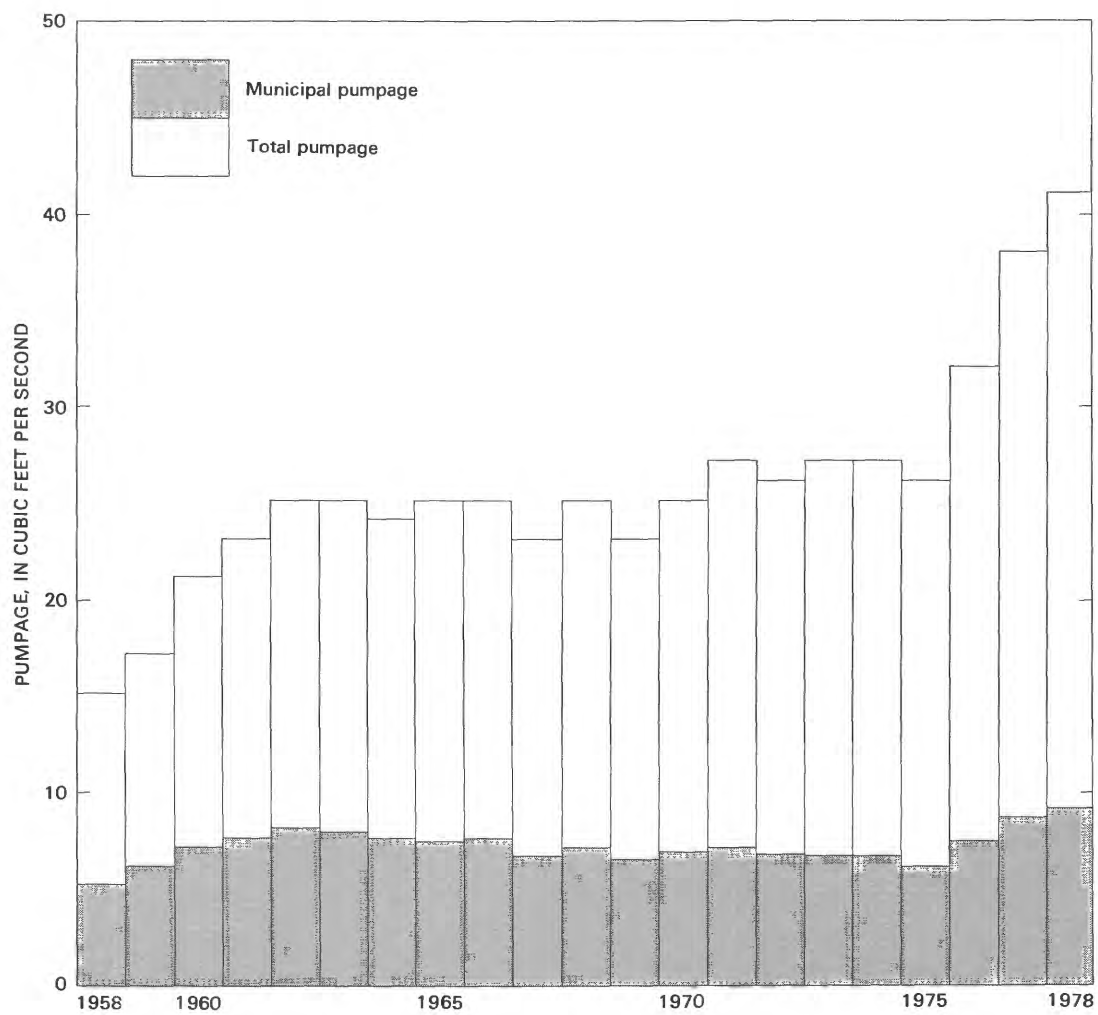


FIGURE 12.—Estimated pumpage from bedrock wells, 1958–78.

greater increase in pumpage between 1975 and 1978. The latter pumpage increase is probably due to (1) an increase in population and development in suburban areas that rely on bedrock wells and (2) the effects of outside water-use restrictions imposed on metropolitan customers by the Denver Water Department during the period 1977–82. The 1978 pumping rate is slightly less than the mean annual natural recharge to the entire bedrock-aquifer system. Most of this pumpage occurs within a 30-mi radius of downtown Denver and has caused major water-level declines in the bedrock formations.

Between 1975 and 1978, about one-half of the bedrock pumpage from the basin was obtained from the Arapahoe aquifer. This is to be expected, considering the large well yields, good quality water, and relatively shallow depths of the aquifer under the metropolitan area. The other three aquifers contributed 15 to 20 percent of the total pumpage during 1958–78.

Measured discharge from bedrock wells is highly variable but typically ranges from 2 to 700 gal/min. Small discharges of several gallons per minute are commonly found in domestic and stock wells or in larger municipal or industrial wells in areas of low transmissivity. Large-capacity wells in areas of high transmissivity usually yield several hundred gallons per minute, with reported discharges of as much as 800 gal/min. Wells in the Arapahoe aquifer generally have the largest yield, followed by those in the Dawson, Laramie–Fox Hills, and Denver aquifers.

WATER QUALITY

Water in the Dawson aquifer generally is of excellent chemical quality, meeting drinking-water standards (U.S. Environmental Protection Agency, 1976, 1977; Colorado Department of Health, 1978) for public water supplies in most of the area (table 3). The water generally contains a preponderance of dissolved calcium and bicarbonate ions, and thus is classified as a calcium bicarbonate–type water. Sodium bicarbonate– or sodium sulfate–type water occurs in a few isolated areas, usually near the margin of the aquifer. Dissolved-solids concentrations range from less than 100 mg/L in the south-central part of the Dawson aquifer to more than 1,000 mg/L near the northern edge of the aquifer, as shown in figure 13*D*. Dissolved-solids concentrations and the pH of the water are smallest near the groundwater divide in the area to the east of Palmer Lake. Dissolved-iron concentrations generally range from 20 to 100 μg/L, which is less than the limit of 300 μg/L recommended for public water supplies (U.S. Environmental Protection Agency, 1977). However, dissolved-iron concentrations between 8,000 and 85,000 μg/L have been measured in water samples from a few wells at scattered locations. Dissolved-sulfate concentrations commonly range from 4 to 10 mg/L in the central part of the aquifer to more than 700 mg/L in an isolated area at the northern margin of the aquifer (fig. 13*D*). In this area, sulfate concentrations exceed

TABLE 3.—*Typical bedrock water quality and drinking water standards*

[Values in milligrams per liter unless micrograms per liter (μg/L) indicated]

Dissolved constituent	Typical analysis for water from bedrock aquifers near Denver: Dawson aquifer	Denver aquifer	Arapahoe aquifer	Laramie–Fox Hills aquifer	Drinking water standard for public water supplies (U.S. Environmental Protection Agency, 1976; 1977; Colorado Department of Health, 1978)
Calcium	30	11	31	4.2	
Iron	80 μg/L	30 μg/L	170 μg/L	100 μg/L	300 μg/L
Magnesium	2.7	.4	3	.9	
Manganese	20 μg/L	10 μg/L	30 μg/L	10 μg/L	50 μg/L
Potassium	3.5	1.0	4.1	2.8	
Sodium	12	57	140	270	
Bicarbonate	120	150	250	640	
Carbonate	0	0	0	0	
Chloride	3.7	3.8	57	43	250
Fluoride	.5	1.6	1.1	2.7	1.8 (for Denver)
Nitrate as N	.11	.05	.04	.03	10
Phosphate	.03	0	4.1	2.8	
Silica	40	13	9.6	14	
Sulfate	12	13	110	7.6	250
Hardness as calcium carbonate	86	29	90	14	
Dissolved solids	164	175	479	662	1,000

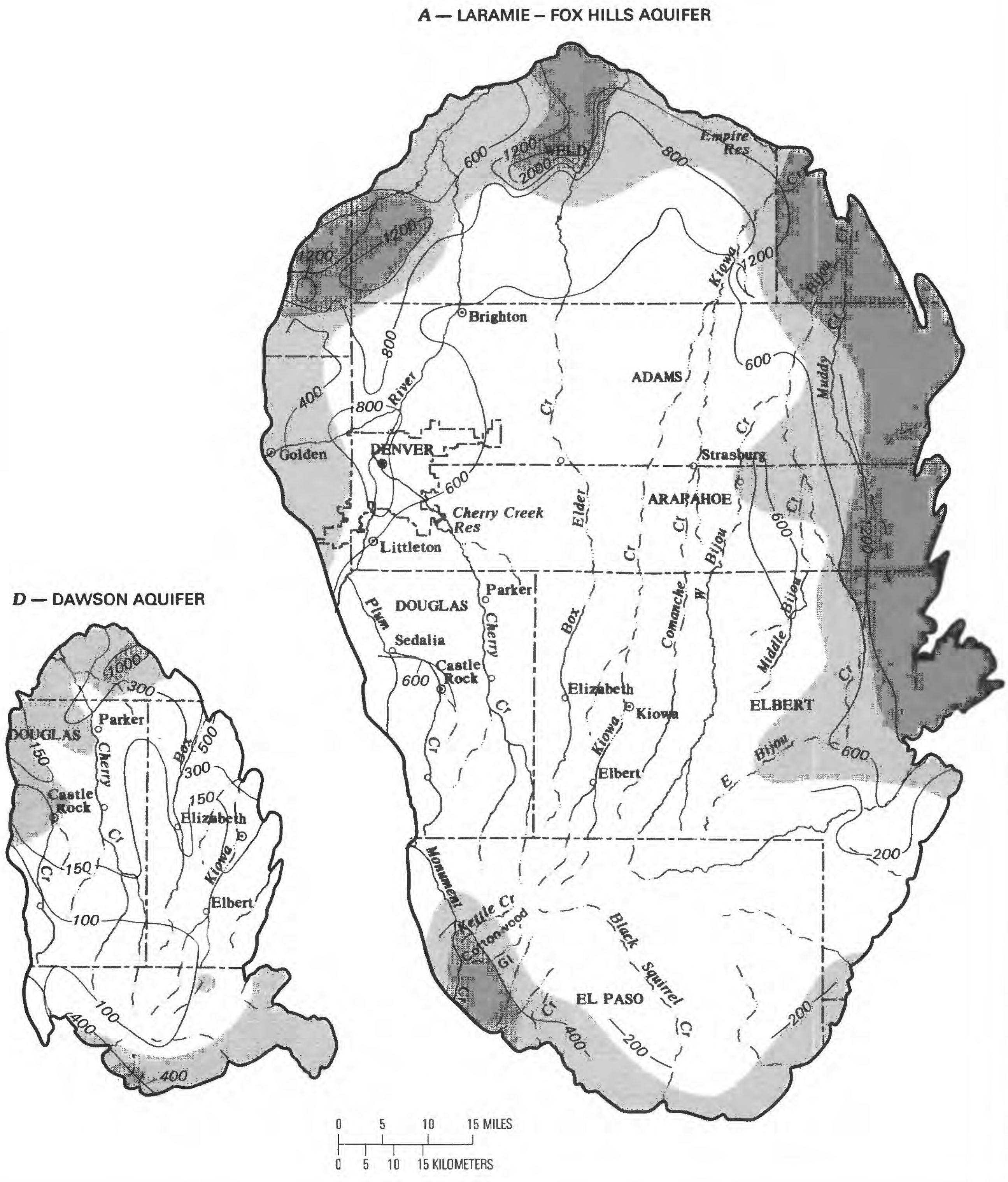


FIGURE 13.—Dissolved-solids and dissolved-sulfate concentrations in the bedrock aquifers. *A*, Laramie–Fox Hills aquifer; *B*, Arapahoe aquifer; *C*, Denver aquifer; *D*, Dawson aquifer. (See fig. 4 for geographic location of aquifers.)

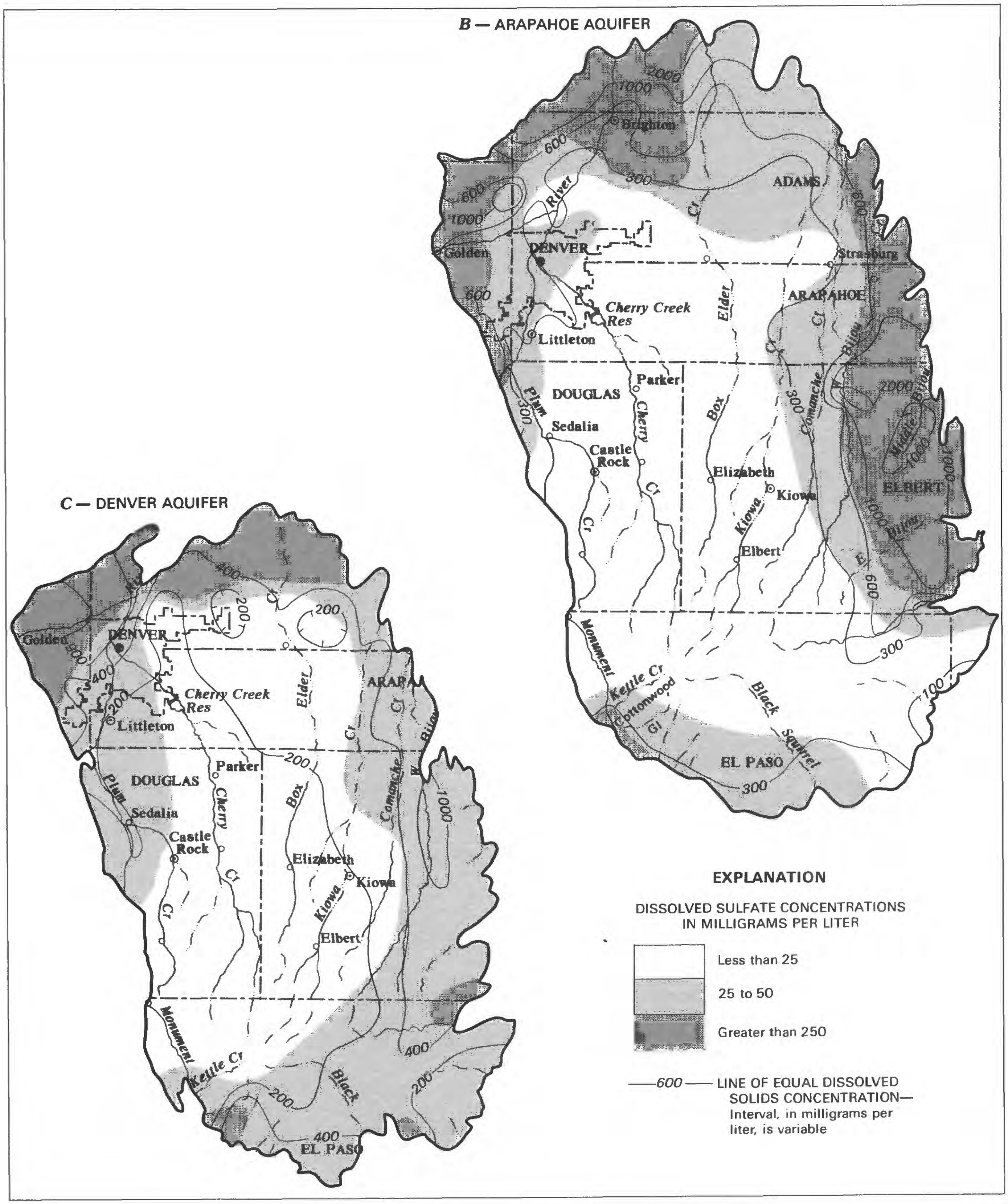


FIGURE 13.—Continued.

the recommended drinking-water standard of 250 mg/L for public water supplies.

A typical analysis of water from the north-central part of the Dawson aquifer is shown in table 3. For comparison, selected drinking-water standards for public water supplies also are shown. Concentrations of dissolved constituents in the bedrock water that exceeds these standards generally are not harmful but they may affect the color, odor, or taste of the water. For example, sulfate concentrations in excess of the standard may produce a laxative effect in people unaccustomed to drinking the water; large concentrations of iron or manganese may affect the taste of the water and stain plumbing fixtures and laundered clothing; large dissolved-solids concentrations may impart a mineralized taste to the water. Large concentrations of other constituents also may be objectionable, although no drinking-water standard has been set. Hardness, for example, is objectionable because hard water may leave a scaly deposit on the inside of pipes, steam boilers, and hot-water heaters; it requires more soap to make a good lather than does soft water; and it roughens washed skin and clothing. Hardness is classified, in terms of calcium carbonate, as soft water (0–60 mg/L), moderately hard water (61–120 mg/L), hard water (121–180 mg/L), and very hard water (more than 180 mg/L).

Water in the Denver aquifer is also of good chemical quality, meeting drinking-water standards for public water supplies in most of the area. A typical analysis of water from the northwestern part of the aquifer is shown in table 3. Water in the central part of the aquifer is classified as a calcium bicarbonate type. Near the margins of the aquifer, a sodium bicarbonate– or sodium sulfate–type water is more common. The calcium bicarbonate water occurs as a result of the calcium bicarbonate water in the overlying Dawson aquifer moving down into the Denver aquifer. As the calcium bicarbonate water moves laterally through the Denver aquifer, the water is naturally softened by cation exchange on the clay minerals that abound in this predominantly silty and clayey formation. This process increases the dissolved-sodium concentration in the water and decreases the dissolved-calcium concentration. As the water in the Denver aquifer moves beyond the limit of the overlying Dawson aquifer, other factors affect the chemical composition of the water. In the outcrop areas, the availability of oxygen in the soil and in the bedrock can lead to the formation of soluble minerals in these sediments and in the coal and other organic material that are common in the formation.

Part of the precipitation that falls on the outcrop area percolates downward, carrying some of these soluble minerals from the soil, rock, and coal into the Denver aquifer. This process, coupled with the cation exchange, produces the sodium bicarbonate– or sodium sulfate–type water found near the margins of the aquifer. Dissolved-solids concentrations are less in the central part of the aquifer, near the source of recharge from the overlying Dawson aquifer, as shown in figure 13*C*. The concentrations of dissolved solids increase to as much as 1,000 mg/L as the water moves toward the north, east, and south margins of the aquifer. Dissolved-iron concentrations generally range from 10 to 150 μg/L; however, concentrations as much as 6,600 μg/L are found in water from a few widely scattered wells. Measured concentrations of dissolved sulfate range from 2 mg/L in the central part of the Denver aquifer to as much as 2,700 mg/L in the northern part of the aquifer (fig. 13*C*). Concentrations in excess of 250 mg/L occur in a 300-mi^2 area along the northern margin of the aquifer and in a few isolated areas in the southern part of the aquifer.

Water in the Arapahoe aquifer generally is of good chemical quality and also meets drinking-water standards for public water supplies in most of the area. A typical analysis of water from the Arapahoe aquifer southeast of Denver is shown is table 3. The water in this aquifer is classified as a sodium bicarbonate type. Calcium bicarbonate–type water also occurs in the aquifer at scattered locations and in the area between Sedalia and Colorado Springs. Water in the Arapahoe aquifer is similar in type to that found in the overlying Denver aquifer, due in part to the downward movement of water from the Denver aquifer to the Arapahoe aquifer. Dissolved-solids concentrations seem to be less in the central part of the aquifer, near the source of recharge from the overlying Denver aquifer. As shown in figure 13*B*, the concentrations increase to more than 2,000 mg/L in some areas as the water moves toward the margins of the aquifer. This occurs as the result of soluble minerals being carried into the aquifer from near-surface sources. Dissolved-iron concentrations generally range from 20 to 200 μg/L; however, concentrations as much as 6,500 μg/L occur in a few widely scattered wells.

In areas of strong reducing conditions in the Arapahoe aquifer, sulfate minerals and organic material may be reduced to hydrogen sulfide and methane gases. When these gases are present in high concentrations, water pumped from the aquifer may effervesce, have a putrid odor, and be of marginal value for many uses. Although this condition is uncommon in the Arapahoe aquifer, a few occurrences have been reported. Measured concentrations of dissolved sulfate range from 5 mg/L in the southeast part of the aquifer to as much as 1,500 mg/L near the northern margin of the aquifer, and are in excess of 250 mg/L in large areas along the east and northwest margins of the aquifer (fig. 13*B*).

Water in the Laramie–Fox Hills aquifer generally is classified as a sodium bicarbonate type. Sodium sulfate-type water is found along the northern and eastern margins of the aquifer. A typical analysis of water from the southeastern part of the Denver metropopitan area is shown in table 3. Data are not available to define the apparently small concentrations of dissolved solids in the central part of the aquifer. The concentrations increase to more than 1,200 mg/L in three areas near the northern and eastern margins of the aquifer (fig. 13*A*). In each of these areas, the Laramie–Fox Hills aquifer is overlain by the shaly upper part of the Laramie Formation and is beyond the edge of the overlying Arapahoe aquifer. When the direction of ground-water movement is considered, poor quality water in these areas seems to occur as a result of soluble minerals being carried into the aquifer from surface sources or from sources within the upper part of the Laramie Formation. Dissolved-iron concentrations generally range from 20 to 200 μg/L. Concentrations of 42,000 and 79,000 μg/L have been found in two wells near Colorado Springs, and concentrations of about 1,000 μg/L have been found at a few other widely scattered wells. In areas of strong reducing conditions in the aquifer, sulfate minerals and organic material may be reduced to hydrogen sulfide and methane gases. When these gases are present in high concentrations, water pumped from the aquifer may have a putrid odor, effervesce, and be of marginal value for most uses. Dissolved-sulfate concentrations range from less than 2 mg/L south of Denver to more than 1,200 mg/L east of Boulder. Concentrations in excess of 250 mg/L occur in four areas near the northern, eastern, and southern margins of the aquifer (fig. 13*A*).

THE SIMULATED HYDROLOGIC SYSTEM

Ground water flow models are mathematical tools used to further our understanding of a ground-water system and to aid in evaluating the hydrologic changes that can occur as a result of changes in water use. Steady-state models are used to evaluate the hydrologic conditions in a basin prior to man's development of the water resources. These models provide estimates of the long-term average recharge and discharge to the aquifers and relate the effects of transmissivity, aquifer configuration, and recharge and discharge to the pristine water levels in the aquifers. Transient-state models are used to evaluate the hydrologic conditions that result from man's alteration of the natural system by such means as pumping wells, building reservoirs, and diverting water from streams. A transient-state model may estimate the time-dependent response of an aquifer system over a historical period (1958–78 in this study), or it may estimate the aquifer response over a future time period.

The quality of any model, whether it be a hydrologic model or a plastic model airplane, can be judged by how well the model represents the prototype. Because models are simplifications of the prototype in either size (the airplane model) or complexity (the hydrologic model), an exact correspondence between the model and prototype never can be achieved. What must be achieved, however, is a correct representation of the essential aspects of the prototype. In hydrologic models, this means that the model must function in a manner similar to that of the prototype without consideration of all the complexities of the prototype. The correspondence between model and prototype function is judged during calibration.

Calibration is accomplished by simulating water-level altitudes over a historical period and comparing these results to measured water-level altitudes for the same period. Differences between the model and prototype response are noted, and the geohydrologic data are checked and reinterpreted in an effort to resolve the differences. When the geoghydrologic data used in the model and the model computations agree satisfactorily with the corresponding measurments of the prototype, the model is considered to be calibrated and ready for further study and use. The process of judging the adequacy of the calibration is not quantitative; rather, it is a qualitative procedure in which the hydrologist must judge the degree of calibration against the worth of the data and the intended use of the model.

MODEL DESCRIPTION

Modeling in this study is based on the equation governing the flow of ground water through a porous medium in three dimensions. The equation may be expressed as:

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y})+b\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})=$$

$$S\frac{\partial h}{\partial t}+bW_{x,y,z,t}, \qquad (1)$$

where

h = hydraulic; head,
T_{xx},T_{yy} = the x and y components of transmissivity,
b = saturated thickness,
K_{zz} = the vertical component of hydraulic conductivity,
S = storage coefficient, and
$W_{(x,y,z,t)}$ = the rate of recharge or discharge expressed as a function of location and time.

In order to solve this equation for a heterogeneous, anisotropic aquifer with irregular boundaries, the area of the aquifer is subdivided into blocks in which the aquifer properties are assumed to be uniform (fig. 14). The continuous derivatives in equation (1) are replaced with finite-difference approximations for the derivatives at points located at the center of each block. Because 40 rows, 24 columns, and 4 layers of blocks were used in the transient-state model, a total of 40×24×4=3,840 equations in 3,840 unknowns is generated. The set of 3,840 simultaneous finite-difference equations is solved on a digital computer, using the iterative, strongly implicit procedure described be Trescott (1975) and Trescott and Larson (1976).

The four layers in the model represent the four aquifers in the basin. Vertical hydraulic conductivity is simulated between the layers, using the quasi-three-dimensional procedure decribed by Trescott (1975). Storage coefficients may be either confined or unconfined, depending on the altitude of the computed heads in relation to the altitude of the top of the aquifer. Where water-table conditions are present, the transmissivity is adjusted in response to changes in the saturated thickness of the aquifer. The linearity of the basic equation is maintained by modifying transmissivity and storage coefficient at the time-step level, and equal-interval time steps are used in most simulations. The data arrays used in the program are indexed to allow computer storage of only non-zero values. This significantly reduces the computer core requirements by eliminating storage space formerly needed for zero values, which occur outside the aquifer limits in each layer.

