Alluvial and Bedrock Aquifers of the Denver Basin— Eastern Colorado's Dual Ground-Water Resource

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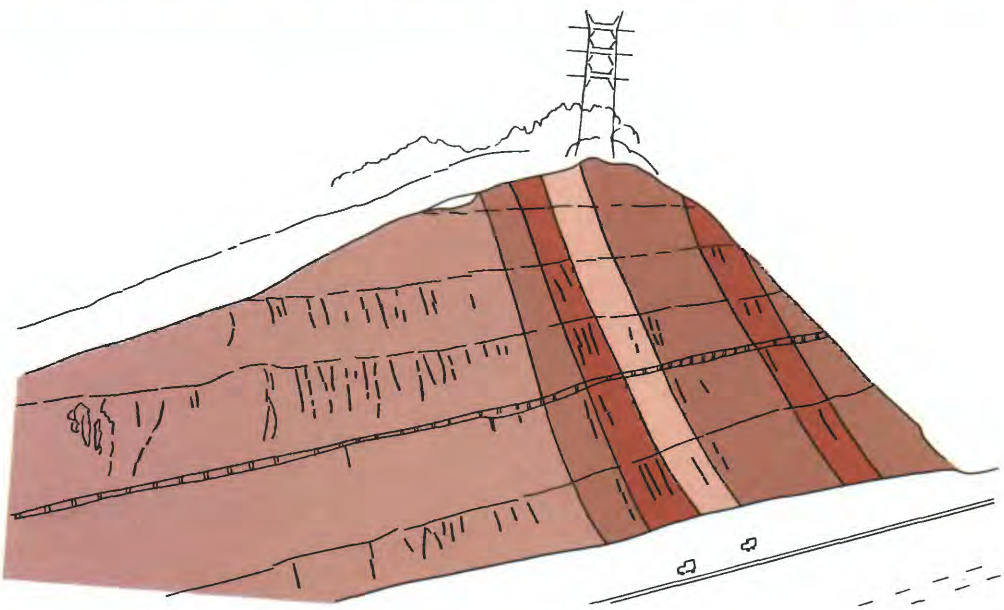
ALLUVIAL AND BEDROCK AQUIFERS OF THE DENVER BASIN— EASTERN COLORADO'S DUAL GROUND-WATER RESOURCE



Frontispiece. Photograph showing highway roadcut and sketch illustrating steeply dipping beds. Bedrock formations dip steeply into the subsurface along the margins of the Denver basin west of Denver. These variously colored beds were orignally deposited as horizontal layers, and have been tilted upward into their present position by the uplift of the Rocky Mountains.

Alluvial and Bedrock Aquifers of the Denver Basin— Eastern Colorado's Dual Ground-Water Resource

By S.G. ROBSON

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2302

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
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FOREWORD

Two of the primary responsibilities of the U.S. Geological Survey are to assess the Nation's water supply and to develop the understanding necessary to predict the environmental consequences of alternative means of developing and managing water resources. To carry out these responsibilities the Geological Survey conducts studies, many in cooperation with State and local agencies, to determine the quantity and quality of the Nation's water resources and the response of hydrologic systems to both natural and manmade stresses. The results of the studies are made available in numerous ways, including published reports, written and oral responses to specific requests, and presentations at scientific and public meetings.

Although most reports are designed to meet the technical needs of those engaged in the development, management, and protection of water supplies, the U.S. Geological Survey has long recognized the need to present the results of its studies in a form that also is understandable to those who are affected by and who benefit from water developments. To better meet this need, the Water Resources Division of the Geological Survey expanded the preparation of general-interest reports in 1980. The reports planned as a part of this program deal both with specific water-related problems and with general topics of broad public interest, such as this report, which describes the ground-water resources of a large area of eastern Colorado.

We welcome your comments on the usefulness of this report, or suggestions on ways we could improve the information-transfer process. Please send your comments or suggestions to

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Reston, Virginia 22092

Ground water is present in the rocks that form the Earth's crust and thus is in the domain of geology. Because the geology of the country is complex, the occurrence of ground water, in detail, is extremely complex. This complexity makes it difficult for many people to develop an understanding of ground-water occurrence and availability and has resulted in problems of ground-water depletion and ground-water pollution whose correction will be both difficult and expensive. Fortunately, such problems are not yet widespread and can, with intelligent application of existing ground-water knowledge, be avoided in most other areas. However, to realize this goal, those engaged in water-resources development and management and the general public need to become better informed on the Nation's ground-water resources. The purpose of this report is to help meet this need.

Ralph C. Heath

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DEFINITION OF TERMS

The following water-resources terms are italicized when first used in this report.

Acre-foot.—The volume of water that will cover an area of 1 acre to a depth of 1 foot.

Alluvium.—Unconsolidated gravel, sand, silt, or clay deposited by streams or other moving water.

Aquifer.—Water-bearing geologic material that will yield usable quantities of water to wells or springs.

Bedrock.—Consolidated (solid) rock, such as conglomerate, sandstone, or shale, that underlies soil or other unconsolidated surficial materials.

Confined aquifer.—An aquifer bounded above and below by confining layers. The water level in a well completed in the aquifer is above the top of the water-yielding materials.

Confining layer.—A layer of relatively impermeable geologic material that hampers the vertical movement of water into or out of an aquifer.

Discharge.—The outflow of water from an aquifer or other source.

Hydraulic conductivity.—A measure of the ability of a unit area of aquifer material to transmit water.

Phreatophytes.—Plants that obtain their water directly from the water table.

Porosity.—A measure of the void space present in geologic materials.

Potentiometric surface.—An imaginary surface representing the level at which water stands in wells.