Input to the model program consists primarily of operational parameters, which control the internal operation of the program, and geohydrologic characteristics of the aquifers. Operational parameters include such items as the number of rows, columns, and layers in the model; configuration of the aquifers; number of time steps; duration of pumping periods; and format of output. Geohydrologic characteristics describe the geologic and hydrologic conditions in each grid block for each of the four aquifers, including altitude of the potentiometric surface at the start of the simulation, storage coefficient and transmissivity of the aquifers at the start of the simulation, vertical leakance between aquifers, structural altitudes of the top and bottom of each aquifer, and location and pumping rate of wells in each aquifer.

Model output consists of row, column, and layer tabulations of the model-calculated heads and water-level declines from the starting conditions. Heads calculated by the model represent the average altitude of the potentiometric surface in the area of the grid block. If a pumping well is simulated in the grid block, the model-calculated head also is the average head in a hypothetical 100 percent efficient well of radius r_e located in the center of the block, where

$$r_e=r_i/4.81, \qquad (2)$$

in which $r_i=\Delta x=\Delta y$ is the dimension of the grid block. Trescott and others (1976) provided additional discussion of the procedure used to calculate the head in a pumping well from the model-calculated head in a grid block. It is important to note that the model-calculated head in a grid block is not equivalent to the head in a pumping well. This must be calculated separately, using the model-output data and equation (2).

A water budget also is calculated as part of the model output. This budget summarizes all the recharge, discharge, and storage terms developed in the computations and presents an error term used to judge the computational accuracy of the finite-difference approximation to equation (1).

THE STEADY-STATE MODEL

A steady-state model was used to investigate the undisturbed hydrology of the bedrock aquifers. This model simulates long-term, constant hydrologic conditions prior to impacts of man and was used to produce estimates of the water budget and the rate of vertical leakance between adjacent aquifers.

In contructing this model, an equal-interval grid of blocks 3 mi on a side, consisting of 41 rows, 27 columns, and 4 layers, was used. The aquifer limits and transmissivity distributions shown in figure 8 were

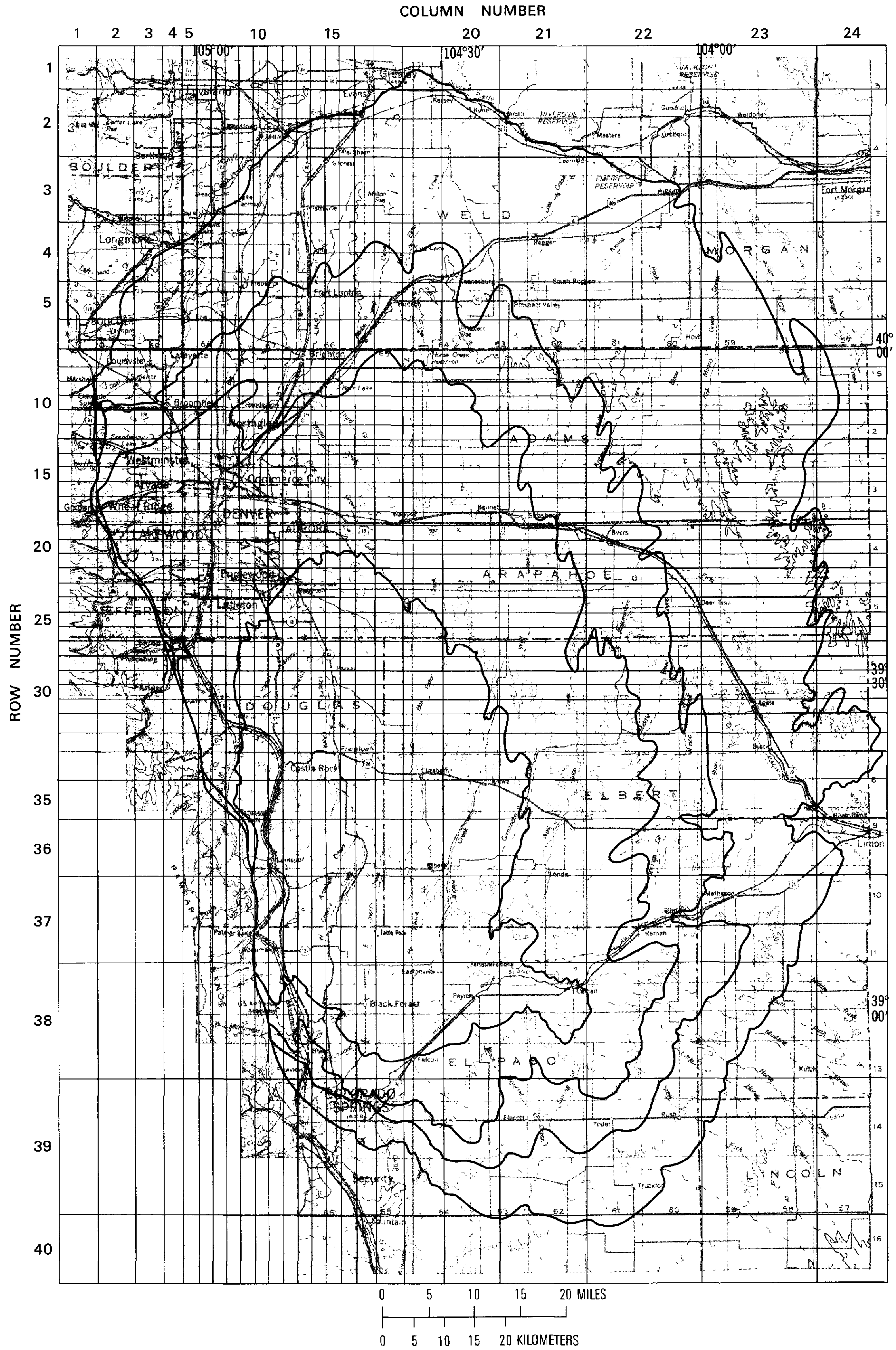


FIGURE 14.—Size and distribution of grid blocks used in the transient-state model.

used, and both starting head and storage coefficient were set to zero, as is common practice in this type of simulation. Constant-head nodes were specified in the outcrop areas of the four aquifers at points of recharge and discharge as indicated by the potentiometric-surface maps. Constant-head nodes located at these points provide recharge or discharge to the model. Water-level measurements in 31 selected wells were available to define the pristine water-level conditions in the basin. Near Denver, measurements made prior to 1885 were used for this purpose; in other areas, more recent measurements were suitable because of the more limited historical decline in water level. The measurements were of adequate depth and areal distribution to define the pristine heads at a number of points in each aquifer.

Calibration consisted of varying the vertical hydraulic conductivity between the aquifers until the model-calculated heads were in close agreement with the pristine heads measured in each aquifer. The level of agreement was judged by use of the mathematical expression call mean square error (MSE), calculated as:

$$MES=\overline{\Delta H^2}+S^2, \quad (3)$$

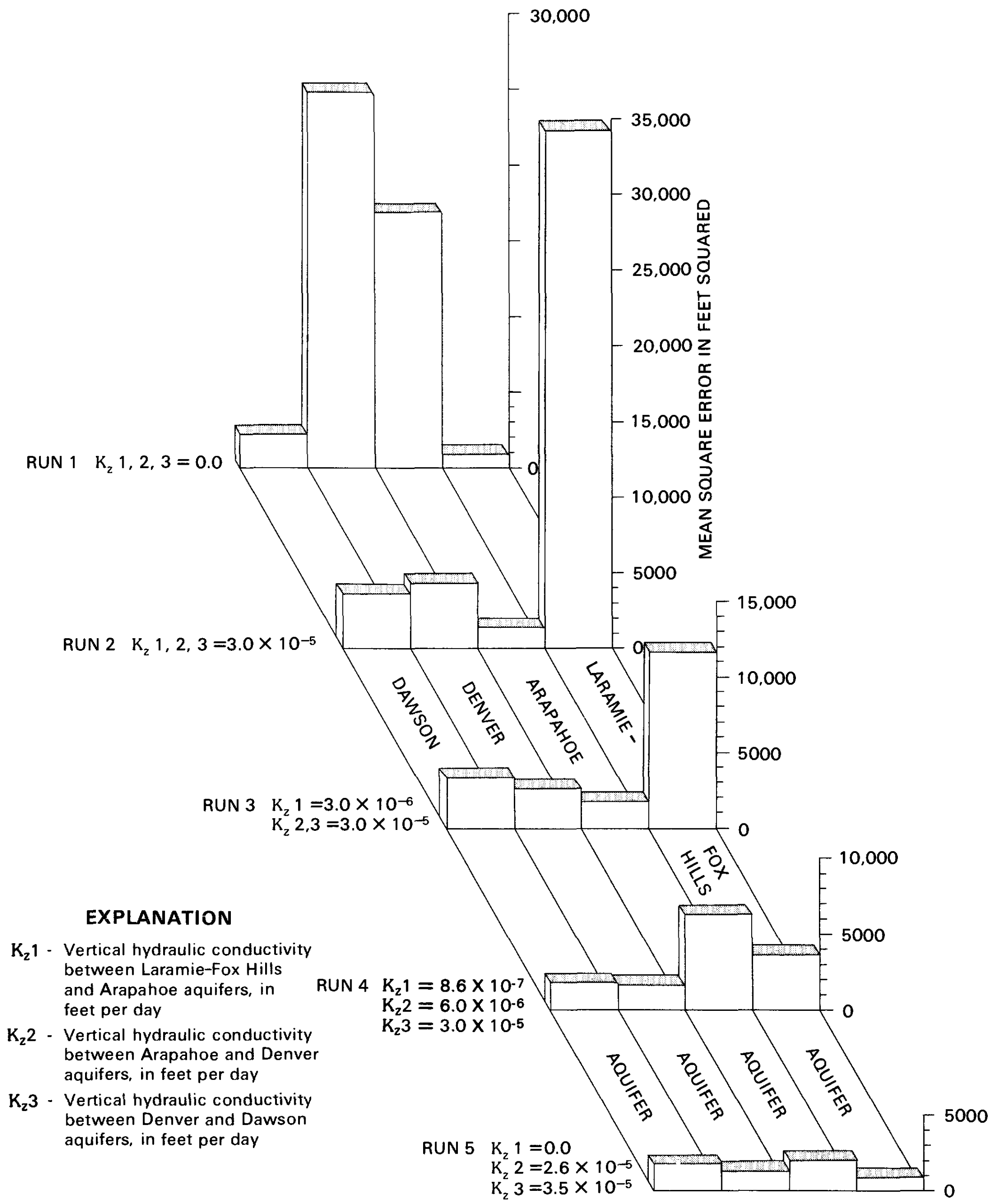


FIGURE 15.—Mean-square-error configuration during steady-state calibration.

where

$$\overline{\Delta H}^2 = \left[\sum_{i=1}^{n} (H_{ci}-H_{mi})/n \right]^2,$$

$$S^2 = \sum_{i=1}^{n} \left(\Delta H_i - \overline{\Delta H} \right)^2/(n-1),$$

$\Delta H = H_c - H_m$,
H_c = the computed head at a grid block where a well is located,
H_m = the measured head at the corresponding well, and
n = number of wells.

MSE thus provides a method of measuring how well the computed heads agree with the measured heads. Large values of MSE indicate poor agreement, whereas small values indicate good agreement. Several values of vertical hydraulic conductivity (K_z) were tried in the model, and the resulting MSE was calculated, as shown in figure 15. For example, when it was assumed that there was no vertical connection between any of the aquifers, a large MSE was produced in the Denver and Arapahoe aquifers (run 1, fig. 15), indicating that this was not a good assumption for these aquifers. However, this may be a reasonable assumption for the Laramie-Fox Hills aquifer, as indicated by the small MSE produced in this layer. Subsequent simulation runs were used to investigate the effects of various combinations of vertical hydraulic conductivity until a uniformly small value of MSE was produced in all of the aquifers (run 5, fig. 15).

The calibration results indicate that the vertical hydraulic conductivity through the Dawson, Denver, and Arapahoe aquifers is about 3×10^{-5} ft/d. Lateral hydraulic conductivity of these aquifers ranges from about 0.05 to 7.0 ft/d, with 3.0 ft/d a common value. The ratio of lateral to vertical hydraulic conductivity is thus about 1×10^5, indicating that these aquifers are about 100,000 times more permeable in the lateral direction than in the vertical direction. In terms of water movement, this means that water-level changes due to pumping primarily will spread laterally through the aquifer and will have much less effect on water levels in overlying or underlying aquifers. The vertical hydraulic conductivity is accurate only to the degree that the lateral hydraulic conductivity was correctly estimated. In the central part to the deeper aquifers, no data are available to define the lateral hydraulic conductivity. In this area, the vertical hydraulic conductivity is also less accurately defined.

The regional-scale steady-state recharge and discharge for the four principal bedrock aquifers as calculated by the steady-state model are shown in table 4. Local-scale recharge and discharge are not considered in this table because their inclusion would not be representative of the effective recharge and discharge for the aquifers. This water budget represents long-term average flow conditions and does not consider temporal changes in hydraulic conditions, such as pumpage or annual variations in precipitation. It can be seen in table 4 that the Dawson aquifer receives most of the recharge (40.6 ft^3/s) and also supplies most of the discharge (33.4 ft^3/s), principally to the drainage areas of Plum, Cherry, Kiowa, and Monument-Fountain Creeks. The difference between the recharge and discharge for the Dawson aquifer (7.2 ft^3/s) is the rate of water movement from the Dawson to the underlying Denver

TABLE 4.—*Regional-scale steady-state water budget for the bedrock aquifers*
[Values in cubic feet per second]

Recharge or Discharge Terms	Aquifer				Total
	Dawson	Denver	Arapahoe	Laramie-Fox Hills	
Precipitation Recharge	40.6	5.5	2.8	5.8	54.7
Discharge to principal drainage area of:					
Plum Creek	6.1	1.1	0.3	--	7.5
Cherry Creek	10.3	.2	--	--	10.5
South Platte River	.3	2.2	2.4	0.5	5.4
Box Elder Creek	2.6	.2	.9	.1	3.3
Lost Creek	--	.1	.6	.2	.9
Kiowa Creek	5.9	.2	.2	.7	7.0
Bijou Creek	.6	2.1	2.1	2.1	6.9
San Arroyo-Badger Creek	--	--	--	1.1	1.1
Big Sandy Creek	.2	.3	.5	.2	1.2
Rush-Steel Fork Creek	--	--	.1	.5	.6
Black Squirrel Creek	0.4	0.7	.5	.2	1.8
Monument-Fountain Creek	7.0	.3	.5	.2	8.0
Total discharge	33.4	7.4	8.1	5.8	54.7

aquifer. Recharge to the Denver aquifer occurs from the Dawson aquifer and from infiltration of precipitation in the outcrop areas (5.5 ft^3/s), with discharge principally occurring in the drainage areas of Bijou Creek and the South Platte River. Recharge to the Arapahoe aquifer occurs from the Denver aquifer (5.3 ft^3/s) and from infiltration of precipitation in the outcrop areas (2.8 ft^3/s). Discharge from the Arapahoe aquifer is primarily into the drainage areas of Bijou Creek and the South Platte River. The Laramie–Fox Hills aquifer does not receive significant recharge from the overlying Arapahoe aquifer; as a result, recharge and discharge occur in the outcrop areas, and each totals 5.8 ft^3/s. Principal discharge areas for the Laramie–Fox Hills aquifer are the drainages of Bijou and San Arroyo–Badger Creeks. The largest discharge from the four bedrock aquifers is into the drainage areas of (1) Cherry Creek, (2) the Monument-Fountain Creek combined area, (3) Plum Creek, (4) Kiowa Creek, (5) Bijou Creek, and (6) the South Platte River.

The accuracy of the water budget is directly related to the accuracy of the hydraulic conductivity data used in the steady-state model. Independent determination of the water budget accuracy is difficult due to unfavorable geologic and hydrologic conditions along most stream valleys. These conditions prevent direct measurement of bedrock aquifer discharge. However, discharge from the Dawson, Denver, and Arapahoe aquifers to Monument Creek can be measured; Livingston and others (1976) indicated that 7.5 ft^3/s of discharge occurs in the reach underlain by these aquifers. This compares favorably with the 7.8 ft^3/s of discharge calculated by the model (table 4).

Results of the steady-state simulations provide both hydrologic insight to the functioning of the aquifer system and information required in transient-state modeling. Successful calibration of the steady-state model indicates that the relationships between recharge, discharge, and water movement described in the previous sections of this report are essentially correct. In addition, the water budget and vertical hydraulic-conductivity results provide a new and quantitative definition of the hydrologic characteristics. These results must be available if the more complex phase of transient-state modeling is to be successful.

THE TRANSIENT-STATE MODEL

The transient-state model expands the simulation ability of the steady-state model by considering time-varying hydrologic conditions. Transmissivity, storage coefficient, and specific yield are no longer held invariant but are allowed to change in response to changing head conditions in the model. Variable pumpage, induced recharge, and capture of discharge also are considered in the transient-state model.

Pumpage variations are simulated as a stepped sequence of pumping periods, three of which were used in the calibration of the transient-state model. The pumping periods are of 3 years' duration (1959–61), 13 years' duration (1962–74), and 4 years' duration (1975–78). The model pumpage is held constant at the average pumping rate for each period.

Induced recharge occurs when the head in an aquifer declines and allows additional water to enter the aquifer, as from an overlying alluvial aquifer, for example. The rate of induced recharge increases as larger head declines occur, ultimately reaching a constant rate due to the effects of anisotropic sediments in and under the alluvial aquifer. Capture of discharge occurs when the head in an aquifer declines and reduces the rate of discharge from the aquifer. A decreasing rate of flow from a bedrock spring is an example of captured discharge. The model program was modified to allow induced recharge or captured discharge to increase as a linear function of head decline until a maximum recharge rate of 0.133 ft^3/s per square mile of alluvial-bedrock aquifer interface was reached. A constant rate of induced recharge was then simulated. Data are not available to document the maximum recharge rate; however, testing of various rates in the model indicated that reasonable head response could be achieved with a value of 0.133 ft^3/s.

A variable-interval grid was used in the transient-state model. Grid blocks ranged in size from 1.5×1.5 mi in the west-central part of the basin to as much as 12×14 mi in the outlying eastern parts of the basin. The greater grid-block density in the Denver metropolitan area allowed greater resolution of head conditions in this critical area.

Calibration of the transient-state model was performed by calculating the potentiometric heads in the aquifer during the period from 1958 to 1978. The model-calculated 1978 heads, shown on plate 2, were then compared to the measured 1978 heads, shown on plate 1, to judge the simulation ability of the model. The agreement between the two groups of maps generally is very good, with minor disagreement limited to local areas. This indicates that the transient-state model is a reasonable simulator of the response of the prototype.

The principal reasons for disagreement between the two groups of maps are (1) inadequate information on the location and rate of pumping from bedrock wells, (2) the inability of the model to simulate small-scale anisotropy due to faulting near Boulder County, and (3) partial vertical stratification of heads in the Dawson and Denver aquifers.

As discussed in the "Supplemental Information" section of this paper, adequate data are not available to make accurate estimates of historical pumpage. The model-calculated 1978 heads are thus affected by errors in the location or rate of pumping, and these errors may be responsible for local differences in head between the two map groups. If pumpage data of better accuracy had been available, closer agreement between computed and measured heads probably would have been obtained.

Faulting in the Laramie–Fox Hills aquifer near Boulder County has markedly affected the local ground-water altitude and direction of movement. The extent of the area affected by faulting has not been determined, but model results indicate that it may extend through much of the area north of Westminster and west of Brighton (fig. 7). Anisotropic transmissivity was modeled in the Laramie–Fox Hills aquifer in this area in an attempt to simulate the large-scale hydrologic effects of the faults. Although an anisotropy ratio of $T_x/T_y=25$ was found to substantially improve the simulation results, the anisotropic effects of the faults could not be fully simulated. This was primarily due to the coarseness of the model grid in relation to the spacing of the faults and the noncoincident alignment of the northeast-trending faults with the east-west-oriented model grid. Because of this limitation, the model will not provide valid simulations of head conditions in the part of the Laramie–Fox Hills aquifer strongly affected by faulting.

When model runs indicated insufficient water-level decline in the water-table parts of the Dawson and Denver aquifers, the accuracy of the pumpage data was initially suspected. However, the modeled pumpage in a 60-mi^2 area near Parker was found to be in reasonable agreement with a more accurate and detailed pumpage estimate made in this area. Further testing of the model indicated that proper water-level declines could be produced when a confined storage coefficient was used in a larger area of these aquifers. The model thus indicated that although water-table conditions occur in the upper parts of these aquifers, at the depths of most wells the aquifers are confined and are not in direct hydraulic connection with the water table. Such partial vertical stratification of heads is normally simulated by use of two or more model layers for each aquifer. Time and computer-core limitations precluded this major revision of the model and required use of a simplifying assumption in order to allow the existing model to be used. It was assumed that confined conditions would occur in the central part of the Dawson aquifer until the water level declined to the upper perforations in most well casings. This distance was estimated to be about 100 ft. Therefore, the computer program was modified such that as soon as water-level declines exceeded this value, unconfined conditions would occur, and specific yield replaced storage coefficient in the model node. A similar modification to the model code allowed the Denver aquifer to remain temporarily confined in part of the outcrop immediately beyond the Dawson aquifer. Head-dependent conversion to unconfined conditions still occurred in this area. Because this assumption only approximates the more rigorous multilayer simulation, it may be responsible for some of the differences between computed and measured heads in the calibration of the Dawson and Denver aquifers. This revision allows the model to more correctly simulate the head conditions at the depth of most wells in the Dawson and Denver aquifers. It also requires that the 1978 potentiometric surface shown in Robson and Romero (1981a, 1981b) be revised to show the head in only the deeper parts of the aquifers. The revised 1978 potentiometric surface is shown on plate 1.

It is important to note that although the model produces a reasonable simulation of the response of the prototype, it may not be unique in this ability. If the temporal and spatial variations in such hydrologic characteristics as natural recharge and discharge, pumpage, lateral and vertical hydraulic conductivity, specific yield, and storage coefficient are well defined by field data, little question remains as to the correct values for the associated model parameters. If these characteristics are poorly defined by field data, the correct values of the associated model parameters are less certain. In this case, the range of acceptable values for the model parameters might be such that more than one combination of values could produce an acceptable model calibration. In the case of the Denver basin model, lateral hydraulic conductivity and specific yield are the parameters best defined by field data. Vertical hydraulic conductivity and natural recharge and discharge were determined through steady-state modeling and are compatible with, but probably less accurate than, the lateral hydraulic conductivity. Indirect techniques were used to arrive at estimates of storage coefficient and pumpage, and a larger range of values is possible. Because of the uncertainties associated with the definition of all of these hydrologic characteristics, a combination of model parameters different from those used might also produce an acceptable model calibration. The differences between the results of the two models probably would not be large due to constraints on the choice of parameters values. However, the question of uniqueness takes on new importance when model simulation time periods and pumping rates greatly exceed those used in calibration. Further discussion of modeling errors and limitations may be found in the "Supplemental Information" section of this paper. This information should be taken into account before using results of model simulations.

TABLE 5.—*Transient-state 20-year water budget for the bedrock aquifers*

[Values in acre-feet]

Aquifer	20-year steady-state period		20-year transient-state calibration period 1958–78				
	Precipitation recharge	Ground-water discharge	Net interaquifer flow	Pumpage	Net decrease in ground-water storage	Net recharge	Net interaquifer flow
Dawson	588,000	−484,000	−104,000	−30,000	7,000	120,000	−97,000
Denver	80,000	−107,000	27,000	−66,000	38,000	96,000	−68,000
Arapahoe	41,000	−118,000	77,000	−219,000	31,000	23,000	165,000
Laramie–Fox Hills	84,000	−84,000	0	−59,000	14,000	45,000	0
Totals	793,000	−793,000	0	−374,000	90,000	284,000	0

The calibrated model is a valuable hydraulic tool, for it provides quantitative information about the hydrologic system. A water budget for the 20 year transient-state calibration period is of particular interest in this respect. A transient-state water budget is more complex than is a steady-state water budget and must be used with caution to avoid misinterpretation. The transient-state water budget for 1958–78 for each aquifer is shown in table 5. A corresponding 20-year steady-state water budget also is shown for purposes of comparison.

During a 20-year steady-state period, the aquifer system, as a whole, would have received 793,000 acre-ft of recharge and would have discharged an equal volume of water. During this 20-year period, 104,000 acre-ft of water would have moved from the Dawson aquifer into the Denver aquifer, and 77,000 acre-ft of water would have moved from the Denver aquifer into the Arapahoe aquifer. This produced a net inflow to the Denver aquifer of 27,000 acre-ft (104,000−77,000).

During the 20-year transient-state calibration period, a total of 374,000 acre-ft of water was pumped from the bedrock aquifers. This pumpage, coupled with the effects of pumping prior to 1958, produced a net imbalance between recharge and discharge (net recharge). (Note that recharge and discharge were equal under steady-state conditions.) The net recharge of 284,000 acre-ft is due to the cumulative effects of pumpage from 1883 to 1978 and occurs as the result of capture of natural discharge, induced recharge of additional water from surface sources, and additional recharge supplied by man's activities (infiltration from Cherry Creek Reservoir, for example).

The cumulative effect of pumpage prior to 1978 altered the interaquifer flow from the steady-state values. Flow from the Dawson aquifer to the Denver aquifer was reduced from 104,000 acre-ft to 97,000 acre-ft, and flow from the Denver aquifer to the Arapahoe aquifer was increased from 77,000 acre-ft to 165,000 acre-ft. This produced a net outflow from the Denver aquifer of 68,000 acre-ft (165,000−97,000) under transient conditions, as compared to a net inflow of 27,000 acre-ft under steady-state conditions.

The net change in the volume of water stored in the aquifers is the difference between the pumpage, net recharge, and net interaquifer flow. The net decrease in the volume of ground water in storage totaled 90,000 acre-ft during the 20-year transient period. Because of model limitations, it is not known how much of the 374,000 acre-ft of pumpage came from a decrease in ground-water storage and how much came from net recharge and net interaquifer flow.

MODEL SIMULATIONS

These model simulations consider only geologic and hydrologic conditions and do not consider economic, legal, or social factors. In addition, the model simulations are *not* predictions of future conditions that will occur in the aquifers. Rather, they are predictions of conditions that could result from a specified rate, distribution, and duration of pumpage. The simulations will predict future conditions in the aquifer only if the modeled pumpage accurately represents future pumpage and the model accurately simulates the prototype.

The accuracy of the following model simulations varies, depending on the particular conditions being simulated. Factors affecting this accuracy include (1) the quality of the model calibration, (2) the uniqueness of the model, (3) the duration of the simulation period compared to the duration of the calibration period, and (4) the rate of simulated pumping compared to the rate of calibration pumping. These factors, discussed in some detail in the "Supplemental Information" section of this paper, effects the accuracy of the calculated head distributions, drawdowns, and mass balances. Simulations involving short time periods and small rates of pumping are probably the most accurate. Long simulation periods and large rates of pumping, when combined

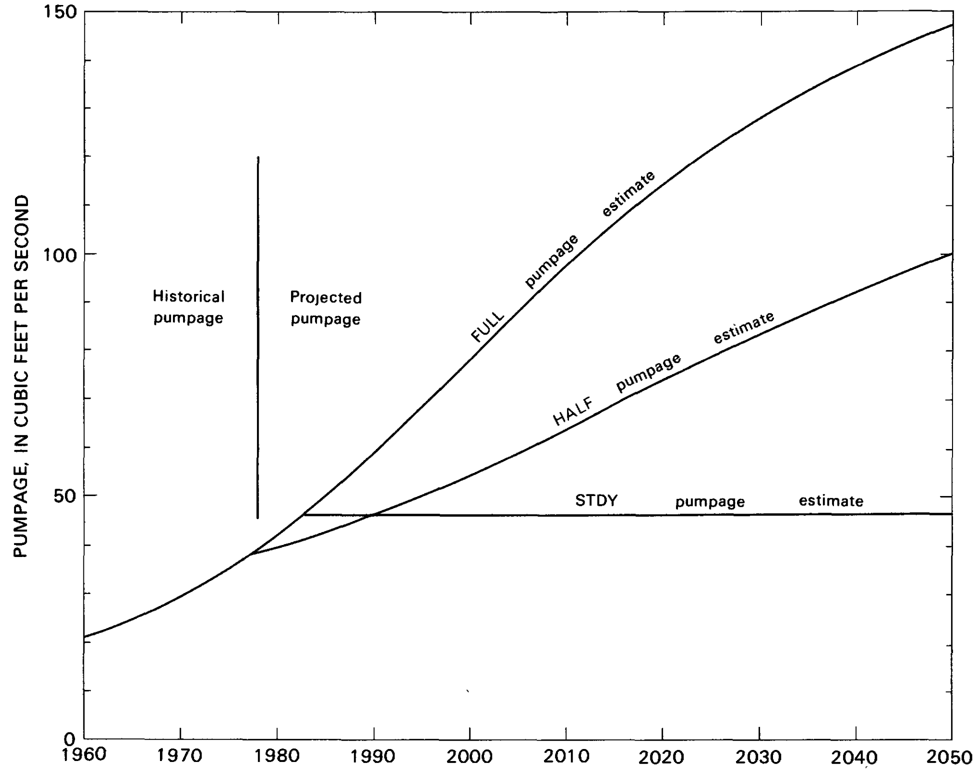


FIGURE 16.—Historical and projected pumpage for the bedrock aquifers.

with the uncertain uniqueness of the model, can produce large errors. The magnitude of these simulation errors is difficult to determine, for they are the result of a complex interaction of conditions that may produce partially offsetting errors. As a result, special caution must be taken in using the results of the long-term, heavy pumped simulations.

The calibrated transient-state model is converted to simulation use by means of two principal revisions. The first involves changing from a 1958 to a 1978 starting head distribution, and the second involves replacing 1958-78 pumpage with 1979-2050 pumpage. These and other minor revisions allow the model to calculate heads in the aquifers over all or part of a 72-year simulation period (1979-2050).

Three 1979-2050 pumpage estimates have been made for simulation use (fig. 16). The first is termed the "FULL" pumpage estimate and is calculated as a constant fraction of the projected water-supply requirements of the Denver metropolitan area (see "Supplemental Information"). This estimate is intended to be a reasonable estimate of the maximum rate of future pumpage that might be expected to occur to the year 2050. A second, more conservative, estimate was calculated as one-half of the FULL pumpage estimate and is termed the "HALF" pumpage estimate. The third, still more conservative, estimate is based on the assumption that no increase in pumpage will occur after 1983. This steady rate of pumping is called the "STDY" pumpage estimate and is intended to be a reasonable estimate of the minimum rate of future pumping that might be expected to occur to the year 2050. Because it is not possible to foretell what the actual rate of future pumping will be, it is not known which of these three estimates will most closely represent future pumpage. As a result, the three pumpage estimates are used to show how the aquifer can be expected to respond to large, medium, and small rates of future pumping.

Colorado State law limits the annual pumpage of a well to 1 percent of the volume of recoverable water in storage in the aquifer under the well owner's land. Because of this statute, the three pumpage estimates were adjusted to prevent the pumping rate from exceeding that allowed by the land area near the wells. This was done on the basis of the area of the grid block in which pumpage was estimated to occur. If pumpage for a particular grid block exceeded 1 percent of the volume of water in storage in the aquifer under that grid block, the pumpage for that aquifer was set to the 1-percent rate and was not allowed to increase further. If little or no pumpage was shown in adjacent grid blocks, the pumping rate was sometimes allowed to exceed the 1-percent limit by considering a larger land area underlying parts of adjacent grid blocks. Limiting

TABLE 6.—*Distribution of FULL pumpage estimate for periods 1979-85 and 2046-50*

[Values in cubic feet per second]

Aquifer	Counties								
	Adams	Arapahoe	Boulder	Denver	Douglas	Elbert	Jefferson	Weld	Totals
Distribution during 1979-85									
Dawson	0	1.01	0	0	6.59	0.60	0	0	8.20
Denver	1.89	2.54	0	0.31	1.53	.06	1.44	0	7.77
Arapahoe	8.63	4.57	0.06	.91	4.83	0	3.54	0.73	23.27
Laramie-Fox Hills	1.52	.98	1.00	.40	1.47	0	.31	2.24	7.92
Totals	12.04	9.10	1.06	1.62	14.42	.66	5.29	2.97	47.16
Distribution during 2046-50									
Dawson	0	5.66	0	0	23.62	0.60	0	0	29.88
Denver	1.89	8.60	0	.30	4.52	.06	.80	0	16.17
Arapahoe	14.82	13.34	.06	1.48	33.05	0	5.46	.73	68.94
Laramie-Fox Hills	4.83	6.66	1.39	1.05	15.91	0	.54	3.56	33.94
Totals	21.54	34.26	1.45	2.83	77.10	.66	6.80	4.29	148.93

the maximum pumping rate from grid blocks had the most pronounced effect on the FULL pumpage estimate. This caused the decrease in slope of the FULL pumpage curve shown in figure 16 and only slightly affected the slope of the upper end of the HALF pumpage curve.

The varying rates of pumpage shown in figure 16 were modeled by use of eight pumping periods. The first period was 7 years (1979–85); followed by six periods, each of 10 years (1986–2045); and ended with a period of 5 years (2046–50). The distribution of pumpage during the first and last pumping period is shown in table 6. This distribution is based primarily on the expected location of future ground-water use as estimated in 1974 by the Denver Water Department (1975). These estimates were updated to consider the more recent patterns of use as indicated by permits issued for construction of new bedrock wells during the period 1978–82. As shown in table 6, the largest increase in pumpage is expected in Douglas, Adams, and Arapahoe Counties. The Arapahoe aquifer is expected to be the source of most of the increased pumpage; the Laramie–Fox Hills and Dawson aquifers supply lesser amounts of water. The pumpage estimates do not consider future pumpage in the outlying and primarily rural parts of Elbert, El Paso, and Morgan Counties.

BASE CONDITIONS

The first series of model simulations was made to estimate the aquifer response to the three pumpage estimates. These simulations also serve as the bases for comparison to subsequent model simulations, which will include specific changes in pumpage or recharge. Potentiometric-surface maps, areas of water-level decline, and water-level hydrographs are shown for each simulation to document the hydrologic changes.

Model-run "STDY-BASE" simulates the hydrologic response of the aquifers to the STDY pumpage estimate. The resulting water-level conditions are shown on plate 3. Results indicate that under the most conservative pumping conditions (STDY), 1979–2050 water-level declines in excess of 100 ft could occur in the Dawson aquifer north of Castle Rock and in a 120-mi^2 area of the Denver aquifer between Aurora and Franktown. In the Arapahoe aquifer, declines exceed 250 ft in a 300-mi^2 area of southern Arapahoe County and north-central Douglas County. The most extensive declines occur in the Laramie–Fox Hills aquifer, where declines exceed 300 ft in a 440-mi^2 area extending from Commerce City to Castle Rock.

The larger water-level declines in the deeper aquifers are due to the hydrologic characteristics of the aquifers and to an increased rate of pumpage from the deeper aquifers. In the Laramie–Fox Hills aquifer near Parker, for example, the aquifer presently is confined and under about 1,700 ft of head. The relatively small transmissivity and small storage coefficient will allow 1,700 ft of rapid water-level decline to occur in this area before unconfined conditions develop. By contrast, in the Dawson aquifer, unconfined conditions already occur, and much smaller rates of water-level decline are produced by pumpage.

A water budget for the final year of the model-calibration period (1978) and the final year of run STDY-BASE (2050) is shown in table 7. The small increase in pumpage between 1978 and 2050 produces correspondingly small adjustments in the other components of the water budget. The net recharge has increased from 23.18 ft^3/s in 1978 to 27.44 ft^3/s in 2050, and the net decrease in ground-water storage has gone from 13.83 ft^3/s to 17.80 ft^3/s. These changes in the water budget are affected by pumpage prior to 1978 but are primarily due to post-1978 pumpage. Thus, a 1978–2050 pumpage increase of 8.23 ft^3/s primarily causes a 4.26-ft^3/s increase in net recharge and a 3.97-ft^3/s decrease in the rate of ground water pumped from storage between 1978 and 2050. About 52 percent of the increased pumpage is derived from an increase in net recharge, and 48 percent is derived from ground-water storage.

Model-run HALF-BASE simulates the hydrologic response of the aquifers to the HALF pumpage estimate. The results of this simulation are shown on plate 4. In the Dawson aquifer, 1979 to 2050 water-level declines of more than 200 ft occur to the north of Castle Rock and near Cherry Creek Reservoir. Water-level declines of 200–300 ft are shown to occur in the Denver aquifer in a 110-mi^2 area between Cherry Creek Reservoir and Franktown. Water-level declines of as much as 800 ft are present in the Arapahoe aquifer; declines in excess of 600 ft occur in a 160-mi^2 area around Parker. In the Laramie–Fox Hills aquifer, water-level declines of 1,500–1,700 ft are present in a 130-mi^2 area west of Parker.

A comparison of the STDY-BASE and HALF-BASE simulations indicates that the larger pumpage in the HALF-BASE run creates much larger water-level declines in the aquifers. The largest declines occur in the deepest aquifers and cause a significant change in the direction of ground-water movement in the Laramie–Fox Hill aquifer. In the STDY-BASE run, a single cone of depression is present in the Laramie–Fox Hills potentiometric surface near Fort Lupton. In the HALF-BASE run, this depression is deepened, and a second cone of depression is formed in northern Douglas County. As a result of these two cones of depression, most of the water present in the northern half of the Laramie–Fox Hills aquifer moves toward the cones of depression and no longer discharges near the northern limit of the aquifer.

The 2050 water budget for run HALF-BASE is shown in table 7. The increase in 2050 pumpage from 45 ft^3/s in run STDY-BASE to 100 ft^3/s in run HALF-BASE causes proportionally larger volumes of water to be removed from storage. This is caused by physical limitations on the volume of induced recharge and captured discharge that may occur. When net recharge is limited in this manner, an increase in pumpage must be balanced by increased removal of ground water from storage. Interaquifer flow also can be seen to increase more slowly than pumpage.

The changes in the water budget from 1978 to 2050 are affected by pumping prior to 1978, but primarily are due to post-1978 pumpage. The increase in pumpage from 1978 to 2050 is 63.58 ft^3/s. This causes a corresponding increase in net recharge of 10.12 ft^3/s and a 53.46-ft^3/s increase in the rate of ground water pumped from storage. Thus, 16 percent of the increased pumpage is derived from an increase in net recharge, and 84 percent is derived from ground-water storage.

TABLE 7.—*Transient-state water budgets for 1978 (calibration run) and 2050 (STDY-BASE run, HALF-BASE run, and FULL-BASE run)*

[Values in cubic feet per second]

Aquifer	Pumpage	Net decrease in ground-water storage	Net recharge	Net interaquifer flow
1978 Water budget from calibration run				
Dawson	−5.94	0.95	11.95	−6.96
Denver	−6.83	3.69	6.21	−3.07
Arapahoe	−18.89	7.10	1.74	10.03
Laramie–Fox Hills	−5.37	2.09	3.28	0
Totals	−37.01	13.83	23.18	0
2050 water budget from run STDY-BASE				
Dawson	−7.65	1.82	14.00	−8.17
Denver	−6.55	3.65	6.84	−3.94
Arapahoe	−23.22	9.15	1.96	12.11
Laramie–Fox Hills	−7.82	3.18	4.64	0
Totals	−45.24	17.80	27.44	0
2050 water budget from run HALF-BASE				
Dawson	−19.14	10.66	17.66	−9.18
Denver	−11.21	10.38	7.43	−6.60
Arapahoe	−46.92	28.99	2.15	15.78
Laramie–Fox Hills	−23.32	17.26	6.06	0
Totals	−100.59	67.29	33.30	0
2050 water budget from run FULL-BASE				
Dawson	−29.19	20.25	18.64	−9.70
Denver	−15.59	15.44	7.90	−7.75
Arapahoe	−68.88	49.14	2.29	17.45
Laramie–Fox Hills	−33.81	27.23	6.58	0
Totals	−147.47	112.06	35.41	0

Model-run FULL-BASE simulates the hydrologic response of the aquifers to the FULL pumpage estimate. The resulting water-level conditions are shown on plate 5. Results indicate that under the maximum pumpage condition (FULL), 1979–2050 water-level declines of 200–310 ft occur in the Dawson aquifer near Parker, southeast of Cherry Creek Reservoir, and north of Castle Rock. Water-level declines of as much as 420 ft occur in the Denver aquifer, and declines exceed 200 ft in a 280-mi^2 area extending from near Aurora to near Larkspur. In the Arapahoe aquifer, a maximum 1979–2050 water-level decline of 1,000 ft occurs near Parker. Declines in excess of 600 ft are present in a 370-mi^2 area extending from near Cherry Creek Reservoir through most of northern Douglas County. Under FULL pumpage, the largest water-level declines appear in the Laramie–Fox Hills aquifer. Declines ranging from 1,500 to 1,830 ft are present in a 220-mi^2 area extending from Cherry Creek Reservoir to near Dawson Butte southwest of Castle Rock. In the later years, the rate of decline diminishes dramatically in some areas (note the hydrograph for Parker, for example), due to the development of unconfined conditions in the aquifer.

The 2050 water budget for run FULL-BASE is shown in table 7. Pumpage is shown to increase from 37.01 ft^3/s in 1978 to 147.47 ft^3/s in 2050 (run FULL-BASE), a net increase of 110.46 ft^3/s. This increase in pumpage is primarily responsible for a 1978–2050 increase in net recharge of 12.23 ft^3/s and a decrease in ground water in storage of 98.23 ft^3/s. Under FULL pumpage conditions, 11 percent of the increased pumpage is derived from an increase in net recharge, and 89 percent is derived from ground-water storage.

The simulations indicate that future rates of water-level decline could vary considerably, depending on the rate of future pumping. The hydrographs on plates 3, 4, and 5 show that rates of water-level decline range from near zero in many areas to over 40 ft/yr in the Laramie–Fox Hill aquifer near Parker, for example. This large rate of decline has not yet been experienced in the basin aquifers on a broad-scale, continuing basis. By comparison, rates of water-level decline, shown in figure 10, averaged about 11 ft/yr between 1885 and 1910, and averaged about 3 ft/yr between 1910 and 1960. If future rates of water-level decline exceed several tens of feet per year on a continuing basis, economic, social, and political constraints will limit further development of some ground-water resources. Factors affecting the economic constraint include (1) increasing costs for energy needed to lift water greater distances to the surface, (2) increasing well construction costs as additional wells are needed to offset the decreasing yield of existing wells, and (3) increasing costs for well modifications needed to install more powerful pumps at greater depths in the wells.

GROUND-WATER DEVELOPMENT PLANS

In 1981, a committee called the Metropolitan Water Roundtable was formed, with Colorado Governor Richard D. Lamm as chairman, to evaluate the future water-supply needs of the Denver metropolitan area. A ground-water task group of the Roundtable submitted its final report to the committee in May 1982. In this report, four ground-water use scenarios were outlined as possible methods of supplementing the water requirements of the metropolitan area. These scenarios involved (1) pumping a satellite well field located in an undeveloped area of the basin and piping the water to the metropolitan area; (2) pumping a well field located within the metropolitan area; (3) using bedrock wells to provide irrigation water for city parks and other public land presently irrigated with treated municipal water; and (4) using the bedrock aquifers for temporary storage of treated municipal water by recharging and, later, pumping the aquifers. These scenarios are used as the bases for the following sequence of model simulations. In some instances, it was necessary to estimate specific details of the plans because information provided by the task group was somewhat generalized.

SATELLITE WELL FIELD

The model was used to investigate the hydrologic response of the aquifers to pumpage from a hypothetical satellite well field located on 36 mi^2 of land in T. 6 S., R. 65 W. in eastern Douglas and western Elbert Counties. The location of the well field and pumping rates were provided by Bishop Associates, Inc.,[1] a subsidiary of Engineering Science, Inc. They are the prime contractors to the U.S. Army Corps of Engineers and are involved in developing a system-wide environmental impact statement for the Denver Water Department. An economic analysis of the satellite well field was made as part of the system-wide environmental impact statement. This phase of the work was done by Engineering Science, Inc., in cooperation with the Denver Water Department, the U.S. Army Corps of Engineers, and the U.S. Geological Survey.

[1]Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

TABLE 8.—*Satellite well-field pumpage*

Aquifer	Pumpage (cubic feet per second)
Dawson	11.1
Denver	10.2
Arapahoe	12.5
Laramie–Fox Hills	7.2
Total	41.0

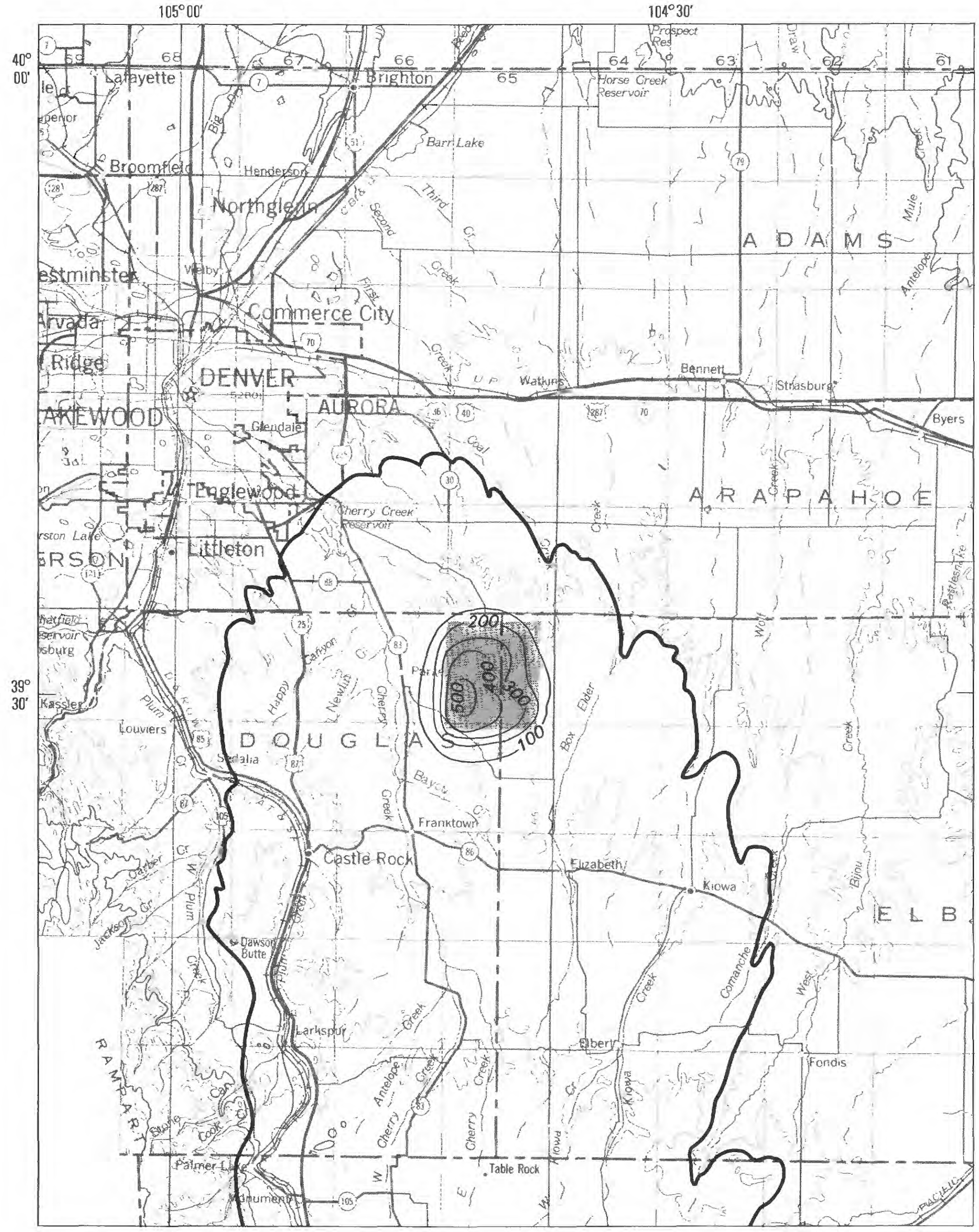
It was assumed that the satellite well field would be pumped at the maximum rate allowed under Colorado law and that the pumping would commence at the start of the 72-year simulation period (table 8). The model simulated the effects of this pumpage in addition to that indicated by the STDY and FULL pumpage estimates. The head distributions calculated in these simulations were then subtracted from those calculated in the STDY-BASE and FULL-BASE simulations to produce maps showing water-level declines due only to satellite well field pumpage. These incremental water-level declines are shown in figures 17–24 for the STDY and FULL pumpage conditions. Total 1979–2050 water-level declines due to the satellite well field may be obtained by adding the incremental declines to the corresponding declines shown on plates 3 and 5 for the appropriate base simulation.

The incremental declines are markedly different for the upper and lower aquifers and also are markedly different for the STDY and FULL pumpage conditions. The larger water-level declines in the deeper aquifers are mainly due to the confined conditions present in these aquifers, as opposed to the unconfined conditions present in the upper aquifer. In the unconfined upper aquifer, gradual rates of water-level decline occur because of the large specific yield of this aquifer. In a confined aquifer, much more rapid rates of water-level decline may occur because of its smaller storage coefficient. The rapid rate of decline can lead to large water-level declines over a period of time if the starting head in the aquifer is well above the top of the aquifer. This situation is most pronounced in the deeper aquifers, leading to their larger incremental water-level decline (figs. 17 and 20).