Recharge.—The inflow of water to an aquifer.

Specific retention.—A measure of the volume of water that will not drain from the pore space of an aquifer under the effect of gravity.

Specific yield.—A measure of the volume of water that will drain from the pore space of an aquifer owing to the effect of gravity.

Storage coefficient.—A measure of the volume of water released from an aquifer in response to a decline in water level in the aquifer.

Transmissivity.—A measure of the ability of an aquifer to transmit water.

Water table.—The top of a water-table aquifer.

Water-table aquifer.—A permeable geologic unit that is not full of water; the water level in wells is below the top of the water-yielding materials.

Alluvial and Bedrock Aquifers of the Denver Basin—Eastern Colorado's Dual Ground-Water Resource

By S.G. Robson

Abstract

Large volumes of ground water are contained in alluvial and bedrock aquifers in the semiarid Denver basin of eastern Colorado. The bedrock aquifer, for example, contains 1.2 times as much water as Lake Erie of the Great Lakes, yet it supplies only about 9 percent of the ground water used in the basin. Although this seems to indicate underutilization of this valuable water supply, this is not necessarily the case, for many factors other than the volume of water in the aquifer affect the use of the aquifer. Such factors as climatic conditions, precipitation runoff, geology and water-yielding character of the aquifers, water-level conditions, volume of recharge and discharge, legal and economic constraints, and water-quality conditions can ultimately affect the decision to use ground water. Knowledge of the function and interaction of the various parts of this hydrologic system is important to the proper management and use of the ground-water resources of the region.

The semiarid climatic conditions on the Colorado plains produce flash floods of short duration and large peak-flow rates. However, snowmelt runoff from the Rocky Mountains produces the largest volumes of water and is typically of longer duration with smaller peak-flow rates. The alluvial aquifer is recharged easily from both types of runoff and readily stores and transmits the water because it consists of relatively thin deposits of gravel, sand, and clay located in the valleys of principal streams. The bedrock aquifer is recharged less easily because of its greater thickness (as much as 3,000 feet) and prevalent layers of shale which retard the downward movement of water in the formations.

Although the bedrock aquifer contains more than 50 times as much water in storage as the alluvial aquifer, it does not store and transmit water as readily as the alluvial aquifer. For example, about 91 percent of the water pumped from wells is obtained from the alluvial aquifer, yet water-level declines generally have not exceeded 40 feet. By contrast, only 9 percent of the water pumped from wells is obtained from the bedrock aquifer, yet water-level declines in this aquifer have exceeded 500 feet in some areas.

Depth to water in the alluvial aquifer generally is less than 40 feet, while depth to water in the bedrock aquifer may exceed 1,000 feet in some areas. Cost of pumping water to the surface and cost of maintaining existing supplies in areas of rapidly declining water levels in the bedrock aquifer affect water use. Water use is also affected by the generally poorer quality water found in the alluvial aquifer and, to a lesser extent, by the greater susceptibility of the alluvial aquifer to pollution from surface sources.

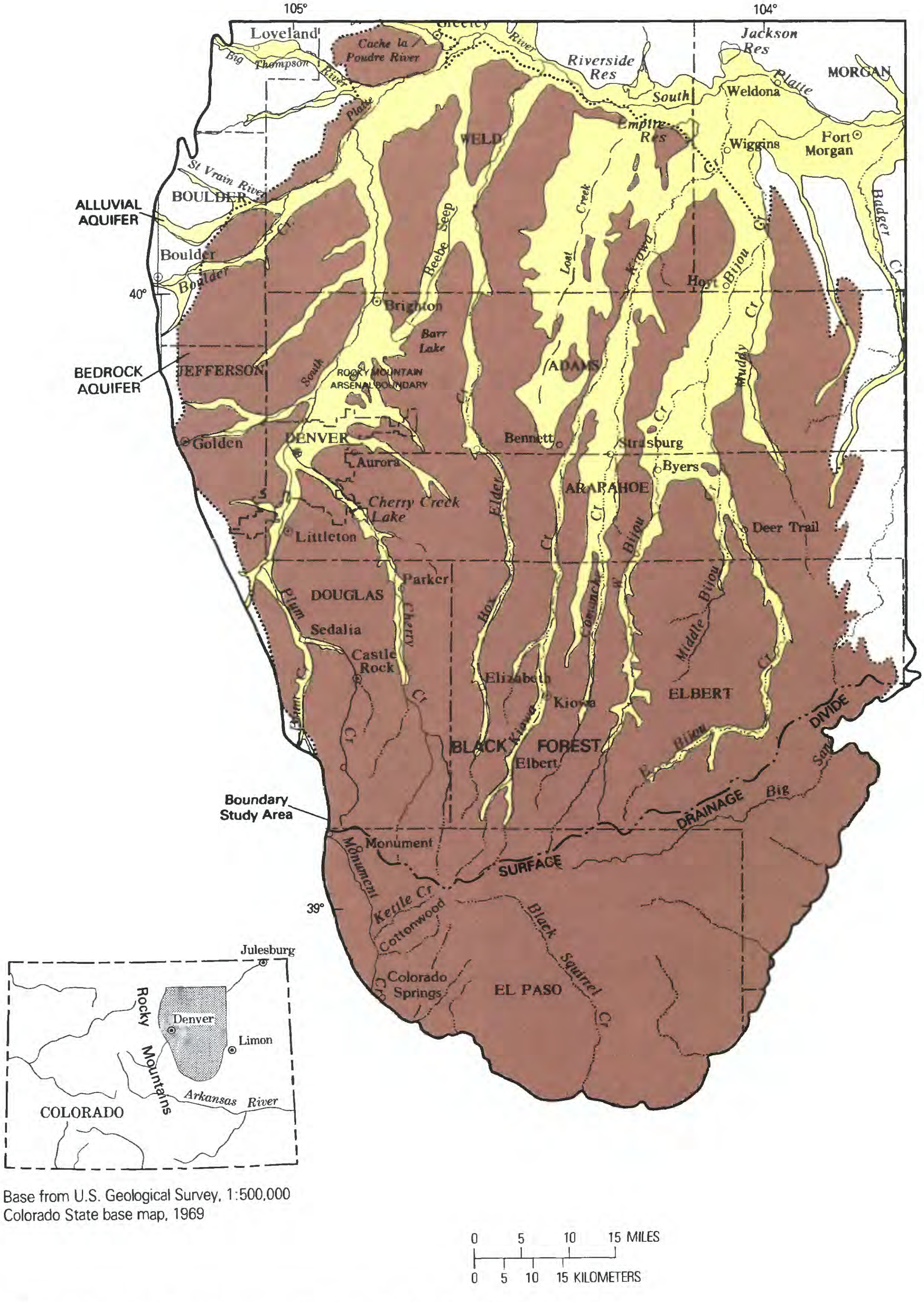
Because of these factors, the alluvial aquifer is used primarily as a source of irrigation supply, which is the largest water use in the area. The bedrock aquifer is used primarily as a source of domestic or municipal supply, which is the smaller of the two principal uses, even though the bedrock aquifer contains 50 times more stored ground water than the alluvial aquifer.