The difference in incremental water-level decline between the STDY and FULL simulations (figs. 20 and 24) is illustrated by the two hydrographs for the aquifer near Parker shown in figure 25. The lines labeled STDY-BASE and FULL-BASE are the water levels calculated from the base simulations for the STDY and FULL pumpage conditions. The lines labeled STDY-SWF and FULL-SWF are the water levels calculated from the satellite well-field simulations for the STDY and FULL pumpage conditions. Quantities A and B are the incremental water-level declines shown for Parker (figs. 20 and 24). The difference between the incremental declines in figures 20 and 24 is the result of the amount of confined head that is pumped off the aquifer under the base conditions. Under FULL-BASE conditions, rapid water-level declines occur until unconfined conditions begin to develop near Parker, at which point the hydrograph (fig. 25) flattens markedly. More rapid declines initially occur under FULL-SWF conditions; however, this hydrograph also flattens in response to unconfined conditions, and a small incremental decline (B) results. This does not happen under STDY conditions. Neither the STDY-BASE or the STDY-SWF hydrographs are affected by unconfined conditions, and the two hydrographs become parallel with about 900 ft of incremental water-level decline (A) between them.

In the Dawson aquifer, incremental water-level declines due to the satellite well field of as much as 500 and 400 ft occur under STDY and FULL pumpage conditions (figs. 17 and 21, respectively). In the Denver aquifer, incremental declines exceed 600 and 500 ft under STDY and FULL pumpage conditions (figs. 18 and 22, respectively). In the Arapahoe aquifer, incremental declines in excess of 100 ft take place in a 1,040-mi^2 area under STDY pumpage conditions (fig. 19). This is about 11 times the area of similar declines shown to occur in the Arapahoe aquifer under FULL pumpage conditions (fig. 23). In the Laramie–Fox Hills aquifer, incremental water-level declines exceed 1,300 ft under STDY conditions (fig. 20) and exceed 600 ft under FULL conditions (fig. 24).

In less analytical terms, the satellite well-field simulations show that the amount of water-level decline produced by the well field will vary, depending on the structural depth of the pumped aquifer and the amount of other pumpage that is occurring in the basin. An equivalent amount of pumpage from a deep aquifer and a shallow aquifer will produce deeper and more widespread water-level declines in the deep aquifer than in the shallow aquifer. The incremental water-level declines caused by the satellite well field will be relatively large if little other pumpage is occurring in the aquifer and will be smaller and less widespread if a large rate of other pumping is taking place in the aquifer. The large, widespread, incremental declines shown to occur in some cases would cause existing shallow wells in some aquifers to go dry and would reduce the yield of other, deeper wells in affected areas. In either case, it would be necessary to redrill or re-equip wells in order to maintain the previous pumping rate.



EXPLANATION

AREA OF SATELLITE WELL FIELD

—100— LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE, 1979-2050—Interval, in feet, is variable

——— AQUIFER LIMIT

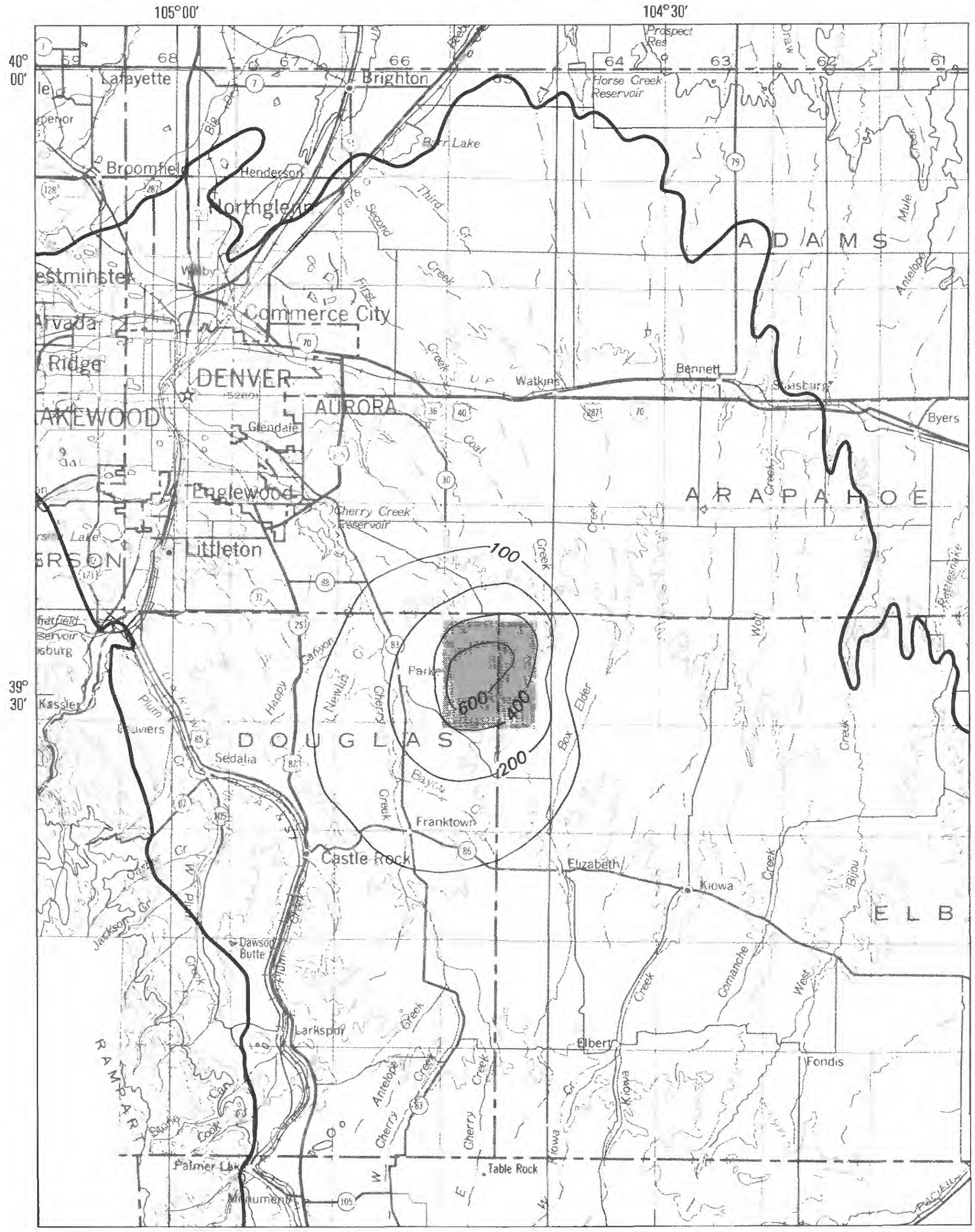
0 5 10 15 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET

NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 17.—Incremental water-level declines for a satellite well field in the Dawson aquifer, using STDY pumpage estimate.



EXPLANATION

AREA OF SATELLITE WELL FIELD

—*100*— LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE, 1979-2050—Interval, in feet, is variable

——— AQUIFER LIMIT

0 5 10 15 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 18.—Incremental water-level declines for a satellite well field in the Denver aquifer, using STDY pumpage estimate.

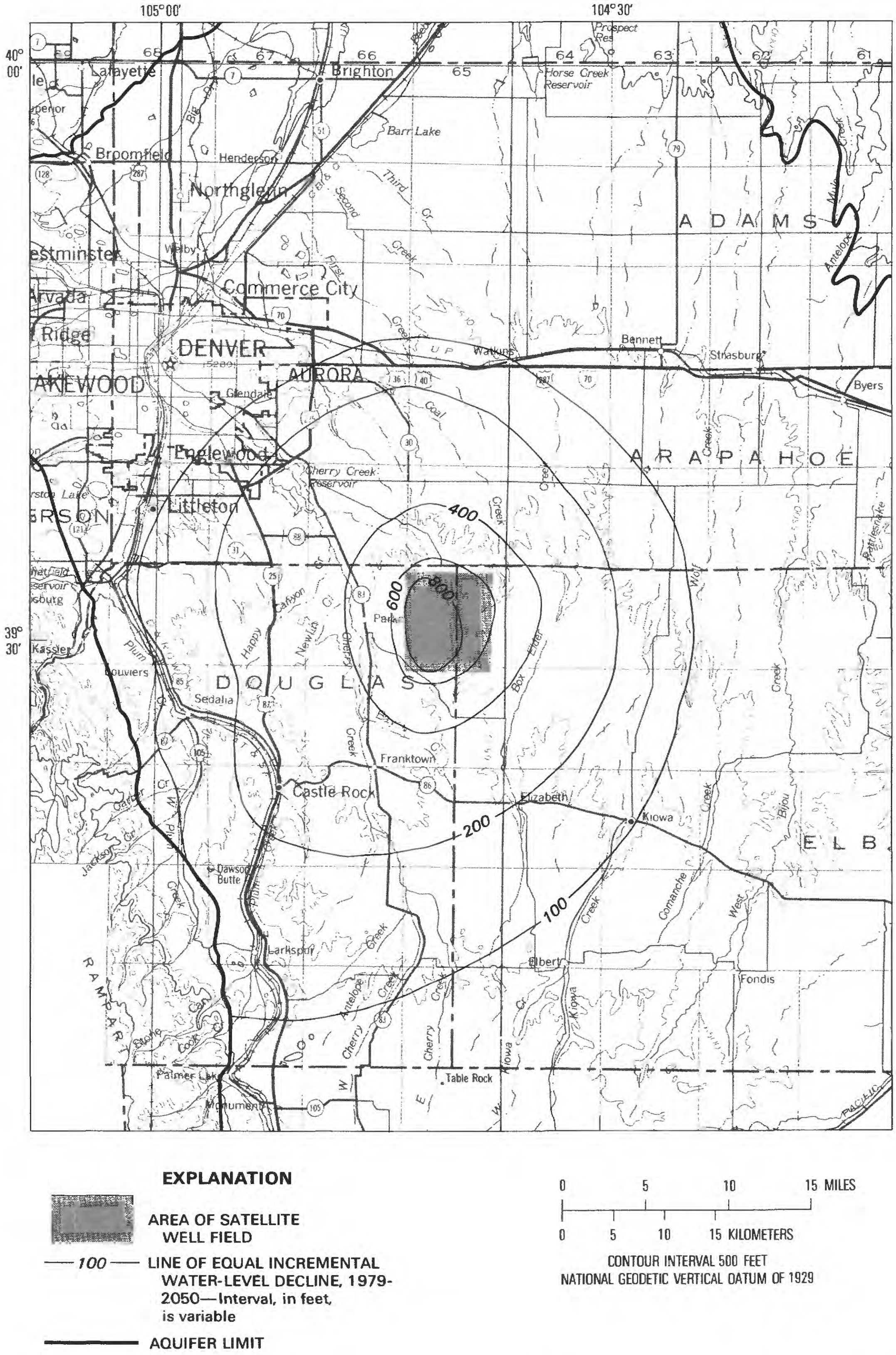
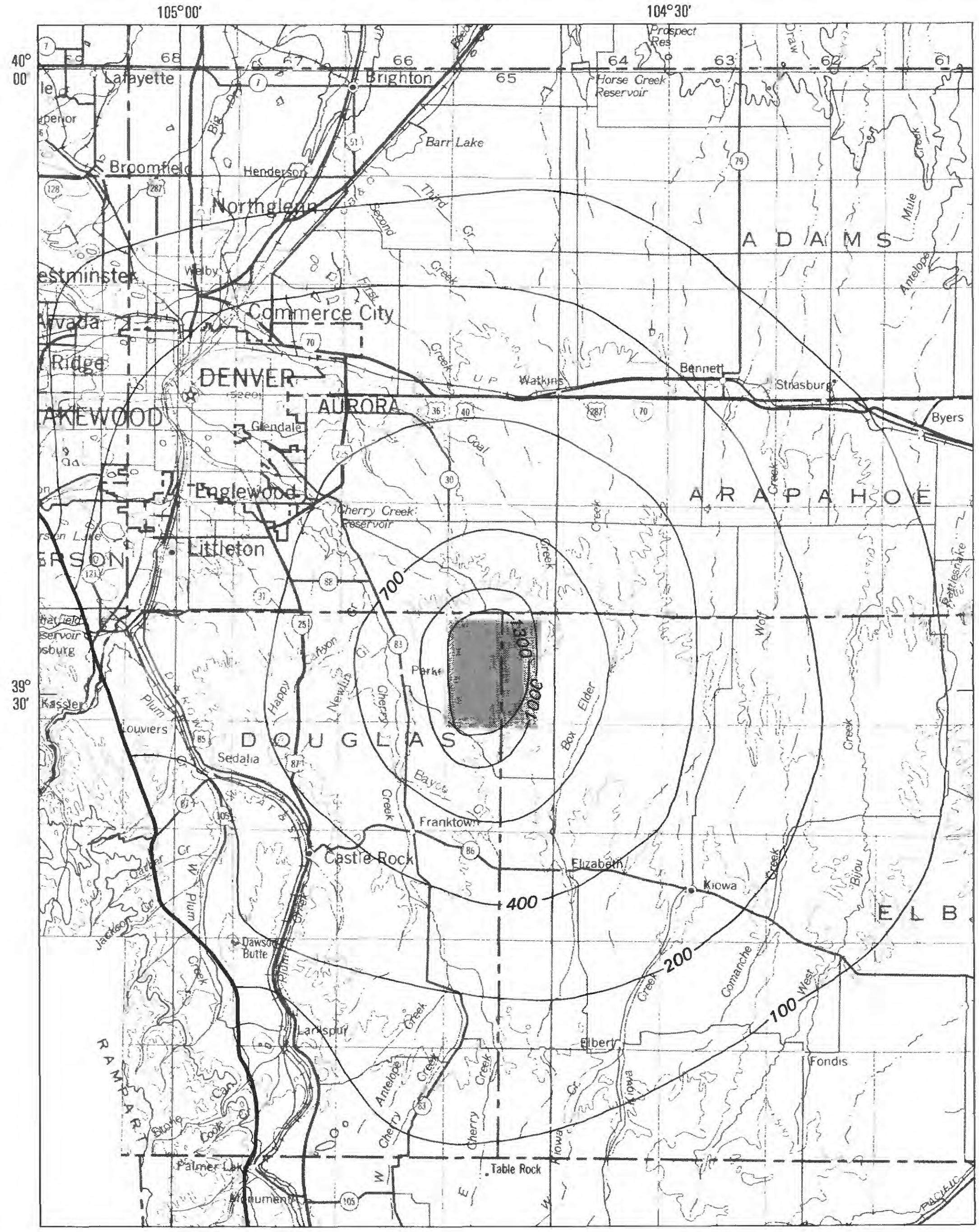


FIGURE 19.—Incremental water-level declines for a satellite well field in the Arapahoe aquifer, using STDY pumpage estimate.



EXPLANATION

AREA OF SATELLITE WELL FIELD

—*100*— LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE, 1979-2050—Interval, in feet, is variable

——— AQUIFER LIMIT

0 5 10 15 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 20.—Incremental water-level declines for a satellite well field in the Laramie-Fox Hills aquifer, using STDY pumpage estimate.

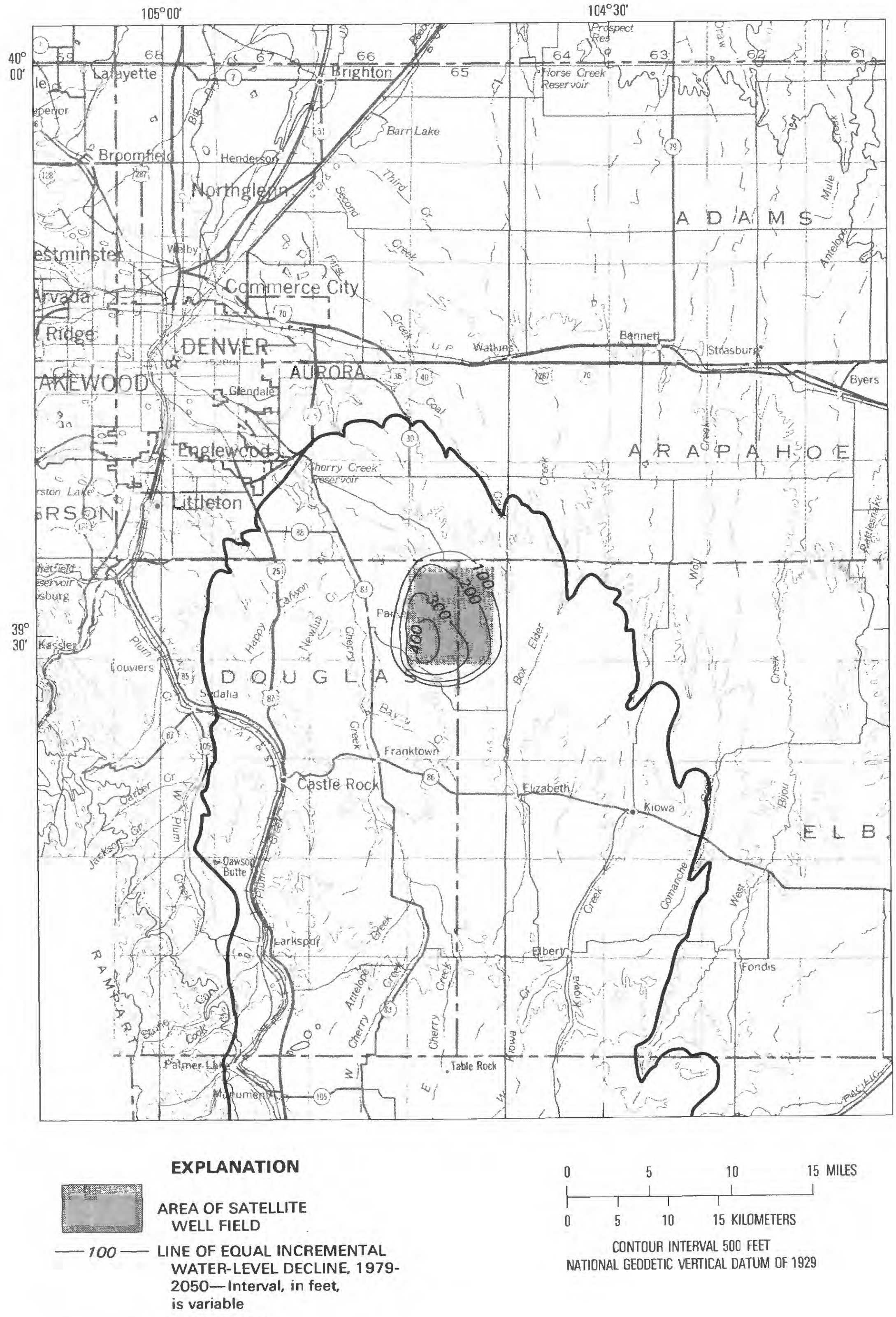
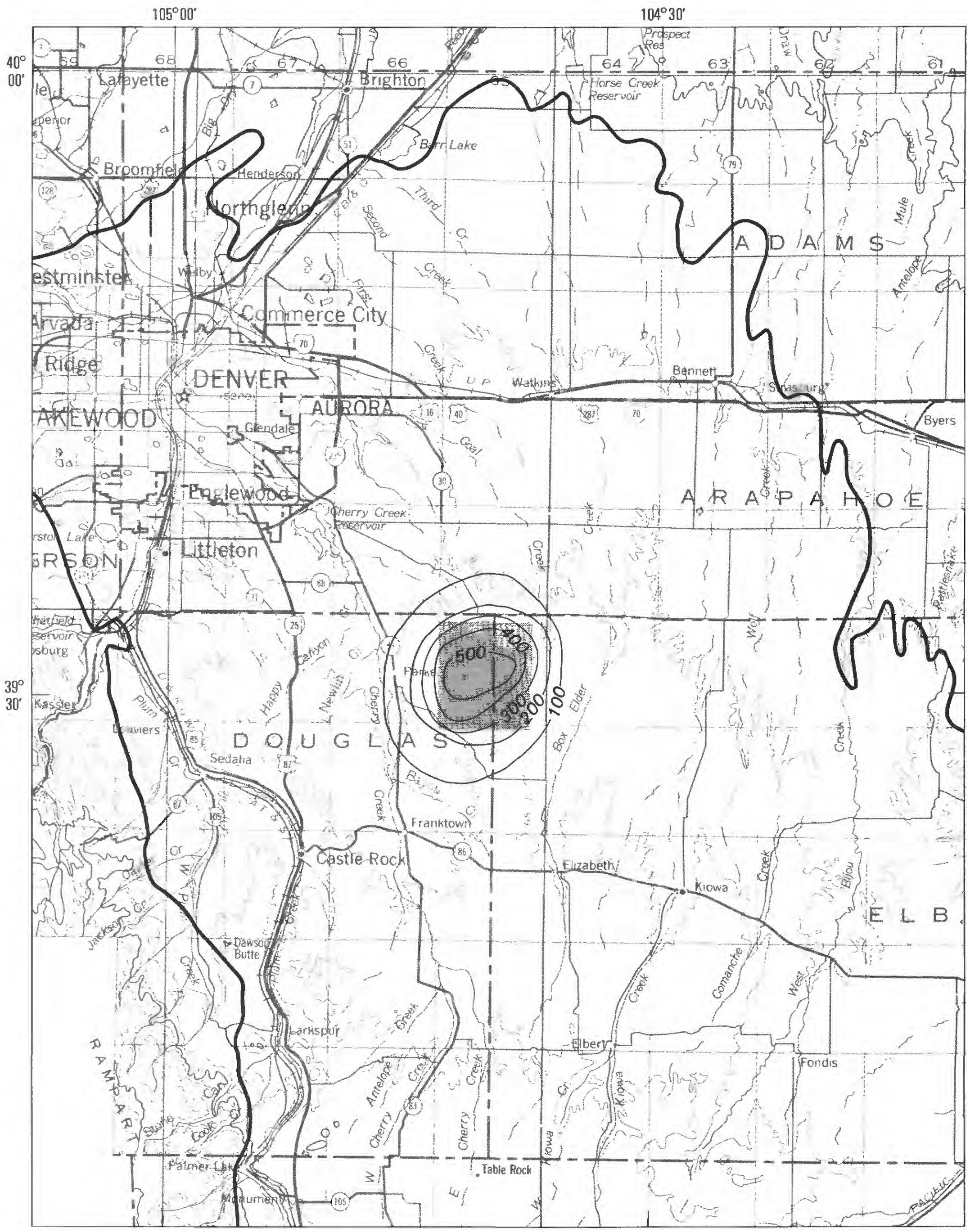


FIGURE 21.—Incremental water-level declines for a satellite well field in the Dawson aquifer, using FULL pumpage estimate.



EXPLANATION

AREA OF SATELLITE WELL FIELD

—100— LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE, 1979-2050—Interval, in feet, is variable

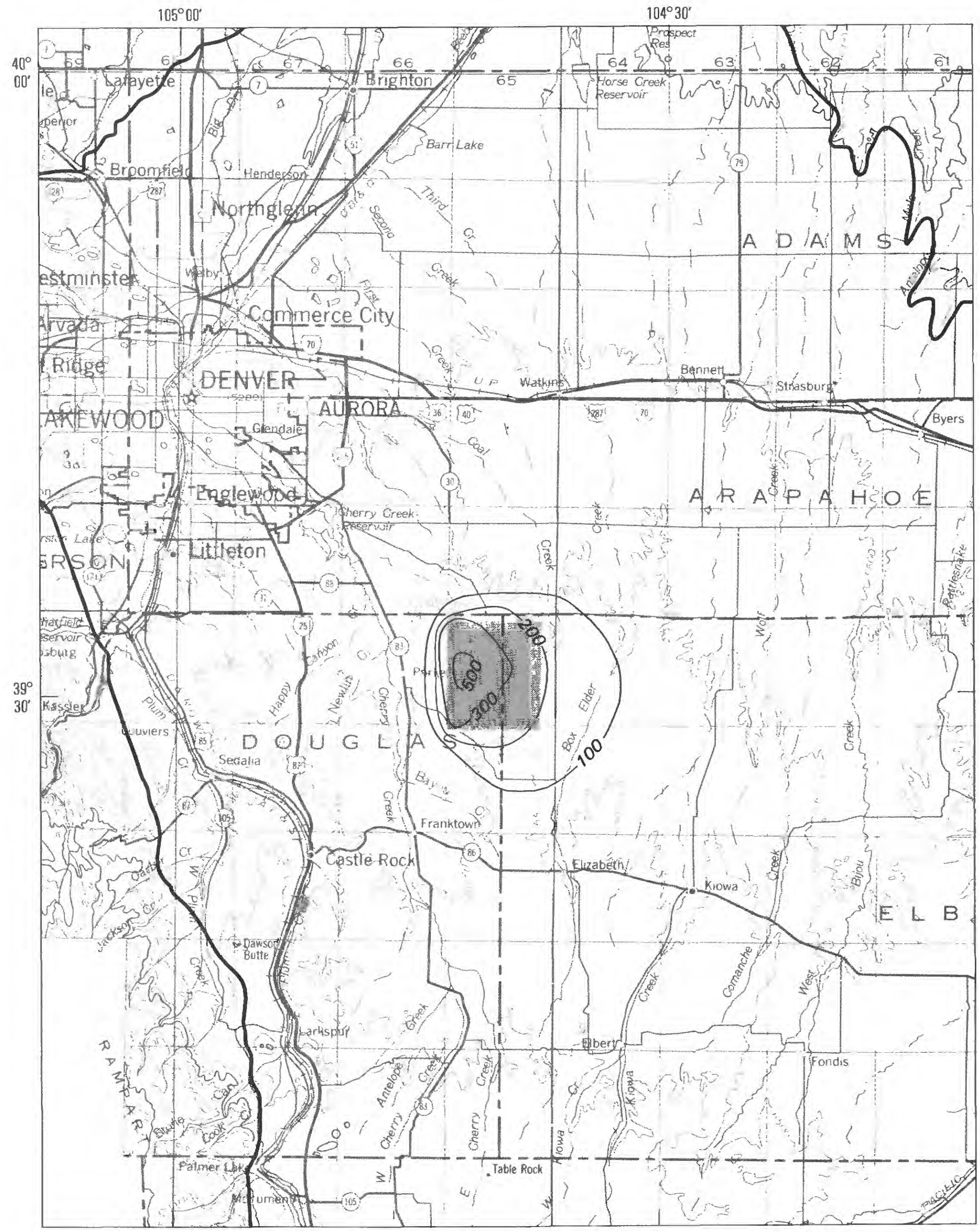
AQUIFER LIMIT

0 5 10 15 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 22.—Incremental water-level declines for a satellite well field in the Denver aquifer, using FULL pumpage estimate.