Manuscript approved for publication December 10, 1985.

INTRODUCTION

Eastern Colorado is a land of surprising contrast. On one hand, it is a region of semiarid climate in which water is in short supply and all available sources seemingly are heavily used and regulated. On the other hand, the Denver basin, a 6,700-square-mile area between Greeley and Colorado Springs, contains more water in underground geologic formations than is contained in Lake Erie. Most of this huge volume of water is contained in a thick *bedrock aquifer* (fig. 1) consisting of water-laden conglomerate, sandstone, and shale. This aquifer underlies the entire basin, contains 97 percent of the stored ground water, yet supplies only 9 percent of the water pumped from wells. An alluvial aquifer consisting of water-laden gravel, sand, and clay is present along the principal streams crossing the Denver basin (fig. 1). This aquifer, by contrast, is present in only 28 percent of the basin area, contains only 3 percent of the stored ground water, yet supplies 91 percent of the water pumped from wells.

Although these facts seem to indicate inconsistent or inappropriate use of these valuable water supplies, this is not necessarily the case, for many factors other than the volume of water in storage affect the use of aquifers. Such factors as climatic conditions, precipitation runoff, geology of the aquifer materials, water-yielding characteristics of the materials, water-level conditions, volume of water moving through the area, legal constraints, and



Base from U.S. Geological Survey, 1:500,000 Colorado State base map, 1969

Figure 1. Location of report area and extent of alluvial and bedrock aquifers.

chemical quality of the water can affect the cost of obtaining a ground-water supply. This cost, in turn, affects the type, method, and extent of water use from each aquifer.

Purpose

It is important that decisions about management and use of a complex hydrologic system such as the alluvial and bedrock aquifers be based on an informed understanding of the system. These valuable, and in some cases nonrenewable, water resources can be properly and effectively used only if their potentials and limitations are well understood. This report attempts to meet this need through a nontechnical comparison of the important geologic, hydrologic, legal, and economic factors affecting the operation and use of these aquifers.

Funding for this report was provided through the Information Transfer Program of the U.S. Geological Survey. The objective of this program is to enable publication of documents of special public interest that could not otherwise be prepared as part of ongoing studies.

Scope

The 8,000-square-mile study area described in this report includes the part of the Colorado plains located approximately south of Greeley (fig. 1) and west of Limon in which streams are tributary to the South Platte River. The Denver ground-water basin underlies most of this area (6,700 square miles), although the southern 20 percent of the Denver basin extends into the Arkansas River drainage. The bedrock aquifer in this part of the Denver basin is included in the study area; alluvial aquifers tributary to the Arkansas River are not considered.

Features of the Area

Land-surface altitudes in the study area range from about 4,300 feet near Fort Morgan to about 7,500 feet on the surface-drainage divide in El Paso County. Surface drainage generally is north or east to the South Platte River, which flows north and east out of the report area. The Rocky Mountains form the western boundary of the area (fig. 2) and contain the headwaters of the South Platte River and its eastward-flowing tributaries. The land overlying the alluvial aquifer generally is relatively flat *alluvium* and commonly is devoted to production of corn, hay, barley, sorghum, beans, and sugar beets, with irrigation water supplied from the alluvial aquifer or from surface diversions from the South Platte River. Highland areas between stream valleys consist of rolling hills devoted to livestock grazing or production of nonirrigated wheat and other grains. In the south-central part of the report area, the stream valleys narrow, the alluvial aquifer becomes thin and discontinuous, and topography steepens. Here, grazing land gives way to pine-forested hillsides, rocky outcrops, and cliffs (fig. 3).

Figure 2. Plains area of eastern Colorado bounded on the west by the Rocky Mountains.

Figure 3. Southern part of the Denver basin. The rolling topography of the plains becomes increasingly mountainous to the south. Here, Cherry Creek is entrenched in Dawson Arkose southeast of Castle Rock.

Land use in the area includes 380,000 acres of irrigated farmland located primarily along the valleys of the South Platte River and its principal tributaries. This land yielded crops worth about $100 million in 1981. Irrigation water is supplied from surface-water sources or from wells. The Denver metropolitan area has a population of about 1.5 million (1980) and is located along the west-central part of the basin. 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. The growth in housing and population has created an increasing demand for water. Part of this demand has been met by pumping from wells.

CLIMATIC CONDITIONS

Precipitation and Temperature

The Rocky Mountains have an important effect on the climate of the area. Prevailing westerly winds carry moisture-laden storms from the Pacific Ocean into western Colorado. As the storm systems gain altitude crossing the Rocky Mountains, the air cools and drops its moisture as rain and snow on the western slope and the Continental Divide. The eastern slope and the plains receive less moisture from these storms (fig. 4). As a result, the study area has a semiarid continental climate with only 11 to 18 inches of average annual precipitation (fig. 5) and 50 to 70 inches of average annual potential evaporation. 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 feet, receives 11 inches (32 inches of snowfall) of average annual precipitation, Denver, at an altitude of 5,280 feet, receives 14 inches (56 inches of snowfall) (fig. 6), and Monument, at an altitude of 6,961 feet, receives 18 inches (83 inches of snowfall). Daytime relative humidity usually is only 20 to 30 percent and sometimes is much less. Clear skies and sunshine are common.

Wide variations in weather are characteristic of the area. Record high temperatures range from 100 to 107 °F and record low temperatures range from −30 to −45 °F. Downslope (chinook) winds exceeding 50 miles per hour are frequent during winter months and have exceeded 135 miles per hour along the mountain front. When such relatively warm winds displace cold continental air on the plains, temperatures may rise 50 °F in a few hours. Less than 7 inches of annual precipitation has been recorded in most of the report area during dry years, yet violent thunderstorms, common from late spring to late summer, have produced as much as 24 inches of precipitation in local areas in a few hours (fig. 5).

Figure 4. Rocky Mountains northwest of Denver. The mountains intercept moisture in eastward-moving storms, creating a semiarid climate on the plains to the east.

Precipitation Runoff

Precipitation runoff is an important source of water both for direct use (as an irrigation or municipal supply) and as *recharge* to the aquifers. Flash floods and snowmelt runoff are the two principal forms of runoff.

Flash Floods

Locally intense rainfall has produced floods of tragic proportions and unusual extent. For example, in May 1878 a flash flood in Kiowa Creek basin washed out a wooden railroad bridge that spanned the normally dry creekbed near Bennett. A passing freight train plunged into the floodwaters and was swept away along with the engineer, fireman, and brakeman. A few days after recovery of the bodies, a search for the missing locomotive was begun along the creekbed. Steel rods were driven into the sand and pits were dug, but the search was abandoned when it was estimated that the sand in the creekbed was as much as 50 feet deep. The locomotive was never recovered.

Intensive rainstorms in June 1965 produced as much as 12 inches of precipitation on the upper drainage area of Bijou Creek. The resulting flash flood caused extensive damage to the towns of Deer Trail and Byers and to farms and ranches in low-lying areas. It is estimated that a peak discharge of 274,000 cubic feet per second occurred from the 302-square-mile drainage area of East Bijou Creek. Farther downstream, a peak discharge of 466,000 cubic feet per second was estimated near Wiggins (fig. 7). This rate of flow is comparable to that of the Mississippi River at Vicksburg, Miss., during late summer (fig. 8) and is an indication of the size of flow that can occur in the normally dry streambeds on the Colorado plains.

By far the most disastrous flood in the area's history occurred in the Big Thompson River during the night of July 31, 1976. At least 139 people were killed by rapidly rising floodwaters that reached a peak discharge of 31,200 cubic feet per second down the steep mountain canyon west of Loveland. The canyon floor is only 80 to 100 feet wide in some places. The flood was caused by as much as 12 inches of precipitation falling on only about 70 square miles of the upper end of the 304-square-mile drainage area. Water velocities of 15 to 20 miles per hour destroyed homes, roads, and bridges and moved boulders as large as 12×12×23 feet and weighing an estimated 275 tons. At least 190 cars were swept away, and many were