EXPLANATION

AREA OF SATELLITE WELL FIELD

— *100* — LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE, 1979-2050—Interval, in feet, is variable

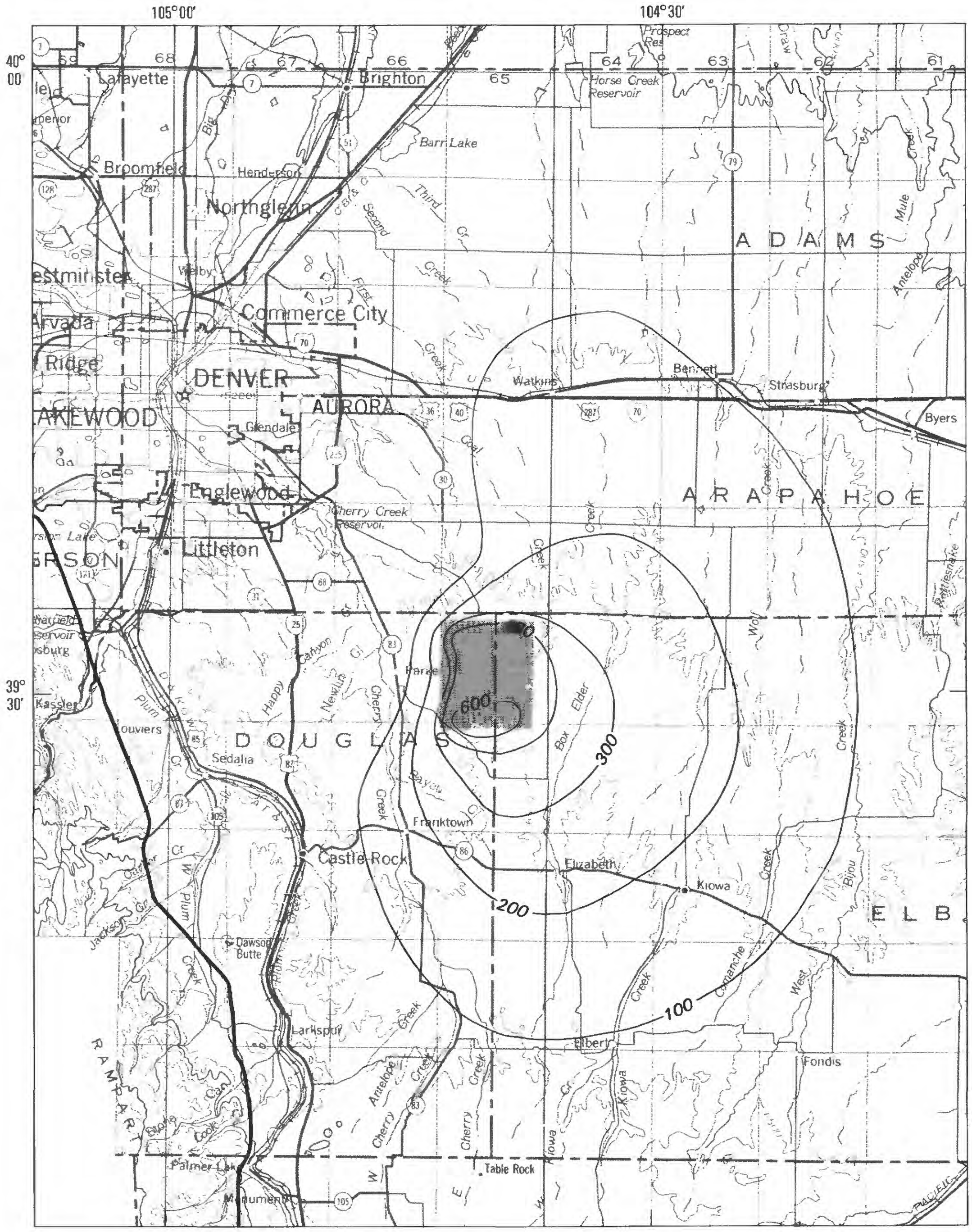
AQUIFER LIMIT

0 5 10 15 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 23.—Incremental water-level declines for a satellite well field in the Arapahoe aquifer, using FULL pumpage estimate.



EXPLANATION

AREA OF SATELLITE WELL FIELD

—100— LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE, 1979-2050—Interval, in feet, is variable

—— AQUIFER LIMIT

0 5 10 15 MILES
0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 24.—Incremental water-level declines for a satellite well field in the Laramie–Fox Hills aquifer, using FULL pumpage estimate.

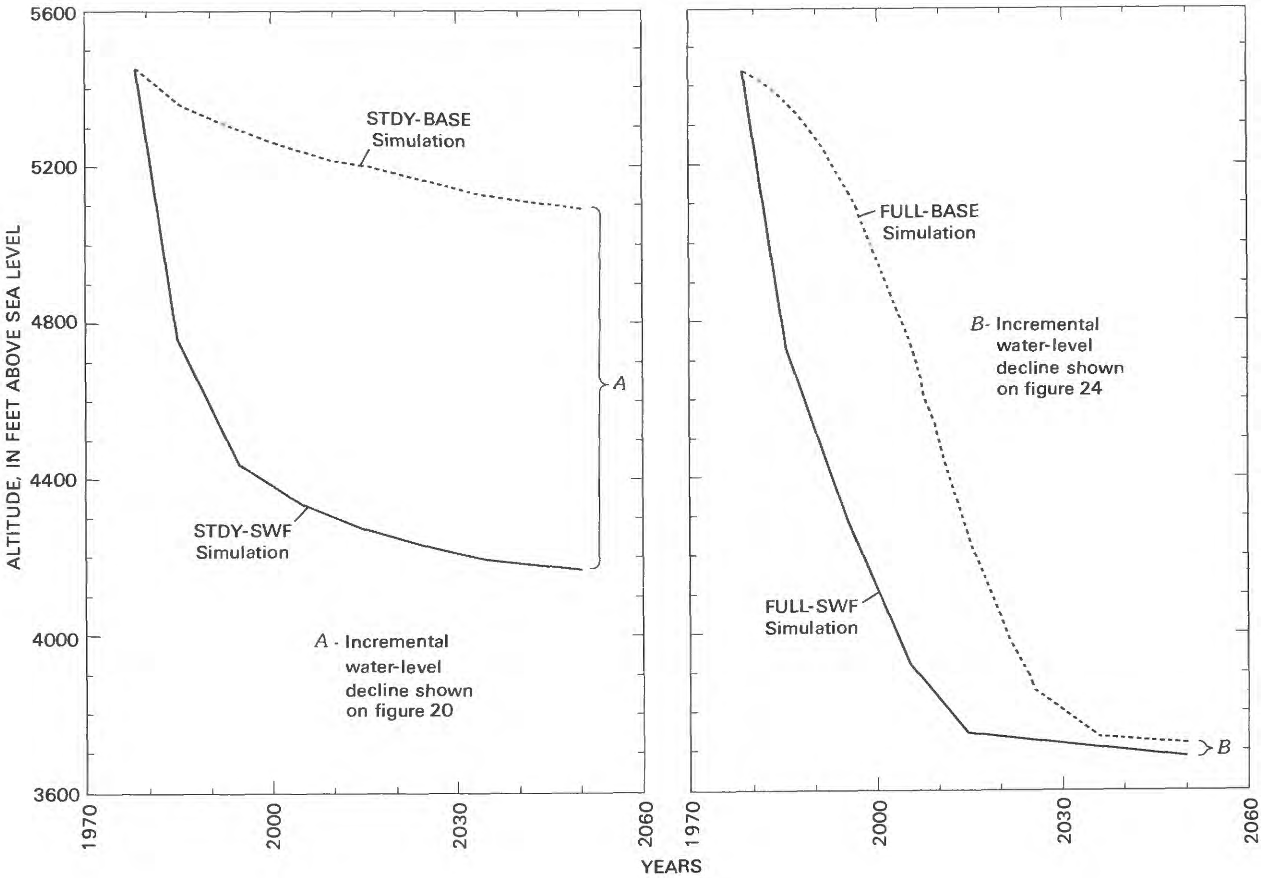


FIGURE 25.—Water-level hydrographs for the Laramie–Fox Hills aquifer at Parker.

METROPOLITAN WELL FIELD

This series of simulations shows the effects of pumping a hypothetical well field located on 36 mi^2 of land in the western half of T. 4 S., R. 67 W., and the eastern half of T. 4 S., R. 68 W. The well field would be primarily located in the southeastern part of the City and County of Denver. It is assumed that the field would be pumped at the maximum rate allowed under Colorado statutes without regard for the fact that the land is owned by numerous individuals and organizations. This assumption presently applies to the metropolitan communities of Federal Heights and Northglenn, which have been permitted to pump water under private property after obtaining the consent of property owners who are supplied with water by the city water departments. The assumption could also apply to the metropolitan well field if some similar action were taken in this area.

Pumping is assumed to commence at the start of the 72-year simulation period (table 9). Only the three deeper aquifers are involved because of the absence of the Dawson Arkose in this area. Although both the satellite well field and the metropolitan well field are of equal area, the difference in aquifer characteristics allows only about one-half as much water to be pumped from the metropolitan well field under Colorado law.

The model was run to simulate the effects of the metropolitan well-field pumping in conjunction with the STDY and FULL pumpage estimates. The head distributions calculated in these two simulations were subtracted from those calculated in the STDY-BASE and FULL-BASE simulations to produce maps of water-level decline resulting from only metropolitan well-field pumping. These incremental water-level–decline maps are shown in figures 26–31. Total 1979–2050 water-level declines for the metropolitan well field may be calculated by adding the incremental

TABLE 9.—*Metropolitan well-field pumpage*

Aquifer	Pumpage (cubic feet per second)
Dawson	0.0
Denver	5.78
Arapahoe	7.63
Laramie–Fox Hills	8.58
Total	21.99

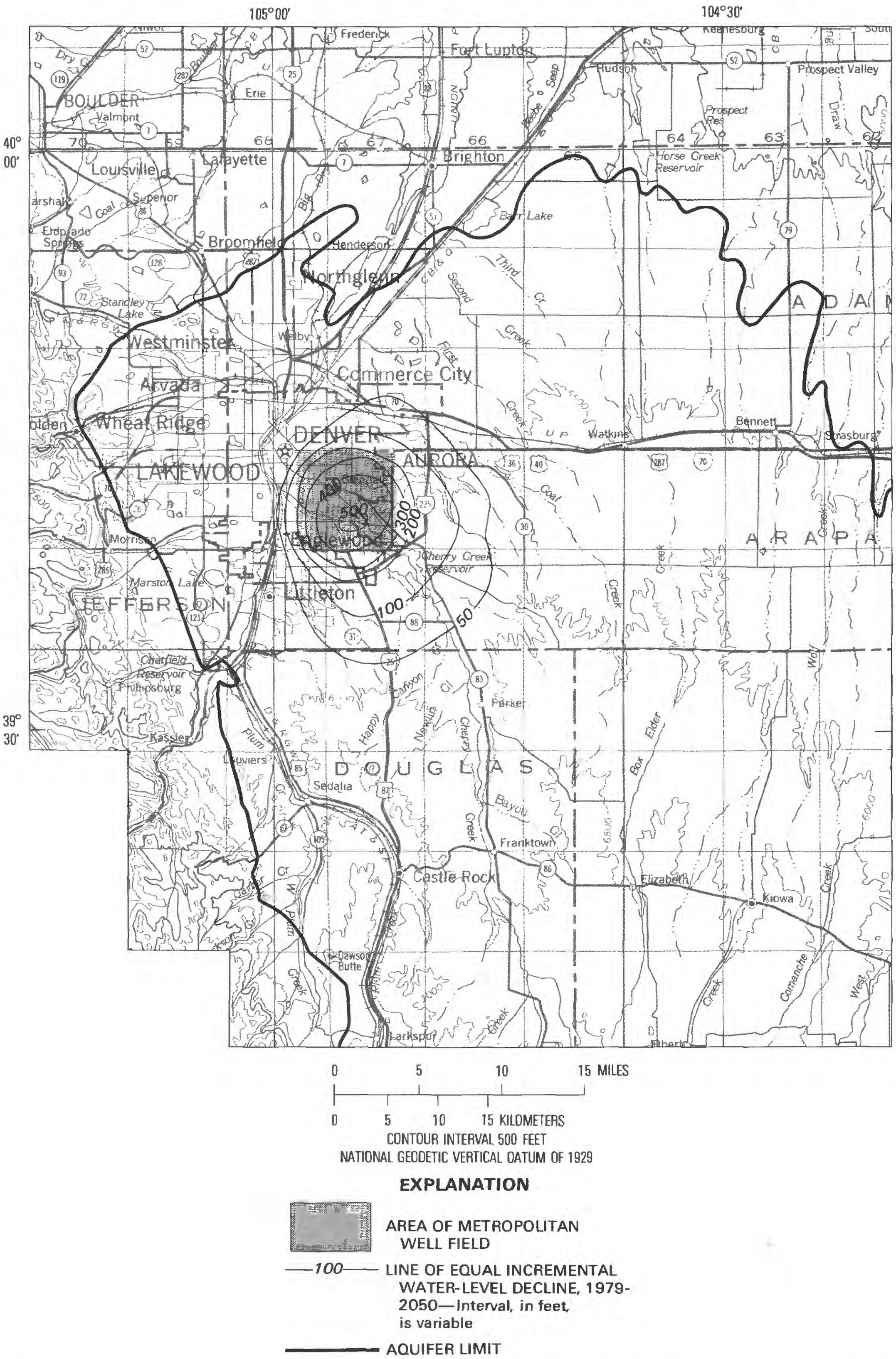


FIGURE 26.—Incremental water-level declines for a metropolitan well field in the Denver aquifer, using STDY pumpage estimate.

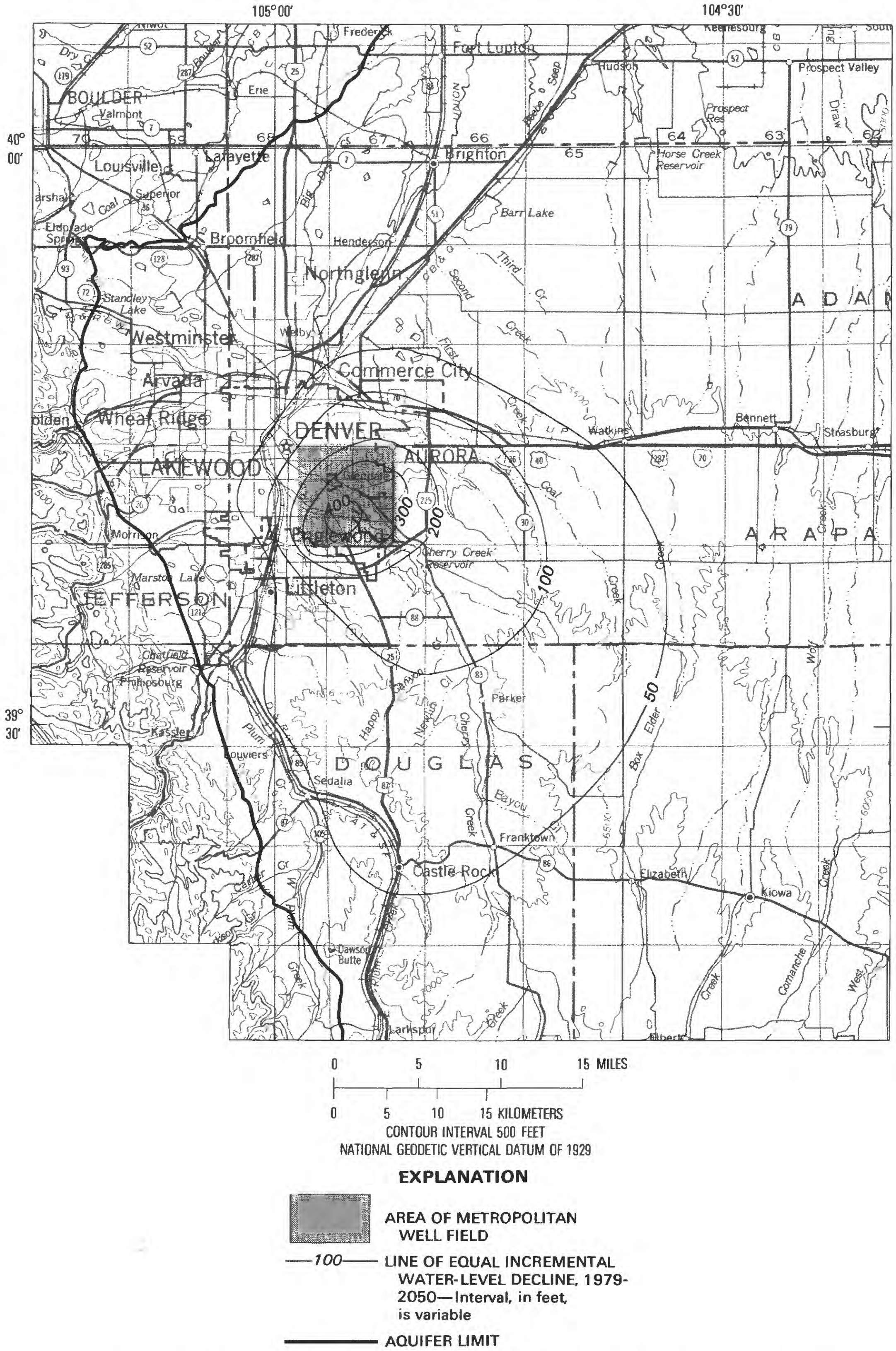
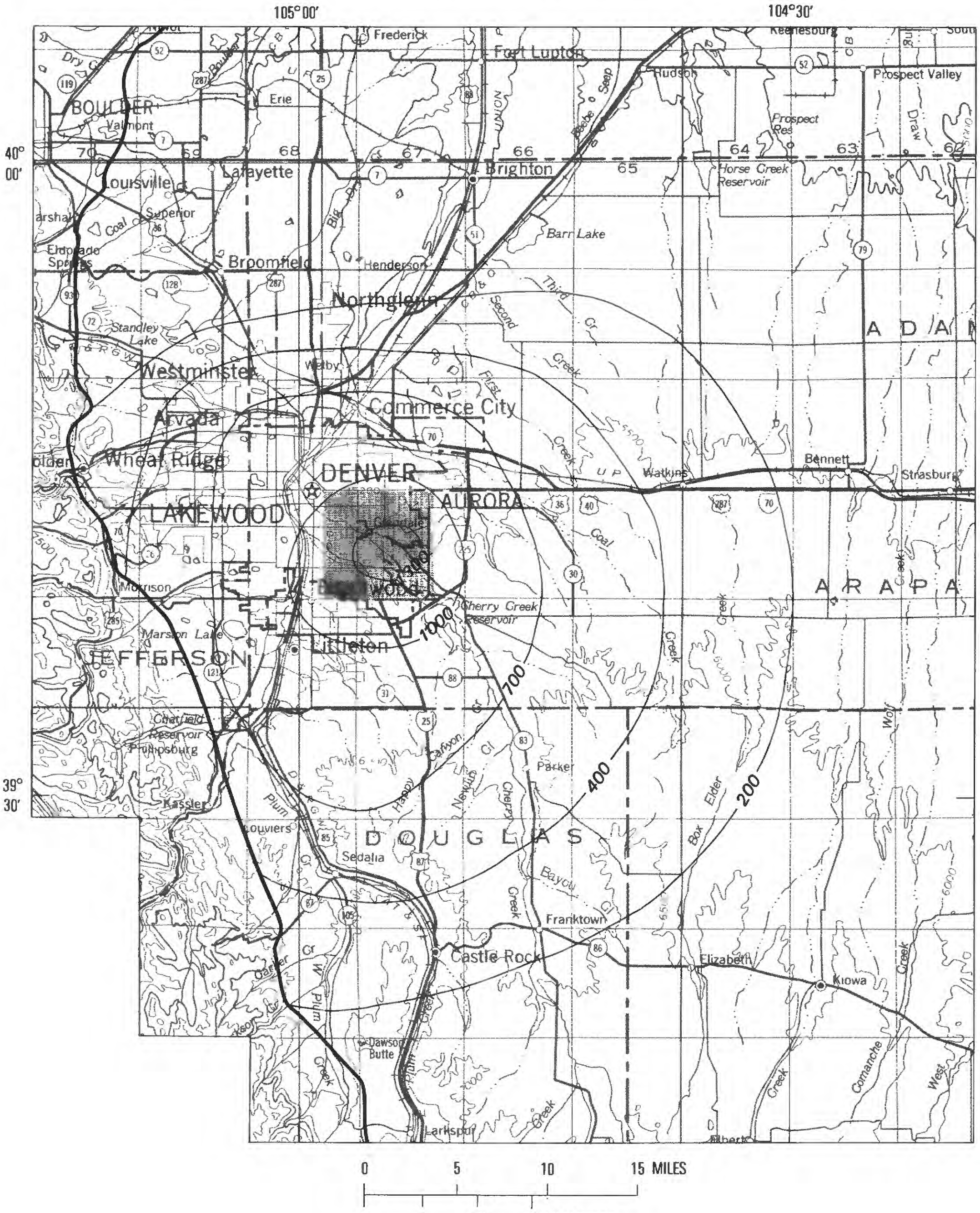


FIGURE 27.—Incremental water-level declines for a metropolitan well field in the Arapahoe aquifer, using STDY pumpage estimate.



CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

AREA OF METROPOLITAN WELL FIELD

—100— LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE, 1979-2050—Interval, in feet, is variable

——— AQUIFER LIMIT

FIGURE 28.—Incremental water-level declines for a metropolitan well field in the Laramie-Fox Hills aquifer, using STDY pumpage estimate.

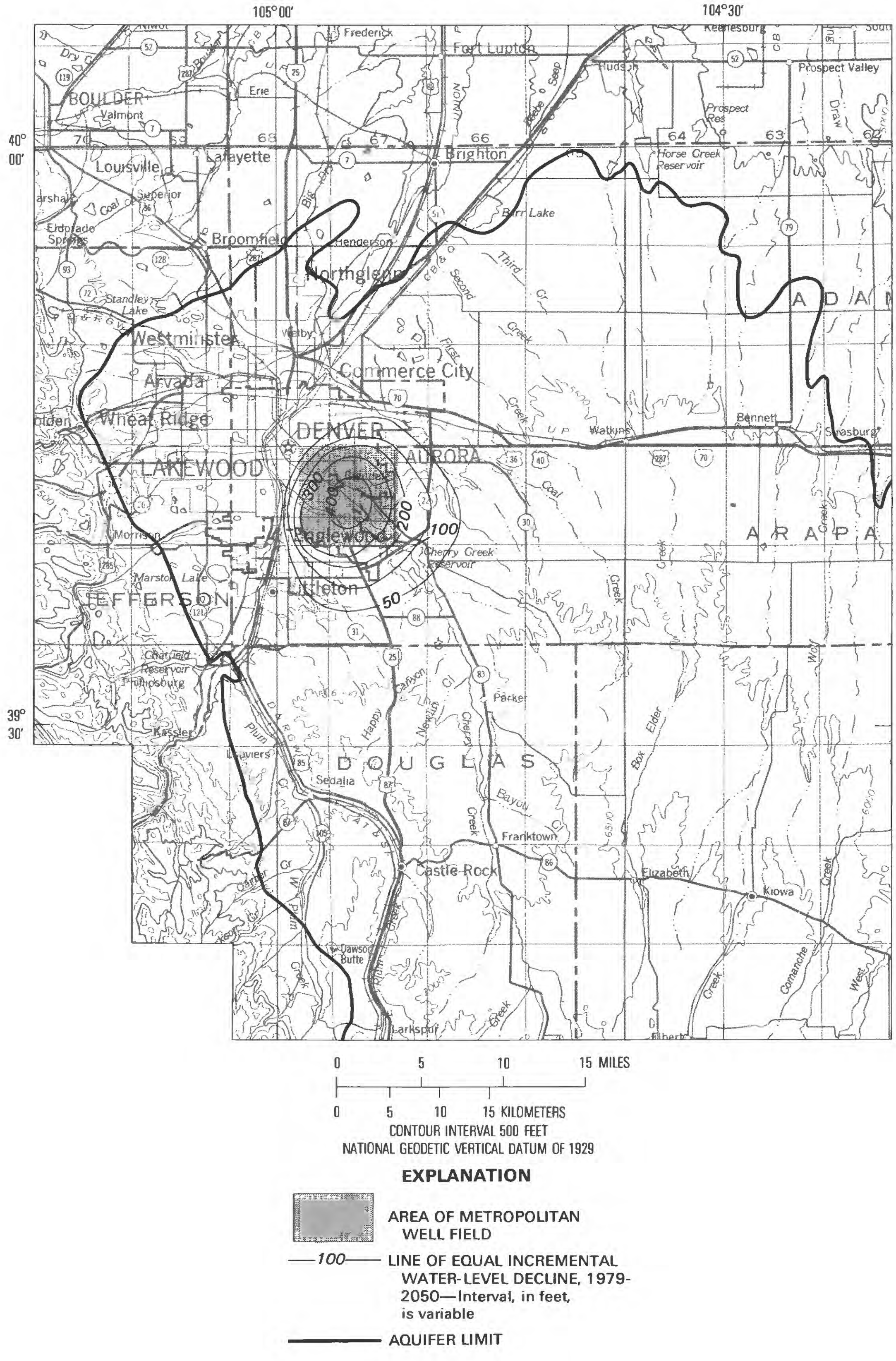


FIGURE 29.—Incremental water-level declines for a metropolitan well field in the Denver aquifer, using FULL pumpage estimate.