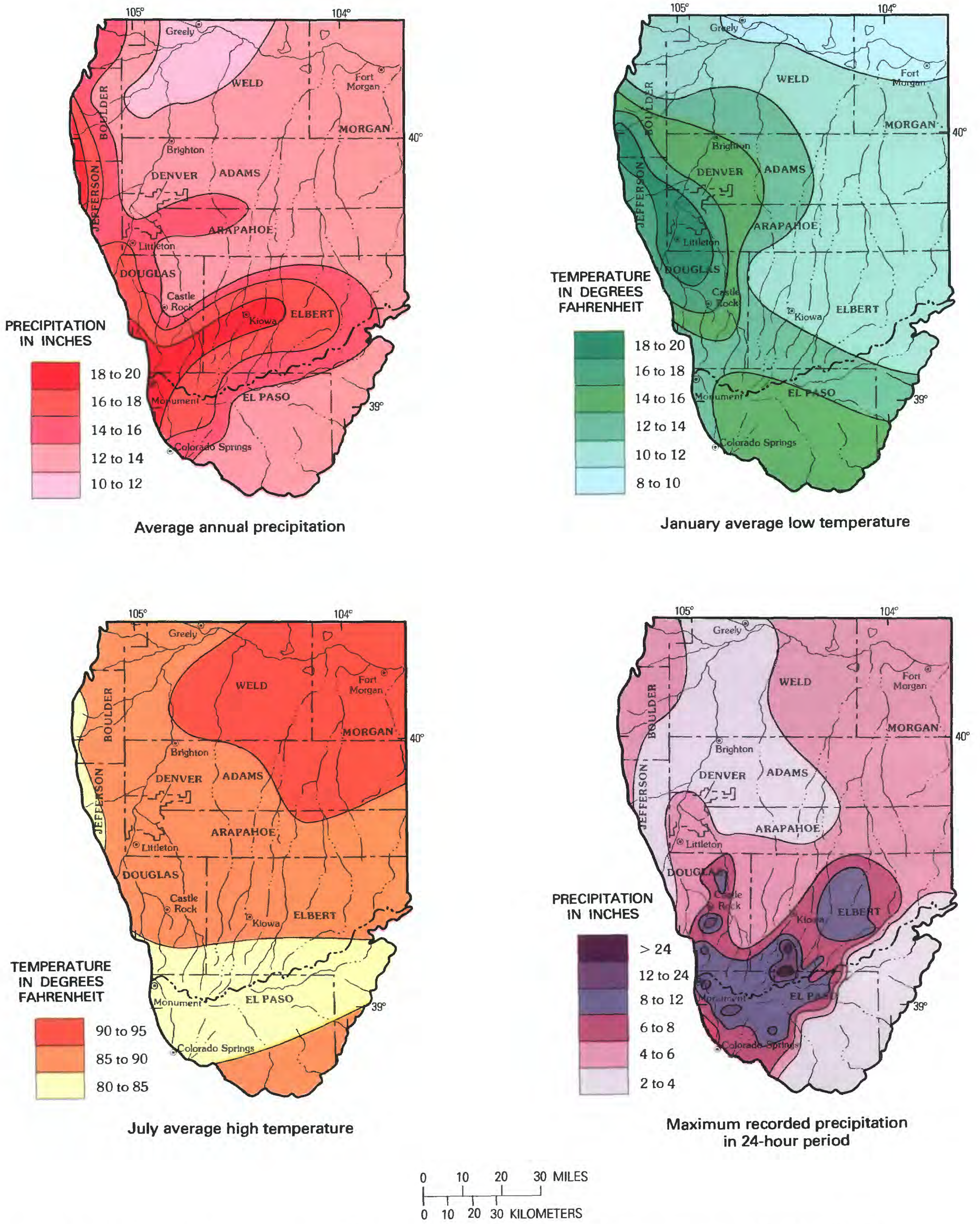


Figure 5. Precipitation and temperature distributions in the study area. Modified from Hansen and others (1978).

Figure 6. Snow accumulation in Denver, December 25, 1982.

Figure 7. Channel of Bijou Creek near Wiggins. The broad, sandy channel normally is dry but is subject to flash floods.

Figure 8. Mississippi River at Vicksburg, Miss. The river is about 70 feet deep and 0.5 mile wide at this location.

later found buried in sediment or flattened and wrapped around boulders and trees (fig. 9) in the severely eroded streambed.

Although large flash floods are uncommon and dramatic, lesser magnitude floods are more common and some exhibit the unusual characteristic of never leaving the drainage area in which they were formed. This occurs primarily in the normally dry stream channels draining the southeastern part of the area. Intense precipitation commonly causes small- to intermediate-magnitude flash floods in the upper reaches of these drainages. As the water moves downstream, part of the flow percolates into the dry, sandy stream channels; in some cases, the entire floodflow can be depleted by this percolation. The shape of the channel of Kiowa Creek is affected by this loss of flow. At Bennett, the active channel is about 400 feet wide as a result of the large floodflows that periodically pass this location (fig. 10). About 45 miles downstream, near Wiggins, the active channel of Kiowa Creek is only a few feet wide or is nonexistent (fig. 11) because of the lack of floodflows past this location.

Figure 9. Flood damage in Big Thompson Canyon. This car is one of many swept away and destroyed by the rapidly moving floodwater. Photograph from U.S. Geological Survey and National Oceanic and Atmospheric Administration (1979).

Figure 10. Channel of Kiowa Creek at Bennett. At flood stage, water extends onto the low tree-lined terraces on either side of this low-flow channel. Cattle in midstream indicate scale.

Snowmelt Runoff

Unregulated snowmelt runoff in mountain streams typically has a smaller peak-flow rate than comparable plains streams but has a sustained period of large flow from April or May through July, and thus transports much more water than do the plains streams.

The flash floods common to the streams draining the plains may produce large instantaneous flow but are of such short duration that the total volume of water transported is comparatively small. The flood of August 10, 1979, on Goose Creek near Hoyt is typical. A peak flow of 400 cubic feet per second occurred at 12:20 a.m. (fig. 12), but the flood had passed by 2:00 p.m. that afternoon and the stream had transported a total of only 86 *acre-feet* of water. This flood, and a smaller flash flood on August 18, were the only *discharges* from Goose Creek for the year. A drainage area of similar size near the Continental Divide about 60 miles west of Greeley is drained by Joe Wright Creek. Melting of the mountain snowpack in 1979 (fig. 13) produced a peak daily flow of only about 60 cubic feet per second, but large flows persisted for 4 months (fig. 12) and yielded about 4,550 acre-feet of water. In 1979, snowmelt runoff in this mountain stream yielded about 1,500 acre feet of water per square mile of drainage area; only 23 acre feet of water per square mile of drainage was produced in the plains stream.

Hydrographs of unregulated mountain streams generally have a characteristic bell-shaped distribution for the period of large flow, as indicated by the dashed line on the hydrograph for Joe Wright Creek (fig. 12). Numerous irrigation and municipal diversions of surface water and large-scale storage and release of water in reservoirs have a significant effect on the large-flow part of the hydrographs of all major mountain streams entering the study area. The cumulative effect of this regulation is shown by the large-flow part of the hydrograph for the South Platte River near Weldona, Colo. The hydrograph (fig. 12) for water year 1979 is typical of flow at this site and does not have a readily identifiable bell-shaped distribution because of the effects of upstream regulation. If no upstream regulation existed, the average hydrograph for this station would be expected to have a general distribution similar to that indicated by the dashed line. The flow past the Weldona gage during the 1979 water year was 681,000 acre-feet, 64 percent above the normal yearly flow of 414,000 acre-feet. However, without upstream regulation a normal flow of about 1,200,000 acre-feet might have occurred.