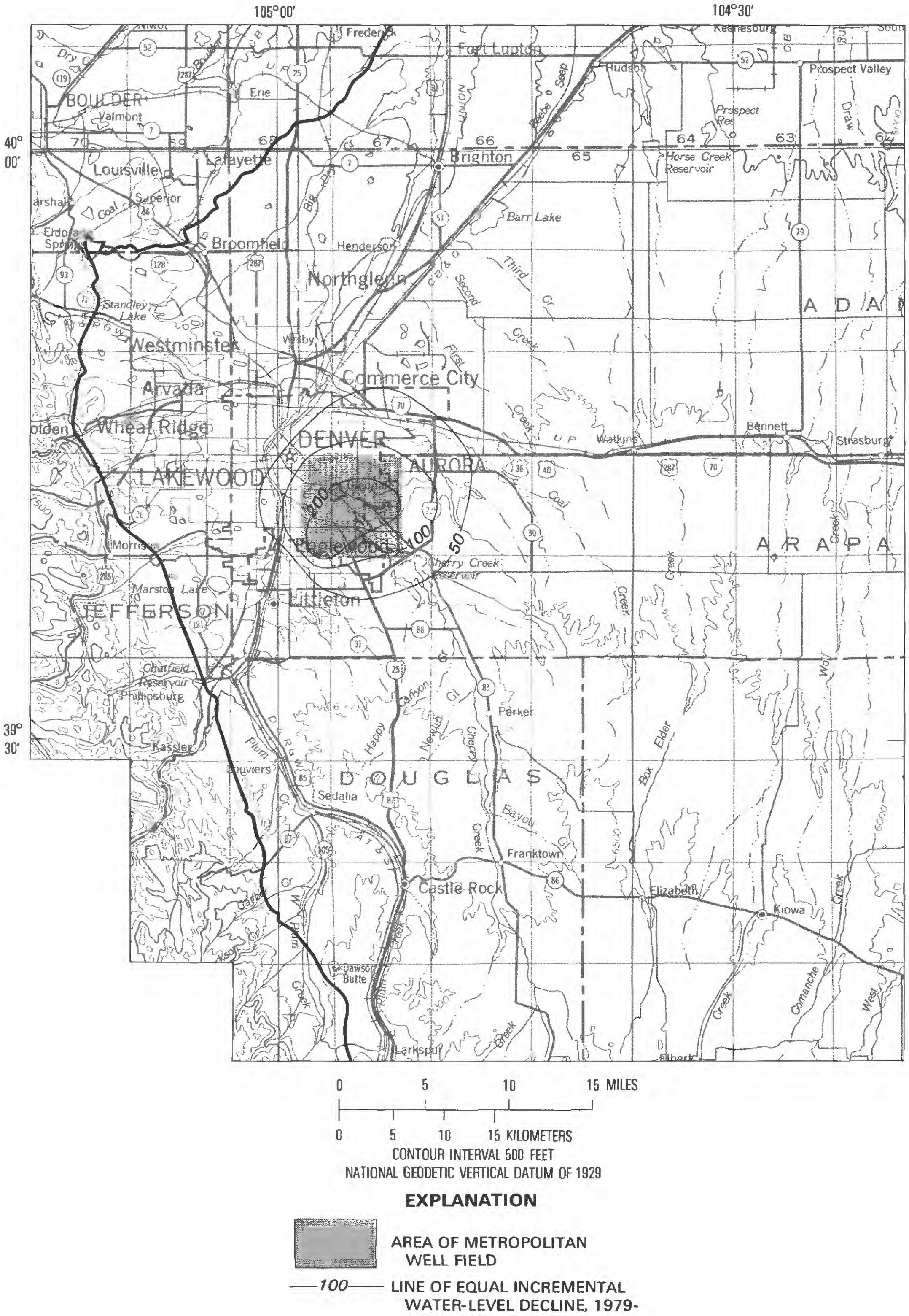


FIGURE 30.—Incremental water-level declines for a metropolitan well field in the Arapahoe aquifer, using FULL pumpage estimate.

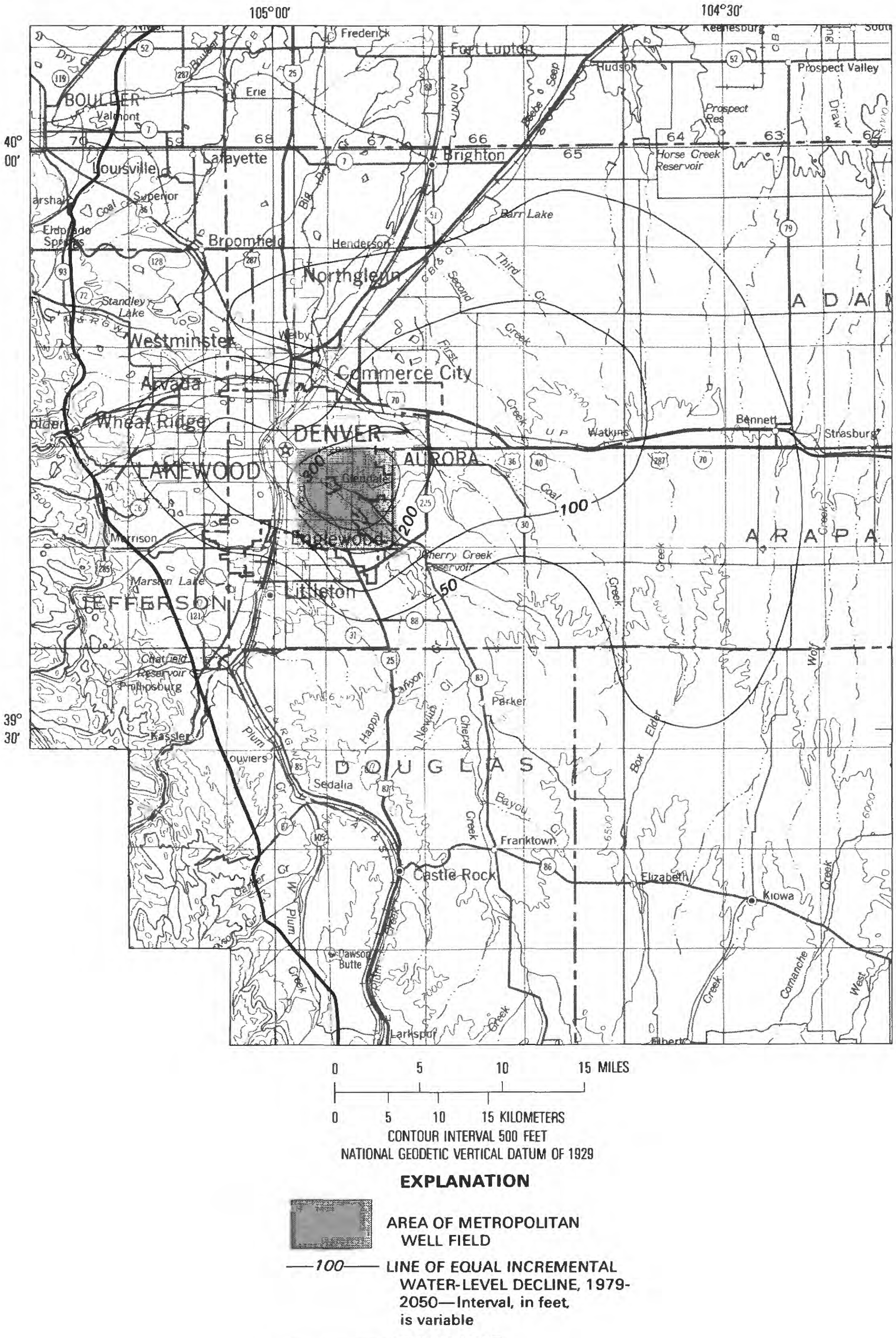


FIGURE 31.—Incremental water-level declines for a metropolitan well field in the Laramie-Fox Hills aquifer, using FULL pumpage estimate.

declines to the corresponding declines shown on plates 3 and 5 for the appropriate base simulation. As in the case of the satellite well field, the magnitude and areal distribution of incremental declines vary markedly with aquifer depth and pumpage estimate used.

When the STDY pumpage estimate is used, incremental water-level declines in the three aquifers range from as much as 500 ft in the Denver aquifer to as much as 1,350 ft in the Laramie–Fox Hills aquifer. Under FULL pumpage conditions, these declines range from as much as 430 ft in the Denver aquifer to as much as 390 ft in the Laramie–Fox Hills aquifer.

In the Denver aquifer, incremental water-level declines in excess of 100 ft occur in a 90-mi^2 area under STDY pumping conditions (fig. 26) and in a 60-mi^2 area under FULL pumping conditions (fig. 29). In the Arapahoe aquifer, these 100-ft declines occur in a 260-mi^2 area under STDY conditions (fig. 27) and in a 50-mi^2 area under FULL conditions (fig. 30). The most extensive declines, which occur in the Laramie–Fox Hills aquifer under STDY pumping conditions, are in excess of 200 ft in a 1,120-mi^2 area (fig. 28). By contrast, these declines extend over only a 50-mi^2 area under the FULL pumpage estimated (fig. 31).

Results of this simulation indicate that large changes in water level can take place as a result of pumping a metropolitan well field. Larger and more areally extensive water-level declines are produced in the deeper aquifers. However, the magnitude of water-level decline produced by the well field can vary considerably, depending on how much other pumpage is occurring in the bedrock aquifers. The largest incremental declines are produced when small (STDY) rates of other pumping are present; conversely, there are small incremental declines when large (FULL) rates of other pumping are considered.

A comparison of the results from the satellite well-field simulations (figs. 17–24) with those from the metropolitan well-field simulations (figs. 26–31) indicates that the aquifer characteristics and the smaller rate of pumping from the metropolitan well field combine to produce less incremental water-level decline in the metropolitan well field. Pumping from the metropolitan well field also has less extensive effects in each of the pumped aquifers. In addition, the metropolitan well field would not tap the Dawson aquifer and, thus, would have mimimal effect on water levels in this aquifer. The comparatively small quantity of water that could be pumped from the metropolitan well field is a hydrologic constraint on this plan.

TABLE 10.—*Park and golf course irrigation pumpage*

Public land	Pumpage from Arapahoe aquifer (cubic feet per second)
Bible Park	0.21
Cheesman Park, City Park and Golf Course	.66
Ruby Hill Park	.27
Willis Case Golf Course	.36
Total	1.50

PUMPAGE FOR PARK AND GOLF COURSE IRRIGATION

The Denver Water Department supplies treated municipal water for irrigation of all or part of several parks and golf courses in Denver. If part of this public land could be irrigated with ground water, additional treated water would be available for higher priority use. This simulation is intended to show the effects of pumping the Arapahoe aquifer to supply water for irrigation of Bible Park, Cheesman Park, City Park and Golf Course, Ruby Hill Park, and Willis Case Golf Course. The 1.50-ft^3/s total pumpage (table 10) was modeled to take place at a constant annual rate, and the effects of seasonal variation in rate are not considered. As a result, the model shows the average annual water-level altitudes in the aquifer, but it does not show maximum or minimum seasonal altitudes, which could be significantly different from the average altitudes at locations near the pumping wells. At greater distances from the pumping wells, the water levels produced by the constant pumping will more closely approximate those produced by a seasonal variation in pumpage. A 27-year (1979–2005) simulation period was used with the HALF pumpage estimate.

As in previous simulations, incremental water-level declines were calculated to show only the effects of the pumping for park and golf course irrigation. The 1979–2005 incremental water-level declines in the Arapahoe aquifer produced by irrigation pumpage under HALF pumpage conditions are shown in figure 32. The hydrograph shows the average water-level altitude near City Park between 1978 and 2005 with park pumpage (HALF-PARK) and without park pumpage (HALF-BASE). Results indicate that 30–40 ft of average water-level decline could occur in the 2.25-mi^2-area grid blocks near the parks and golf courses. Declines in excess of 5 ft primarily extend to the southeast from the pumping sites, over a 380-mi^2 area. Maximum water-level declines in the Denver aquifer usually do not exceed a few feet because of the poor vertical connection between the Denver and Arapahoe aquifers.

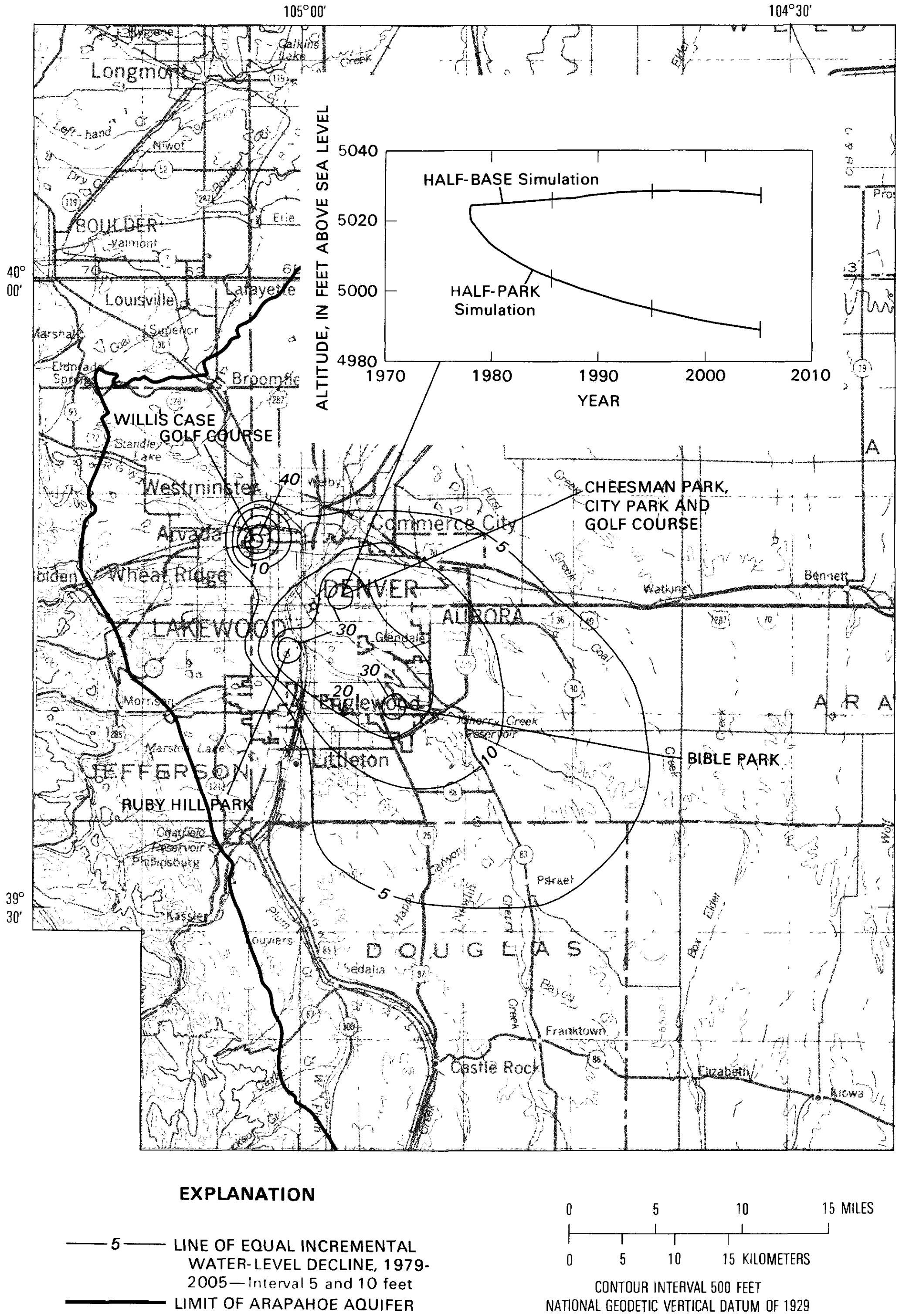


FIGURE 32.—Incremental water-level decline in the Arapahoe aquifer due to park and golf course pumpage, using HALF pumpage estimate.

Results of this simulation indicate that relatively small incremental water-level declines will be produced in the metropolitan area as a result of pumping the Arapahoe aquifer to supply irrigation water to selected public land. This simulation considers pumping from only the Arapahoe aquifer. If two or three of the aquifers were used to jointly supply the water, the resulting incremental declines in each aquifer could be less than that shown in figure 32. Further work is needed to evaluate engineering and economic considerations before the feasibility of this water supply would be known.

BEDROCK STORAGE OF MUNICIPAL WATER

The municipal water-distribution system for Denver, like all well-designed systems, is built with adequate capacity to meet the peak water demands of the customers. Because of seasonal variations in demand, the system capacity is strained during summer months when lawn irrigation is required and demands are large; conversely, it has excess capacity during winter months when most vegetation is dormant and water demands are small. Increased water demands due to an extension of the service area or increased per capita consumption can require large capital outlays for expansion of water-collection, treatment, and distribution facilities. If the bedrock aquifers in the metropolitan area could be used as storage reservoirs for treated municipal water, the need for costly system expansion might be delayed or, in some cases, eliminated. Such reservoirs might be operated by injecting treated municipal water into the aquifers through wells during winter months when excess treatment and distribution capacity is available in the municipal system. The injected water then would be available for later withdrawl to help meet summer peak demands on the municipal system. It is likely that little or no additional treatment of the pumped water would be required prior to municipal use.

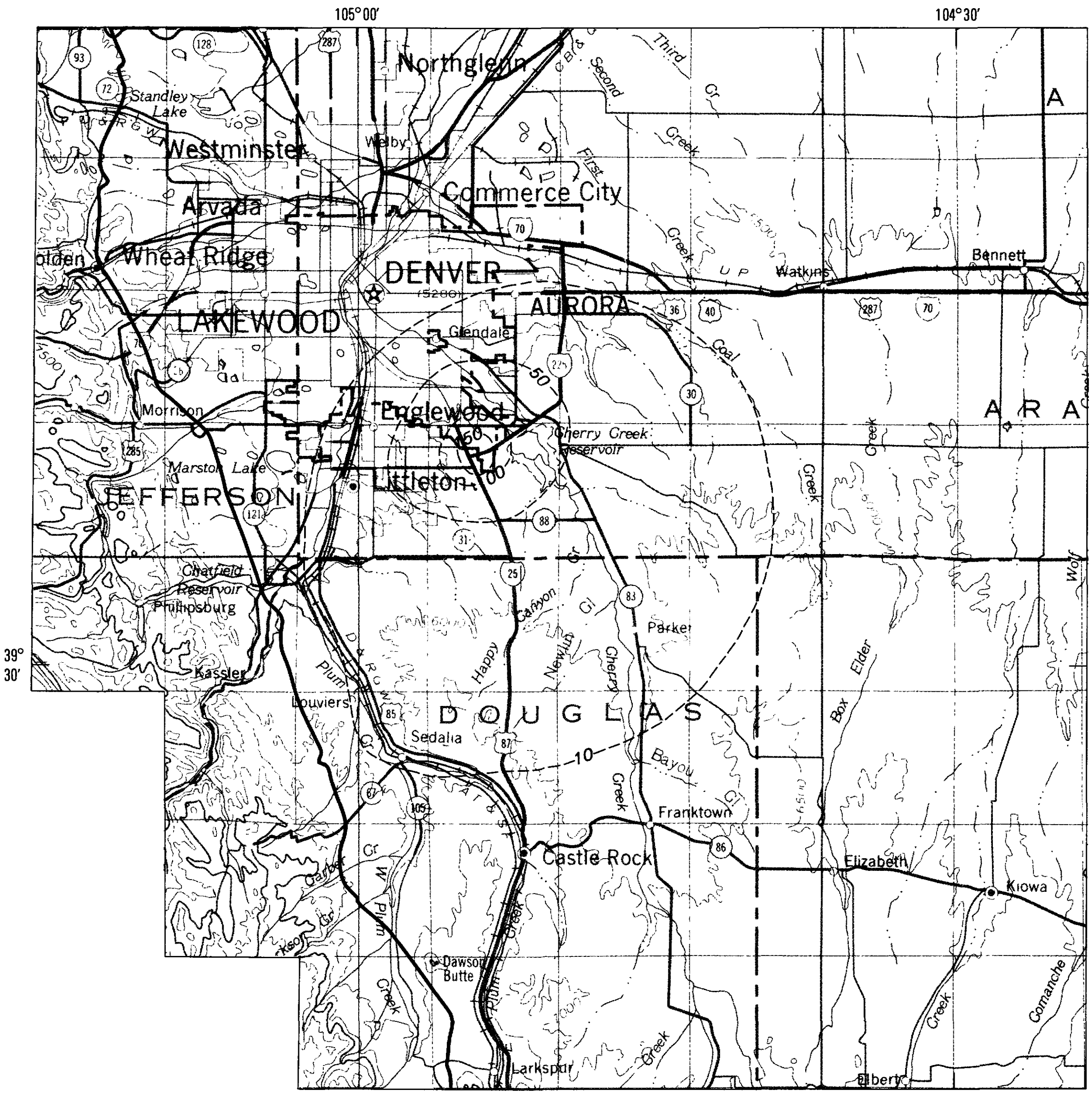
The bedrock reservoir could be operated on either an annual or multiyear cycle. If the volume of water injected during one winter were balanced by an equal amount of pumping the following summer, an annual cycle would result with no net change in the volume of greund water in storage. This plan of operation probably would not require the availability of additional municipal water supplies; it simply allows for more efficient use of existing water supplies, treatment, and distribution facilities by storing water in the aquifers rather than in surface reservoirs. The impacts of this plan on the aquifers primarily consist of large seasonal variations in water level near the injection-pumping wells. If the injection-pumping well field were located in or near Denver (an area of relatively few wells), the seasonal fluctuation in water level would not significantly affect large numbers of wells. Additional study is needed to evaluate economic considerations and water-chemistry compatibility problems between the native and injected water before feasibility of injection is known.

If the reservoir were operated on a multiyear cycle, treated municipal water would be injected during periods of low system demand over a span of several years. The water would be held in the aquifer for use during an exceptionally dry year when demands might exceed system capacity or available supplies of raw water. This plan of operation would require the availability of additional water during years when injection exceeded pumpage. The impacts of this plan on the ground-water resources were investigated by use of model-simulation techniques.

The multiyear injection-pumpage cycle was simulated in the Arapahoe aquifer at two sites in the southeastern suburban area. Site 1 is located on 2.25 mi^2 of land to the west of Cherry Creek Dam in T. 5 S., R. 67 W. Site 2 is of similar area and is located in northern Douglas County near secs. 16 and 17 of T. 6 S., R. 67 W. Total injection rates for the well fields at each site were estimated by model simulation such that the water level at the sites would not rise above land surface by the end of a 4-year injection period. Thus, the model injection rates are controlled by the hydrology of the site. The injection rate at site 1 was 1.7 ft^3/s and at site 2 was 10.0 ft^3/s. The difference between the two injection rates is due to larger aquifer transmissivity and greater depth to water at site 2. Four years of injection followed by 1 year of pumping were simulated. Pumping rates, calculated to remove one-half of the injected water, are 3.4 ft^3/s at site 1 and 20.0 ft^3/s at site 2. Incremental water-level changes are calculated as the difference between the STDY-BASE and STDY-INJ estimate (4-year injection simulation) and the STDY-BASE and STDY-PMP estimate (1-year pumping simulation). The STDY pumpage estimate was used for the simulations because it causes minimum water-level decline in the aquifers and will produce a conservative estimate of the injection rates. Larger rates of injection would be possible under HALF or FULL pumpage estimates.