Recharge from Runoff

Both flash floods and snowmelt runoff are important sources of recharge to the alluvial aquifer and also supply some recharge to the bedrock aquifer. The alluvial aquifer along stream valleys in the plains generally receives water directly from percolation of surface flow. In the

Figure 11. Channel of Kiowa Creek near Wiggins. Flow in Kiowa Creek passing Bennett rarely extends as far as this brush-choked reach about 45 miles downstream. Nearby, the channel has been obscured by agricultural activities.

South Platte River valley, high ground-water levels near the river commonly prevent such direct recharge from the river. However, surface flow diverted into an extensive network of irrigation canals and lakes (fig. 14) and into irrigated fields readily percolates into the soil and supplies large volumes of water to the alluvial aquifer. Surface flow in streams is a less important source of recharge to the bedrock aquifer, because surface water generally is not diverted onto bedrock formations where recharge might occur.

GEOLOGIC HISTORY

The extent and composition of the bedrock aquifer differ greatly from the extent and composition of the alluvial aquifer because of differences in the geologic process that led to the formation of each aquifer. The bedrock aquifer was formed by accumulation of layers of gravel, sand, and clay along stream channels, in river deltas and swamps, and along the shoreline of an ancient inland sea. The successive accumulation of layer upon layer during tens of millions of years ultimately produced a sequence of sediments several thousand feet thick that extended over most of eastern Colorado. The Rocky Mountains began forming during the latter part of this period. As the mountains rose, older layers of sediment were tilted and deformed along the mountain front, and erosion of the uplifted areas supplied new sediment to the area east of the mountain front. Faults were formed as rocks under the mountains broke and slid past the more stationary rocks under the plains. Vertical movement on these faults exceeded 20,000 feet, and today, similar rocks are found at depths of 12,000 feet under Denver and near the crest of the Continental Divide 9,000 feet above Denver.

Most of the sediments that would form the bedrock aquifer were deeply buried for long periods of time during which these formerly soft sandy materials were altered into hard rock such as the conglomerate, sandstone, and shale commonly found today in the bedrock formations. These rocks (in ascending order) are known as the Fox Hills Sandstone, the Laramie Formation, the Arapahoe Formation, the Denver Formation, and the Dawson Arkose (fig. 15). Changes in climate and in the flow of the ancient South Platte River caused an increase in the rate of erosion, which eventually removed most of these rocks from eastern Colorado. The Denver basin is one of the few areas in Colorado where they are still present. Because of this geologic history, the bedrock formations extend throughout a 6,700-square-mile area near Denver and yield water to wells at depths of as much as 3,200 feet below land surface.

The alluvial aquifer, by contrast, consists of relatively young geologic materials deposited by the South Platte

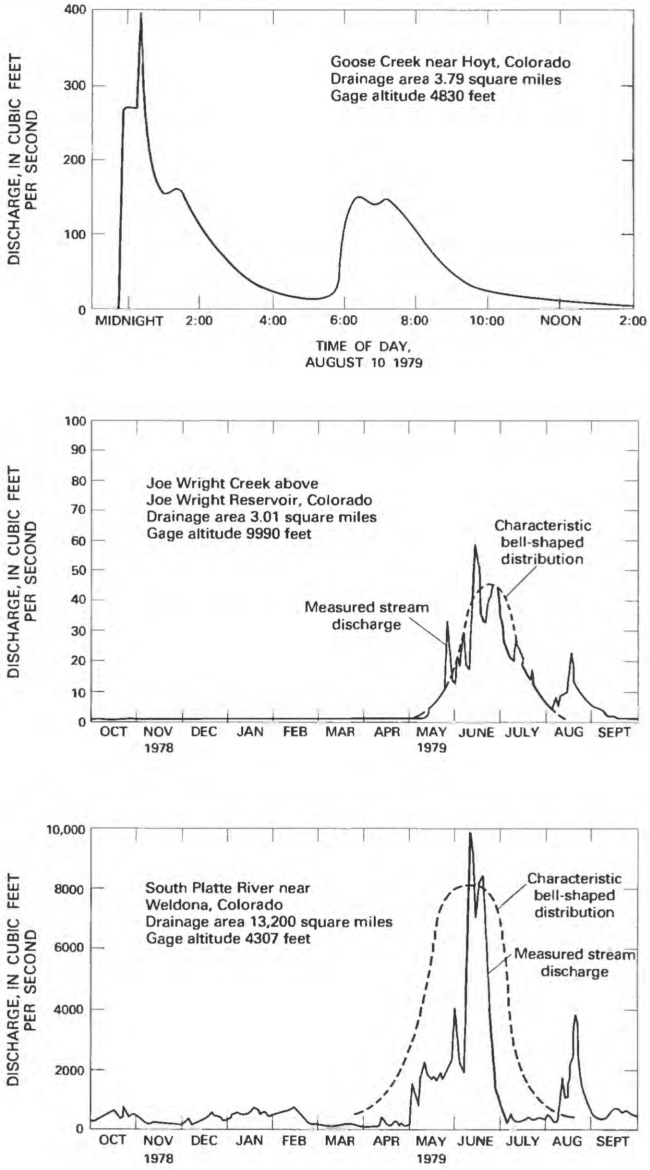


Figure 12. Hydrographs of surface-water flow in selected streams.

River and its tributaries during the last 2 million years. Streams originally cut broad valleys into the bedrock formations and later partly filled these valleys with layers of gravel, sand, and clay (fig. 15). As a result, the alluvial aquifer in most places is only 1 to 5 miles wide and follows the course of present or ancient streams. The aquifer along Beebe Seep (fig. 1), for example, occupies an abandoned stream valley of the South Platte River. After the river deposited cobbles, gravel, and sand in the ancient valley, it changed its course, leaving these deposits in a valley drained by a stream that today is too small to have moved such coarse sediments. The alluvial aquifer generally begins near the headwaters of streams in southern

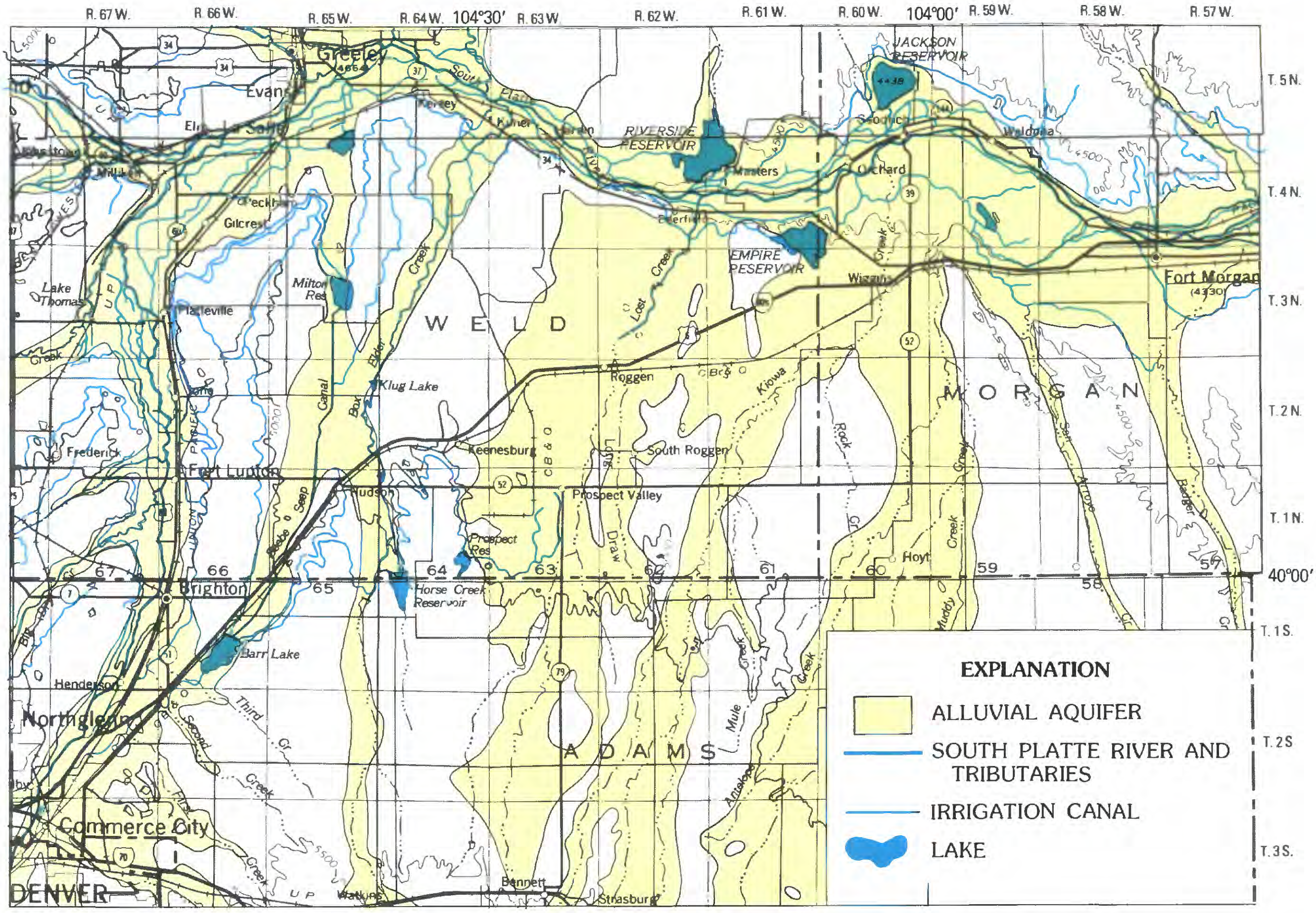
Figure 13. Snowmelt runoff in the Rocky Mountains of Colorado.

Douglas and Elbert Counties, or near the western mountain front, and becomes wider and thicker downstream.

COMPOSITION OF THE AQUIFERS

Sand and gravel form the principal water-yielding materials in the alluvial aquifer. However, a layer of cobbles and boulders, present near the bottom of the aquifer to the north of Barr Lake and in the upper reaches of the South Platte valley, yields large quantities of water to some wells. These water-yielding materials generally are interlayered with silty clay that does not yield water to wells. All of these materials are unconsolidated; that is, the grains of rock that make these sediments are not cemented together but are only pressed together by the weight of the overlying sediments.