Results indicate that there could be as much as 198 ft of incremental water-level rise in the Arapahoe aquifer under site 1, and rises in excess of 50 ft could be present in a 47-mi^2 area surrounding the site (fig. 33). After 4 years of injection, the well field is pumped for 1 year, forming a cone of depression at the center of the former recharge mound produced by the injection. As shown in figure 34, remnants of the recharge mound are present, mainly to the east and south of site 1. Water-level declines in excess of 50 ft occur in a 21-mi^2 area near the pumping site.

At site 2, there is as much as 424 ft of incremental water-level rise under the site as a result of the larger rates of injection. Water-level rises in excess of 50 ft are present in a 448-mi^2 area surrounding the site (fig. 35). When 1 year of pumpage is simulated to take place after



EXPLANATION

— —10— — LINE OF EQUAL INCREMENTAL WATER-LEVEL RISE—Interval 40 and 50 feet

———— LIMIT OF ARAPAHOE AQUIFER

0 5 10 15 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 33.—Incremental water-level change in the Arapahoe aquifer at site 1, after 4 years of injection, using STDY pumpage estimate.

4 years of injection, a cone of depression forms with an excess of 400 ft of drawdown at the site, as shown in figure 36. Again, remnants of the recharge mound formed by the injection are still present in surrounding areas.

In the same time span, injection at site 1 placed 4,900 acre-ft of water into storage and injection at site 2 placed 29,000 acre-ft of water into storage. The water-level rises shown in figures 33 and 35 represent pressure changes in the confined Arapahoe aquifer and do not indicate the lateral extent of movement of the injected water. The water injected at site 1 could, theoretically, be contained within an area of aquifer 3,100 ft in diameter. At site 2, the injected water could, theoretically,

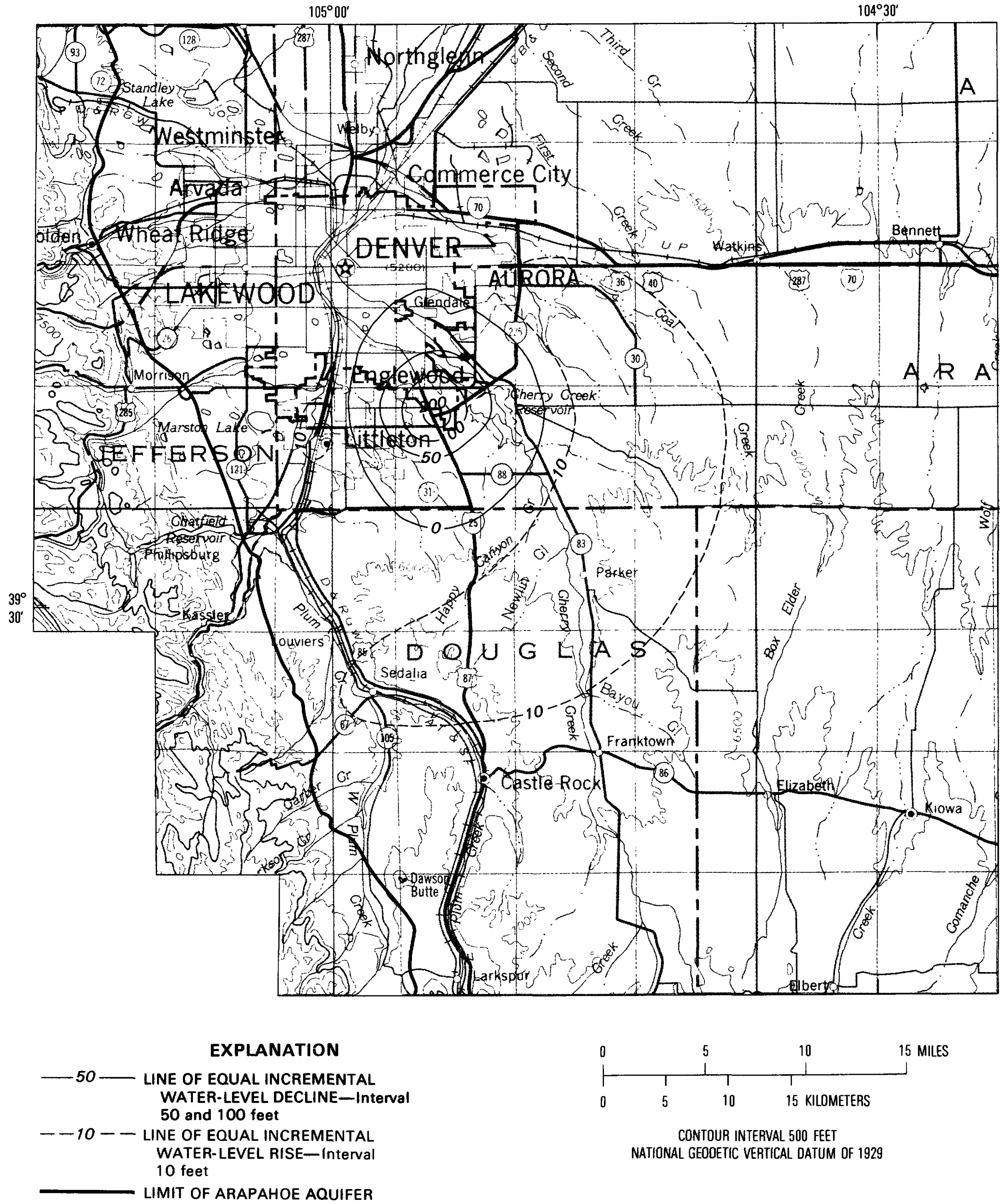


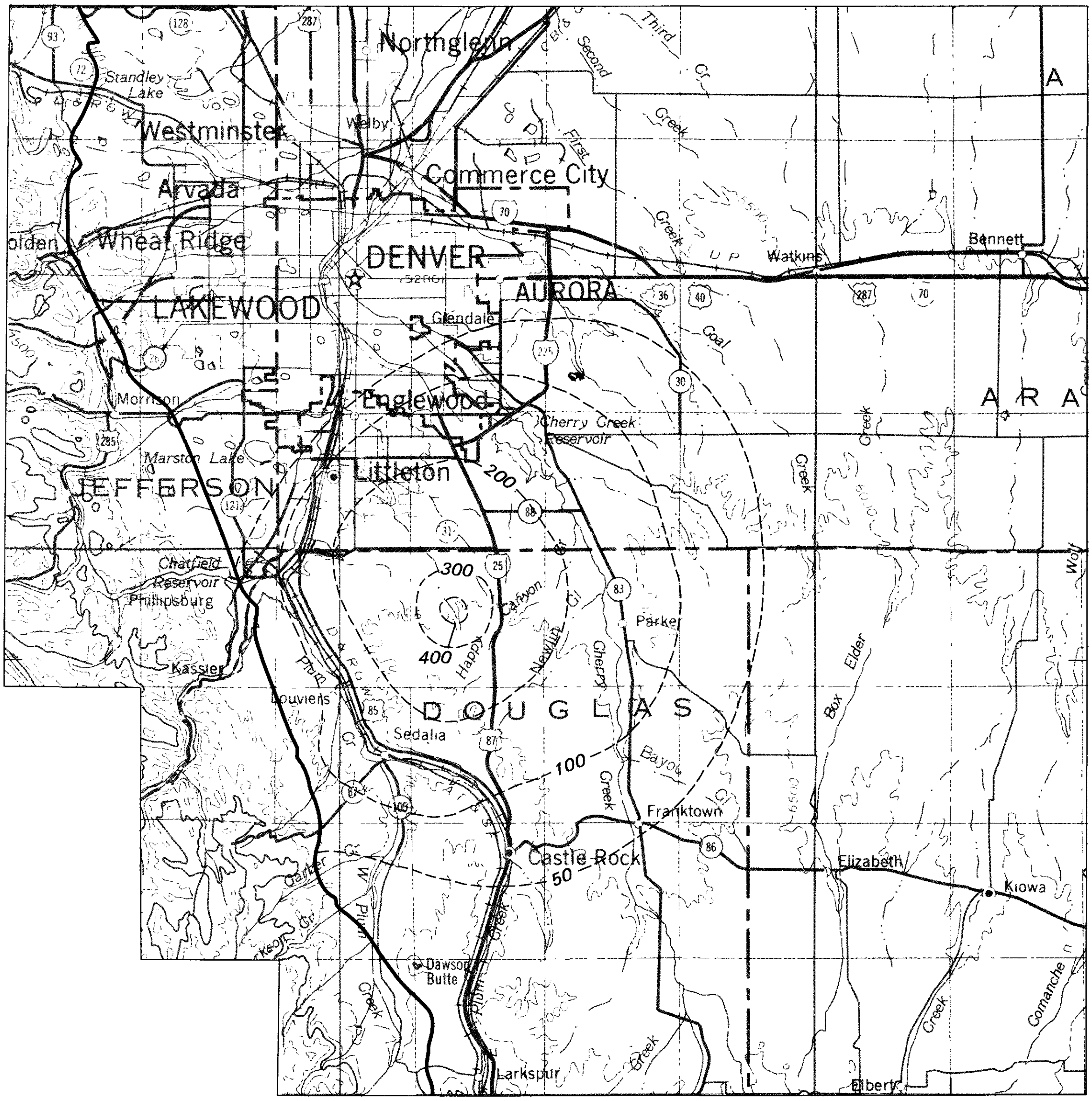
FIGURE 34.—Incremental water-level change in the Arapahoe aquifer at site 1, after 1 year of pumping, using STDY pumpage estimate.

be stored in an area of aquifer 5,800 ft in diameter. Thus, although pressure changes due to injection extend over large areas, the injected water would be contained in a local area near the well field and would be available for removal by subsequent pumping of the injection wells.

These simulations indicate that the choice of a site for bedrock storage of municipal water is critical, for it can drastically affect the volume of water that can be stored in, and pumped from, the aquifer. Both the Denver and Laramie-Fox Hills aquifers underlie sites 1 and 2. If these aquifers were utilized in addition to the Arapahoe aquifer, injection and pumping rates much larger than those simulated for the Arapahoe aquifer alone could be

105°00′ 104°30′

39° 30′



EXPLANATION

——10—— LINE OF EQUAL INCREMENTAL WATER-LEVEL RISE—Interval 50 and 100 feet

———— LIMIT OF ARAPAHOE AQUIFER

0 5 10 15 MILES

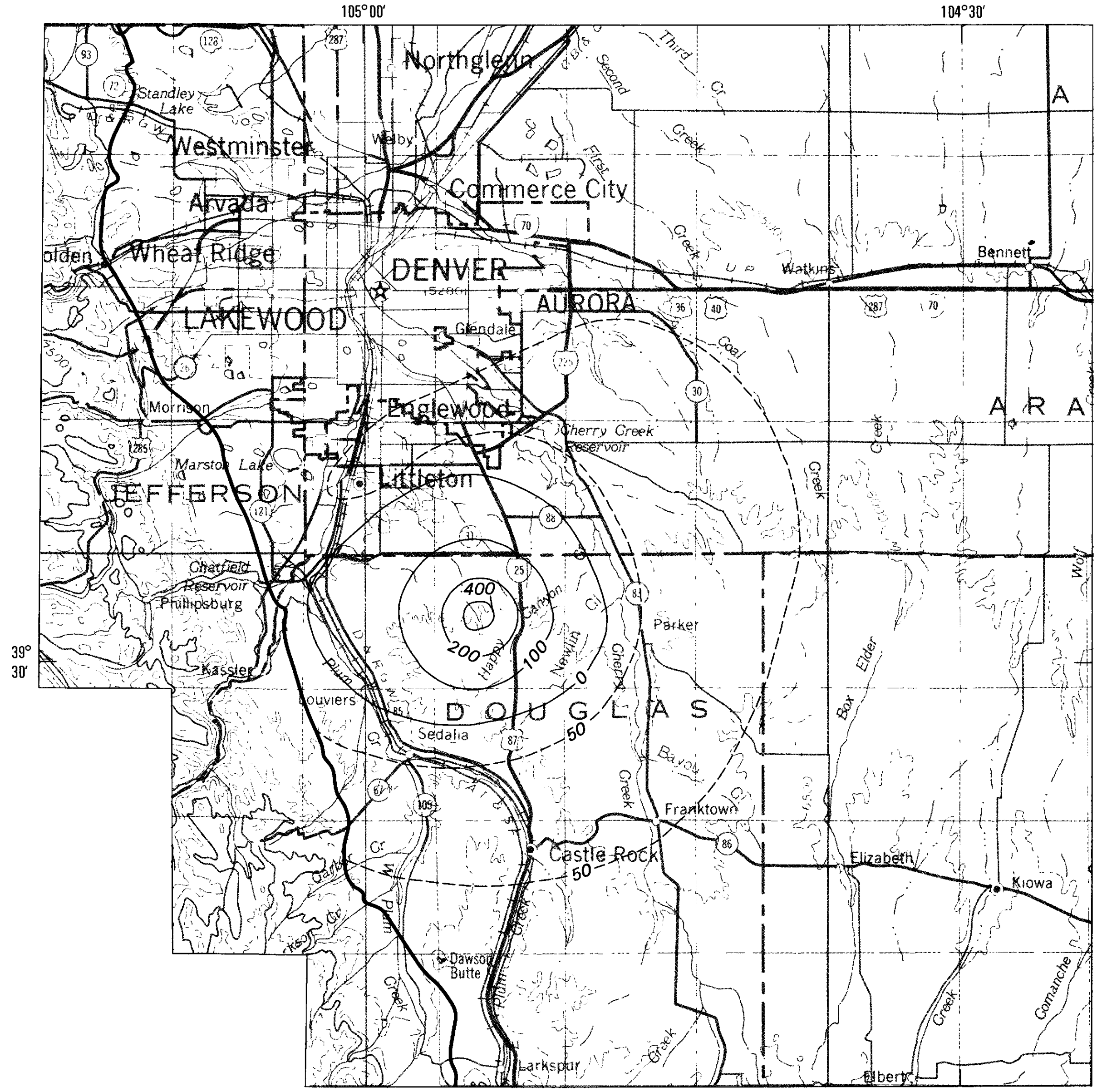
0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET

NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 35.—Incremental water-level change in the Arapahoe aquifer at site 2, after 4 years of injection, using STDY pumpage estimate.

possible. Also, injection rates for the Arapahoe aquifer may be conservative (based on STDY pumpage estimate). Therefore, it may be possible for large volumes of water to be injected, stored, and pumped from the bedrock aquifers near Denver. If more water were injected than pumped, a net increase in the volume of ground water in storage would result, with beneficial effects for surrounding well users. The effects of one



EXPLANATION

——100—— LINE OF EQUAL INCREMENTAL WATER-LEVEL DECLINE — Interval 100 and 200 feet

– –50– – LINE OF EQUAL INCREMENTAL WATER-LEVEL RISE—Interval 50 feet

———— LIMIT OF ARAPAHOE AQUIFER

0 5 10 15 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

FIGURE 36.—Incremental water-level change in the Arapahoe aquifer at site 2, after 1 year of pumping, using STDY pumpage estimate.

5-year cycle of injection and pumpage are shown in figures 33 through 36. The cones of depression shown to occur at the end of the 1-year pumping phase would be short-lived, for subsequent injection in the next cycle would quickly raise the water levels in this area. Further work is needed to evaluate engineering and economic considerations and to investigate the chemical compatibility of the native and injected water before the feasibility of such a system can be known.

CONCLUSIONS

Transmissivity is a measure of the ability of an aquifer to transmit water. It is shown to range from zero near the margins of the bedrock aquifers to as much as 1,000 ft^2/d in the Laramie–Fox Hills aquifer, 2,100 ft^2/d in the Arapahoe aquifer, 400 ft^2/d in the Denver aquifer, and 1,200 ft^2/d in the Dawson aquifer. The area of highest transmissivity is located south of Littleton in the Laramie–Fox Hills and Arapahoe aquifers. In the Denver and Dawson aquifers, the area of highest transmissivity is farther south, near Castle Rock and Palmer Lake. In general, larger well yields may be obtained in areas of larger transmissivity; thus, the bedrock aquifers south of Littleton offer the greatest potential for ground-water resource development. This area also is well suited for artificial recharge by deep-well injection due to the large transmissivity and the deep water levels.

It is estimated that 470×10^6 acre-ft of water is in storage in the bedrock aquifers of the Denver basin. Of this amount, about 260×10^6 acre-ft is theoretically recoverable through gravity drainage of the aquifers. However, less than 0.1 percent of the total volume of water in storage in the basin is stored under confined conditions. Thus, if ground-water development is to make use of the large volume of water in storage, water levels in the aquifers must decline to allow release of water from unconfined storage at the water table. Development of the ground-water resources in this manner will become increasingly difficult as water-level declines require not only the redrilling of existing shallower wells but also drilling of larger numbers of deeper wells to offset decreasing well yields.

In spite of their outward appearances, bedrock formations have elastic properties and are compressible when subjected to pressure, such as that caused by large water-level declines. It is estimated that the 1883–1960 water-level decline in the Arapahoe aquifer in Denver may have produced from 0.8 to 8.0 in. of subsidence in the land surface. Subsidence also may be occurring in surrounding areas but is likely of lesser magnitude. Water-level rises since 1960 may have produced some rebound in the surface elevation in Denver if elastic compaction was primarily responsible for the initial subsidence. If future pumpage causes large water-level declines in the aquifers, as the model results indicate, several feet of land-surface subsidence might occur. Severe subsidence in other areas has caused damage to well casings, development of surface fissures, and disruption in water flow through sewage lines, ditches, and other surface conveyances. Resurveys of benchmark altitudes in the metropolitan area are needed to provide direct measurement of changes in land-surface elevation. An alternative would be the installation of compaction-monitoring equipment on a few unused wells in areas of large water-level decline. Either procedure would allow monitoring of subsidence and would provide advanced warning of subsidence-related problems.

The mean annual precipitation on the Denver basin supplies 6,900 ft^3/s of water to the area, of which only about 55 ft^3/s recharges the bedrock aquifers. Under long-term steady conditions, the Dawson aquifer is estimated to receive the majority of the recharge (40.6 ft^3/s) and also to supply the majority of the discharge (33.4 ft^3/s), primarily to streams. Under these conditions, interaquifer flow is 7.2 ft^3/s from the Dawson aquifer to the Denver aquifer and 5.3 ft^3/s from the Denver aquifer to the Arapahoe aquifer. No significant interaquifer flow occurs between the Arapahoe aquifer and the Laramie–Fox Hills aquifer. The largest natural discharge from the bedrock aquifers is into the drainage area of Cherry Creek, followed by the Monument–Fountain Creek combined area, Plum Creek, Kiowa Creek, Bijou Creek, and the South Platte River.

Estimates of discharge from bedrock wells range from about 5 ft^3/s of flow from uncapped wells in 1884 to between 15 and 41 ft^3/s of pumpage between 1958 and 1978. Most of the 1958–78 pumpage occurred within a 30-mi radius of Denver and represents an overdraft on the aquifers in this area, which has caused major water-level declines in the bedrock formations. Estimates of pumpage from bedrock wells are difficult to obtain because of lack of data. The importance of this limitation is illustrated by modeling results, which indicate that the rate of pumping will significantly affect future water levels in the aquifer. If the major users of bedrock aquifers submitted annual pumpage data to a central agency, such as the State Engineers Office of the Colorado Department of Natural Resources, the ground-water resources of the basin could be more effectively studied, and better model simulations of future water-level conditions would be possible.

Three 1979–2050 pumpage estimates were made for use in simulating effects of various ground-water development plans. These estimates represent large, medium, and small rates of increase that might be expected to occur in future pumpage from the bedrock aquifers. Results of model simulation of the small pumpage estimates indicate that maximum 1979–2050 water-level declines of 410 ft will take place in the Laramie–Fox Hills aquifer, 280 ft in the Arapahoe aquifer, 120 ft in the Denver aquifer, and 280 ft in the Dawson aquifer. Simulation of the medium rate of pumpage indicates maximum 1979–2050 water-level declines of 1,700 ft in the Laramie–Fox Hills aquifer, 800 ft in the Arapahoe aquifer, 300 ft in the Denver aquifer, and 280 ft in the Dawson aquifer. When the large pumpage estimate is used, maximum 1979–2050 water-level declines of 1,830 ft occur in the Laramie–Fox Hills aquifer, 1,000 ft in the Arapahoe aquifer, 420 ft in the Denver aquifer, and 310 ft in the Dawson aquifer. These results indicate that large water-level declines will primarily occur in the deeper aquifers when medium or large rates of pumping are considered. Rapid water-level declines take place in these aquifers until water-table conditions develop nearby, at which time the rate of water-level decline decreases.

Large water-level declines can be delayed by limiting the rate of increase in pumpage. This has begun on a local basis through use of stringent water-conservation practices or through land-use zoning that limits population density and thereby limits pumpage. Minimal rates of increase in pumpage are shown to produce moderate water-level declines in the aquifers and will assure prolonged availability of bedrock water supplies.

An alternative to limiting pumpage would be to encourage pumping from the shallow aquifers where water-table conditions allow slower rates of water-level decline. However, this would accelerate the water-level declines in these aquifers and would cause the shallower wells commonly used as domestic water supplies to go dry more quickly.

If large water-level declines are allowed to occur, economic factors likely will cause some users of the deep aquifers to seek sources of water from the shallow aquifers or from surface sources. If these other sources are not available, continuing water-levels declines in the deep aquifers are likely. It is important to note, however, that none of the pumpage estimates produced significant dewatering of the aquifers. Thus, future pumping in the basin to the year 2050 probably will not cause the aquifers to go dry; rather, water will still be available in the aquifer, but the cost of maintaining initial rates of pumping will increase markedly as water levels decline and individual well yields decrease. Although water still may be available in the aquifer, wells that do not fully penetrate the aquifer may go dry as a result of the declining water levels.

Four ground-water development plans that consider possible methods of supplementing the municipal supply for Denver were simulated. These plans involve (1) pumping a satellite well field and piping water to the metropolitan area, (2) pumping a well field located in the metropolitan area, (3) using bedrock wells to provide irrigation water for city parks, and (4) using the bedrock aquifers for temporary storage of municipal water for later use. Model simulations of the effects of pumping the satellite and municipal well fields indicate that larger incremental water-level declines will be produced by the well-field pumpage if small rates of other pumpage are occuring in the basin. Conversely, smaller incremental water-level declines are produced by the well-field pumpage if large rates of other pumping are occurring in the basin. Comparison of the effects of pumping the satellite and metropolitan well fields indicates that the metropolitan well field will produce only about one-half as much water as the satellite well field. However, pumping from the metropolitan well field will have a less adverse effect on water levels in surrounding aquifers. The Dawson aquifer, for example, is not affected by the metropolitan well field due to the location of the well field. Both well fields offer the advantage of providing supplemental water from a source separate from the current surface-water sources. As such, the well fields might provide an emergency or backup source for part of the metropolitan area. Further analysis of both well fields are needed to determine the feasibility of this method of supplementing Denver's water supply.

Simulations of the effects of pumping the Arapahoe aquifer to supply irrigation water for several city parks and golf courses indicate that 30 to 40 ft of incremental water-level decline are produced near the parks. These model results do not consider the seasonal variation in water level that would occur as a result of pumping for summer irrigation use. Seasonal water levels would differ from the average annual decline shown by the model. If pumpage were to occur from the Denver or Laramie–Fox Hills aquifers, in addition to the Arapahoe aquifer, lesser rates of incremental water-level decline would be produced in the Arapahoe aquifer. Again, evaluation of other constraints will affect the feasibility of this water source.

If the bedrock aquifers could be used to store treated municipal water during periods of low demand on the municipal system, additional water could be pumped back into the system at a later date to help meet peak water requirements. Model simulation of two injection-pumping well fields in the Arapahoe aquifer indicates that a field located in northern Douglas County would allow injection rates of 10 ft^3/s, whereas a field located near Cherry Creek Reservoir would allow an injection rate of only 1.7 ft^3/s. If, after 4 years of injection at these rates, the well fields are pumped at twice these rates for 1 year, a cone of depression would form near the former center of the injection-recharge mound. Remnants of the recharge mound are shown to be present to the north, east, and south of the cone of depression after 1 year of pumping. A total of 4,900 acre-ft of water was injected in 4 years near Cherry Creek Reservoir, and a total of 29,000 acre-ft of water was injected in northern Douglas County. Results indicate that large volumes of water may be injected into the bedrock aquifer and subsequently removed by pumping. The choice of location of the injection-pumping site is critical to achieving large flow rates. Additional work is required to evaluate other constraints and to investigate chemical compatibility of the native and injected water.

REFERENCES CITED

Anna, L. O., 1975, Map showing availability of hydrologic data published as of 1974 by the U.S. Environmental Data Service and by the U.S. Geological Survey and cooperating agencies, Colorado Springs-Castle Rock area, Front Range Urban Corridor, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-857-D, scale 1:100,000, 1 sheet.

Bull, W. B., 1975, Land subsidence due to ground-water withdrawl in the Los Banos-Kettleman City area, California, Part 2, Subsidence and compaction of deposits: U.S. Geological Survey Professional Paper 437-F, p. F1-F90.

Chronic, Felicie, and Chronic, John, 1974, Bibliography and index of geology and hydrology, Front Range Urban Corridor, Colorado: U.S. Geological Survey Bulletin 1306, 102 p.

Clark, S. P., Jr., ed., 1966, Handbook of physical constants: Geological Society of America Memoir 97, 587 p.

Colorado Department of Health, 1978, Primary drinking water regulations for the State of Colorado: Denver, Water Quality Control Division, 60 p.

Colton, R. B., and Lowrie, R. L., 1973, Map showing mined areas of the Boulder-Weld coal field, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-513, scale 1:24,000, 1 sheet

Cross, C.W., Chisholm, F. F., Chauvenet, Regis, and Van Deist, P. H., 1884, The artesian wells of Denver: Colorado Scientific Society, Proceedings, v. 1, p. 76-108.

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

Denver Regional Council of Governments, 1978, Regional water supply plan; preliminary report: Denver Regional Council of Governments, 59 p.

Denver Water Department, 1975, Metropolitan water requirements and resources 1975-2010: Prepared under the direction of the Denver Regional Council of Governments for the Colorado State Legislature, Metropolitan Denver Water Study Committee, v. I, 146 p.; v. II, 383 p.; v. III, 153 p.

Emmons, S. F., Cross, C. W., and Eldridge, G. H., 1896, Geology of the Denver basin in Colorado: U.S. Geological Survey Monograph No. 27.

Fatt, I., 1958, Compressibility of sandstones at low to moderate pressures: American Association of Petroleum Geologists Bulletin, v. 42, no. 8, p. 1924-1957.

Hampton, E. R., 1975, Map showing availability of hydrologic data published by the U.S. Environmental Data Service and by the U.S. Geological Survey and cooperating agencies, Greater Denver area, Front Range Urban Corridor, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-856-C, scale 1:100,000, 1 sheet.

Hampton, E. R., Clark, G. A., McNutt, M. H., 1974, Map showing availability of hydrologic data, Boulder-Fort Collins-Greeley area, Front Range Urban Corridor, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-855-C, scale 1:100,000, 1 sheet.

Hansen, W. R., Chronic, John, and Matelock, John, 1978, Climatography of the Front Range Urban Corridor and vicinity, Colorado: U.S. Geological Survey Professional Paper 1019, 59 p.

Hillier, D. E., Brogden, R. E., and Schneider, P. A., Jr., 1978, Hydrology of the Arapahoe aquifer in the Englewood-Castle Rock area, south of Denver, Denver basin, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1043, scale 1:100,000, 2 sheets.

Holzer, T. L., 1977, Ground failure in areas of subsidence due to ground-water decline in the United States, *in* International Symposium on Land Subsidence, 2d, Anaheim, 1976, Proceedings: International Association of Hydrological Science-Association Internationale des Sciences Hydrologiques Publication No. 121, p. 423-433.

Hurr, R. T., and Schneider, P. A., 1972, Hydrologic characteristics of the valley-fill aquifer in the Brighton reach of the South Platte River valley, Colorado: U.S. Geological Survey Open-File Report 72-332, 2 p.

Kirkham, R. M., 1978, Coal mines and coal analyses of the Denver and Cheyenne basins, Colorado: Colorado Geological Survey Open-File Report 78-9, 104 p.

Livingston, R. K., Klein, J. M., and Bingham, D. L., 1976, Water resources of El Paso County, Colorado: Colorado Water Conservation Board, Colorado Water Resources Circular 32, 85 p.

Major, T. J., Robson, S. G., Romero, J. C., and Zawistowski, Stanley, 1983, Hydrogeologic data from parts of the Denver basin, Colorado: U.S. Geological Survey Open-File Report 83-274, 425 p.

Mayuga, M. N., and Allen, D. R., 1970, Subsidence in the Wilmington oil field, Long Beach, California, U.S.A., *in* Symposium on Land Subsidence, International Hydrologic Decade, Tokyo, 1969, Proceedings: International Association of Hydrological Sciences-Association Internationale des Sciences Hydrologiques Publication No. 88, p. 66-79.

McConaghy, J. A., Chase, G. H., Boettcher, A. J., and Major, T. J., 1964, Hydrogeologic data for the Denver basin, Colorado: Colorado Water Conservation Board Basic-Data Report 15, 224 p.

McCoy, A. W., III, 1953, Tectonic history of the Denver basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 37, no. 8, p. 1873-1875.

Norris, J. M., Robson, S. G., and Parker, R. S., 1983, Summary of hydrologic information for the Denver coal region, Colorado: U.S. Geological Survey Open-File Report 84-4337, 68 p.

Robson, S. G., 1983, Hydraulic characteristics of the principal bedrock aquifers in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-659, scale 1:500,000, 3 sheets.

Robson, S. G., and Romero, J. C., 1981a, Geologic structure, hydrology, and water quality of the Dawson aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-643, scale 1:250,000, 3 sheets.

_____1981b, Geologic structure, hydrology, and water quality of the Denver aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-646, scale 1:500,000, 1 sheet.

Robson, S. G., Romero, J. C., and Zawistowski, Stanley, 1981a, Geologic structure, hydrology, and water quality of the Arapahoe aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-647, scales 1:500,000 and 1:250,000, 3 sheets.

Robson, S. G., Wacinski, Andrew, Zawistowski, Stanley, and Romero, J. C., 1981b, Geologic structure, hydrology, and water quality of the Laramie-Fox Hills aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-650, scale 1:500,000, 3 sheets.

Romero, J. C., 1976, Ground-water resources of the bedrock aquifers of the Denver basin, Colorado: Colorado Division of Water Resources, 109 p.

Romero, J. C., and Hampton, E. R., 1972, Maps showing the approximate configuration and depth to the top of the Laramie-Fox Hills aquifer, Denver basin, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-791, scale 1:500,000, 1 sheet.

Schneider, P. A., Jr., 1980, Water-supply assessment of the Laramie-Fox Hills aquifer in parts of Adams, Boulder, Jefferson, and Weld Counties, Colorado: U.S. Geological Survey Open-File Report 80-327, 21 p., scale 1:50,000, 6 sheets.

Todd, D. K., 1967, Ground water hydrology: New York, John Wiley, 336 p.

Trescott, P. C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 107 p.

Trescott, P. C., and Larson, S. P., 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow, Supplement to Open-File Report 75-438: U.S. Geological Survey Open-File Report 76-591, 20 p.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

Tweto, Odgen, 1979, Geologic map of Colorado: U.S. Geological Survey Special Geologic Map, scale 1:500,000, 1 sheet.

U.S. Bureau of the Census, 1981, Final population and housing unit counts, Colorado (1980): Report PHC 80-V-7.

U.S. Environmental Protection Agency, 1976, National interim primary drinking water regulations: EPA 570/9-76-003, 159 p.

______1977, National secondary drinking water regulations: Federal Register, v. 42, no. 62, Thursday, March 31, 1977, Part 1, p. 17143-17147.

SUPPLEMENTAL INFORMATION

HISTORICAL PUMPAGE ESTIMATES

Pumpage from bedrock wells for the period 1958-78 was estimated by first assessing the annual municipal pumpage for this period. This value was converted to total pumpage by use of a conversion factor calculated on the basis of data for the years 1960, 1974, and 1977.

Municipal pumpage values were based, to the extent possible, on pumpage records provided by municipal water agencies for the period 1958-78. The quality of these records varied considerably, requiring that estimates be provided for missing and erroneous data. Estimates for missing data were based on per capita consumption and population in the service area. In some cases, erroneous data could be corrected or adjusted by, for example, separating pumpage from bedrock and alluvial wells. In other cases, correction was not possible, and data of questionable accuracy were included in the municipal pumpage estimate. The resulting municipal pumpage data are probably accurate within about ±20 percent.

The municipal pumpage from bedrock wells is shown to range from 5 ft³/s in 1958 to 9 ft³/s in 1978 (fig. 12). Between 1960 and 1977, municipal pumpage probably constituted 20 to 30 percent of the total bedrock pumpage.

More detailed bedrock-pumpage estimates were tabulated for 1960, 1974, and 1977 in order to allow calculation of a conversion factor:

$$F=P_t/P_m, \tag{4}$$

where P_t represents total pumpage and P_m represents municipal pumpage. The pumpage estimates were tabulated using four categories of water use: (1) municipal, (2) domestic and stock, (3) commercial and industrial, and (4) irrigation. Municipal pumpage for 1960, 1974, and 1977 was obtained from the previous estimates.

Domestic pumpage was estimated on the basis of a per capita use of 175 gal/d and a mean occupancy rate of three people per house (U.S. Bureau of the Census, 1981). This is equivalent to a pumping rate of 0.6 acre-ft/yr per domestic well, assuming one domestic well per household. Yields from stock wells may vary considerably, but a value of 0.6 acre-ft/yr also seems reasonable for these wells. The number of active bedrock wells in each of the four categories can be approximated from well data available for the years 1960, 1974, and 1977. The number of active domestic and stock wells multiplied by the yield per well (0.6 acre-ft/yr) produced the initial estimates of domestic and stock pumpage. Because of uncertainty in the number of domestic and stock wells in use and the average pumping rate for these wells, the accuracy of this estimate is probably only about ±30 percent. Bedrock pumpage for domestic and stock use increased from about 10 percent of the total pumpage in 1960 to about 30 percent of the total pumpage in 1977.

Commercial and industrial pumpage estimates were based on the average yield of wells in this category. Average yield was calculated from measured discharge of 20 typical bedrock wells (5 percent of the total number of commercial and industrial wells) and was adjusted for a pumping cycle of 4 hours pumping per day, 5 days per week, 52 weeks per year. An average yield of 9 acre-ft/yr per well was obtained and multiplied by the number of active wells in this category to initially estimate the commercial and industrial pumpage. Because little data were available on which to base these estimates, the resulting pumpage for commercial and industrial use is of lower accuracy than is the domestic and stock pumpage estimate. Pumpage for this water-use category ranged from about 30 percent of the total pumpage in 1960 to about 20 percent in 1974 and 1977.

Irrigation pumpage was estimated in a manner similar to that used for commercial and industrial pumpage. Average yield for these wells was calculated from measured discharge of 10 typical bedrock wells

(7 percent of the total number of irrigation wells) and was adjusted for a pumping cycle of 12 hours' pumping per day for a 100-day irrigation season. An average yield of 41 acre-ft/yr per well was obtained and multiplied by the number of wells in this category to estimate the initial irrigation pumpage. Again, little data are available to document these estimates, and the resulting pumpage for irrigation wells is probably of lower accuracy than are the other pumpage estimates. On the basis of these estimates, irrigation pumpage likely constituted about 25 percent of the total pumpage in 1960, 1974, and 1977.

The sums of the pumpage estimates for the four categories of water use were calculated for 1960, 1974, and 1977. The factor defined in equation (4) ranged from 3.0 to 3.7 for the above period, indicating that total bedrock pumpage is about three to four times the magnitude of municipal bedrock pumpage. This pumpage factor was used to make initial estimates of total pumpage from municipal pumpage for each year from 1958 to 1978. Subsequent modeling of the ground-water system indicated that these pumpage estimates were too small to be consistent with the water-level changes and hydrologic characteristics of the aquifers. A pumpage factor ranging from 3.5 to 4.5 was found to provide more satisfactory modeling results and was used to estimate total pumpage from municipal pumpage. The revision of the initial pumpage estimate is reasonable because (1) the 0- to 20-percent increase in the pumpage factor is within the error of estimate for the initial pumpage, and (2) the initial pumpage estimate is one of the more poorly documented parameters used in the model and is thus subject to revision on the basis of other, better-defined model parameters.

FUTURE PUMPAGE ESTIMATES

Municipal pumpage estimates for 1979–2050 were based on the estimated water requirements for the Denver metropolitan area as presented in a study of the metropolitan water requirements for 1975–2010 (Denver Water Department, 1975). In making the municipal pumpage projections, it was assumed that the historical ratio of bedrock supply rates to surface-water supply rates would be maintained in the future. The resulting pumpage was a constant fraction of the increasing total water demand for the metropolitan area. This pumpage probably is an overestimate of future municipal pumpage because, historically, pumpage has not increased as rapidly as has total water demand. In addition, the population and water-demand estimates contained in the Denver Water Department (1975) report were considered to be too large by the Denver Regional Council of Governments and were revised downward by the Denver Regional Council of Governments (1978) for their purposes.

Pumpage estimates for private users or new (post-1975) municipal suppliers were based on the assumption that this pumpage will increase at the same rate as the projected supply requirements of municipal suppliers located to the southeast of the metropolitan area. Municipal suppliers in this area were chosen because most of the new (1978–82) well construction has been in this area. Water-supply requirement data for Aurora, Willows Water District, Parker Water District, Denver Southeast Suburban Water and Sanitation District, Silver Heights Water District, and the town of Castle Rock were used to determine the future rate of increase in water requirements. This rate was applied to the permitted pumping rate for new wells in the area to distribute the pumpage over 1979–2010. This pumpage was added to a base pumpage and the municipal pumpage to obtain the total pumpage estimate for 1979–2010. The base pumpage was included to represent nonmunicipal pumping in established areas where pumpage is not expected to increase. Pumpage estimates for the period 2010 to 2050 were based on a linear extrapolation of the 1975–2010 total pumpage estimate. This pumpage estimate is termed the "FULL" pumpage estimate in this paper. A second pumpage estimate was made in order to provide a more conservative alternative to the initial (FULL) estimate. This estimate was arbitrarily taken to be one-half of the FULL estimate and is termed the "HALF" pumpage estimate. A third, still more conservative, estimate was made by assuming that no increase in pumpage could occur after 1983. This estimate is termed the "STDY" pumpage estimate.

MODELING ERRORS AND LIMITATIONS

In both the steady-state and transient-state calibrations, differences between measured and calculated water-level altitudes are due to errors associated with (1) the simplifying assumptions made in describing the aquifer system, (2) the computational scheme used to approximate the solution to the basic equation, (3) the aquifer characteristics, (4) the initial conditions specified for a model simulation, (5) the determination of water-level altitudes in the prototype, and (6) the rate and distribution of recharge and discharge.

Errors associated with the description of the aquifer system usually result from the simplifying assumptions that are made in gaining a conceptual understanding of the operation of the prototype, Simplifying assumptions also are required in order to reduce the complexity of the system to a level that can be simulated by the model. Examples of simplifying assumptions include the assumption that a uniform vertical head distribution occurs within each aquifer, or the assumption that storage coefficient is either confined or unconfined through the entire thickness of each aquifer. Errors associated with simplifying assumptions are probably of small to moderate importance in both models and may be partly responsible for differences between measured and calculated heads.

Errors associated with the computational scheme result from the numerical approximation of the solution to the governing equation and are also of small importance in both models. In the transient-state model, these errors become more pronounced as the size of the grid blocks become large in the outlying parts of the study area. Use of transient-state simulations should be limited to areas having small to moderate grid spacing, in order to reduce error and provide greater resolution.

Aquifer characteristics such as transmissivity and vertical hydraulic conductivity are a small source of error in the steady-state model and, with storage coefficient, are a moderate to large source of error in the transient-state model. The value of storage coefficient can significantly alter the computed heads in the transient-state model. Because the effective value of this characteristic is not well documented, differences between calculated and measured water levels may be due, in part, to use of an inappropriate storage coefficient in the transient model.

The water-level altitudes at the start of a transient-state simulation period must be specified. The model uses these altitudes as the starting point for further head computations. Errors in these and other initial conditions may be carried forward and may affect the heads calculated at later times. These effects tend to diminish with the duration of the simulation period, so that heads calculated by the transient-state model are normally not seriously affected by initial condition errors. Water-budget computations also can be affected by initial condition errors if the duration of the simulation period is relatively short. For this reason, use of the water budget to determine percent of pumped water derived from storage might lead to erroneous results if the change in storage is strongly affected by incorrect initial conditions.

Errors in prototype water-level altitudes are of moderate importance in the calibration of both the steady-state and transient-state models. These errors are due to sampling errors, such as measuring a recently pumped well or measuring a well completed in the wrong aquifer, or are due to interpretation errors, such as incorrectly extrapolating equal-potential lines into areas without data or incorrectly computing a water-level altitude. An important interpretation error can be produced by assuming that the water level in a well represents the average water level in the aquifer. This assumption is particularly troublesome in aquifers with numerous partially penetrating wells, such as the Dawson and Denver aquifers. Some differences between measured and calculated water levels, therefore, may be due not to model deficiencies, but to errors in the prototype water levels, which normally serve as the standard in judging the calibration of the model. In this situation, the model results may be a more accurate representation of the water-level conditions than the measured water levels.

Errors associated with recharge and discharge include errors in estimating the rate, distribution, or duration of natural recharge, natural discharge, and historical pumpage. Natural recharge and discharge are a moderate source of error in the calibration of the transient-state model; however, historical pumpage is probably the largest single source of error in the calibration of this model. Because historical pumpage is not well defined by data, this parameter was most readily adjusted during calibration to produce better agreement between measured and calculated water-level altitudes.

The lack of data to define both historical and future pumpage estimates limits the type of model simulations that should be made. As an illustration, consider the following three questions that could be asked in a modeling study:

1. What will be the future pumpage, and how will the prototype respond to this pumpage?
2. What will be the prototype response to a specified rate of pumpage?
3. What will be the difference in response of the prototype to two specified rates of pumpage?

The model-generated answer to the first question will contain errors resulting from all of the above-mentioned sources, but will be most profoundly affected by errors in estimating future pumpage. Because it is impossible to foretell what the rate, distribution, and duration of future pumpage will be, the model results also will be an incorrect prediction of future conditions. The answer to the second question will not contain errors in model results due to errors in pumpage estimates because the rate of pumping has been specified. The answer to the third question involves comparison of model results for two specified rates of pumping. This eliminates the effects of initial conditions, so this model result is not affected by either pumpage errors or initial condition errors. Simulations on the Denver basin model are made using the latter technique whenever possible to improve the accuracy of the model results.

The accuracy of a model simulation is affected by (1) the quality of the calibration, (2) the uniqueness of the

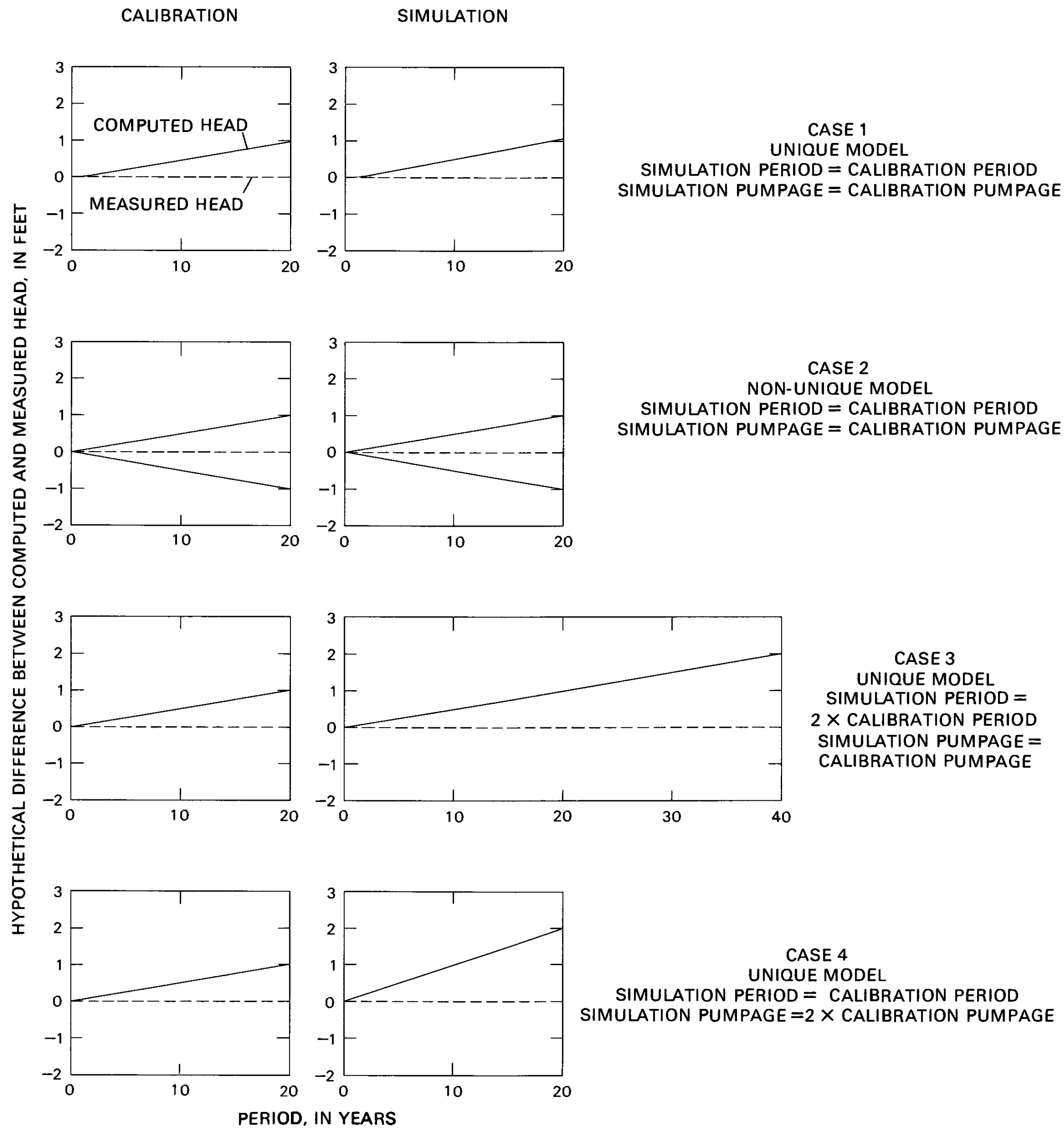


FIGURE 37.—Graphs showing hypothetical effects of modeling conditions on simulation accuracy.

model, (3) the duration of the simulation period compared to the duration of the calibration period, and (4) the rate of pumping during the simulation period compared to that during the calibration period. These four effects are illustrated in elementary form in figure 37.

The most accurate simulations are possible when the model simulation period and pumping rate are less than, or comparable to, the calibration period and pumping rate. In the case of a unique model (fig. 37, case 1), the accuracy of the calibration is indicative of the accuracy of the simulation. If at the end of a 20-year calibration period the calculated head in the model is 1 ft above the observed head, then a similar head error could be expected at the end of a 20-year simulation period.

If the model is not unique (see the section "Transient-State Model"), a second model exists that will calibrate as well as, or better than, the original model and will be based on an alternate intrepretation of the field data. If such a model exists, constraints on the interpretation of the field data normally require that the second model be similar to the original model. In an extreme case, the second model might produce a calibration head distribution that is the mirror image of the head distribution of the original model. In the example of case 2 (fig. 37), the second model might produce a calculated head 1 ft below the observed head, although the original model produces a calculated head 1 ft above the observed head. Both models are calibrated to within 1 ft of the observed head but differ from each other by 2 ft. A similar accuracy could be expected in the simulation results. This indicates that simulations from a non-unique model could be different from those produced by a second, equally acceptable model, and this difference could be of greater magnitude than the accuracy of the calibration.

If the duration of the simulation period is much greater than the duration of the calibration period, errors that accumulate through time can lessen the accuracy of the simulation results. As shown in case 3 (fig. 37), the calibrated head is 1 ft above the observed head at the end of a 20-year calibration period. By the end of a 40-year simulation period, the calculated head is 2 ft above the observed head. Thus, if all of the errors in a model calibration are of a cumulative nature, a simulation of twice the duration of the calibration will exhibit about twice the error of the calibration.

The rate of recharge or discharge (primarily pumpage in this case) during the simulation period also can affect the accuracy of the simulation results. If all of the errors in a model calibration are due to incorrect model response to pumpage, then a doubling of the pumping rate in a simulation could lead to an approximate doubling of the simulation error over that shown by the calibration (fig. 37, case 4).

The degree to which the above conditions affect the simulation results of the Denver basin model is difficult to determine. Errors in a model calibration or simulation are normally not due to one cause alone, but are a complex interaction of many causes. The net result is often a series of partially offsetting errors that defy quantitative description. In general terms, the shorter duration model simulations involving small pumping rates are probably the most accurate; the longer duration simulations involving large pumping rates are probably the least accurate. It can be seen from the simulation results shown in figure 37 that the cumulative effect of errors from a nonunique model used for a long simulation period with a large rate of pumping could be large. Although is is unlikely that those errors would be fully additive, the results of such long-term, heavily stressed simulations must be used with special caution.

U S GOVERNMENT PRINTING OFFICE 1987—773-047 46,029 REGION NO 8