Sandstone and conglomerate are the principal water-yielding material in the bedrock aquifer and constitute 30 to 60 percent (table 1) of the formations. Shale and similar rock, such as claystone and mudstone, constitute most of the remaining 40 to 70 percent of the bedrock formations, but they generally do not yield water to wells. The sandstone and conglomerate may occur as thick layers that extend over large areas, or the layers may be thinner, lens shaped, and of limited extent. The sandstone and conglomerate generally are moderately well consolidated, but scattered thin beds may have the consistency of a concrete sidewalk or be so soft that the rock can be crushed in the bare hand. Water-yielding rocks are interlayered with shale. Shale may occur as numerous layers a few inches thick scattered through the sandstone and conglomerate, or as a relatively continuous layer of shale 400 feet or more thick extending over most of the basin.



Base from U.S. Geological Survey, 1:500,000
Colorado State base map, 1969
Highways corrected to 1972

0 100 200 MILES
0 100 200 KILOMETERS

Figure 14. Network of irrigation canals and lakes along the South Platte River between Denver and Fort Morgan.

Table 1. Distribution of sandstone and shale in the bedrock formations

Formation	Percent sandstone (includes conglomerate)	Percent shale
Dawson Arkose	45	55
Denver Formation	30	70
Arapahoe Formation	40	60
Laramie Formation and Fox Hills Sandstone	60	40

THICKNESS OF WATER-YIELDING MATERIALS

The thickness of the alluvial aquifer ranges from less than 20 feet in the upstream reaches of the aquifer to more than 200 feet in the South Platte River valley near Wiggins (fig. 16). The troughlike shape of the buried bedrock channel that underlies the alluvial aquifer allows the thickness of the alluvium to change more quickly across the valley than along the valley. In some places, the buried sides of the bedrock channel are nearly vertical and thick alluvium is present near the margin of the aquifer; in most places, the aquifer gradually thins toward the margins.

Water-yielding materials in the bedrock aquifer extend throughout broad areas, and the thickness of the aquifer generally does not change markedly in short distances. Aquifer thickness increases from zero at the

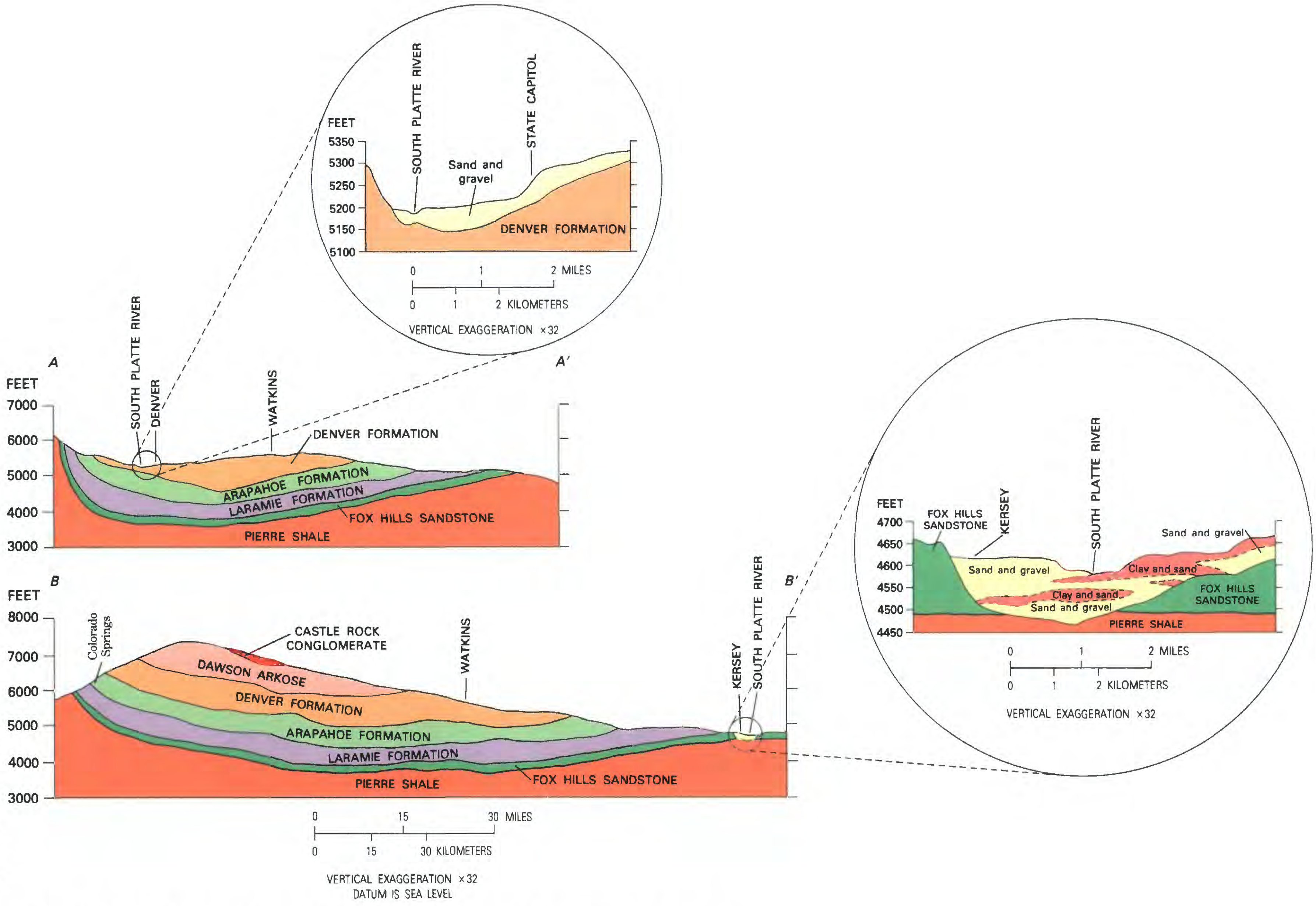
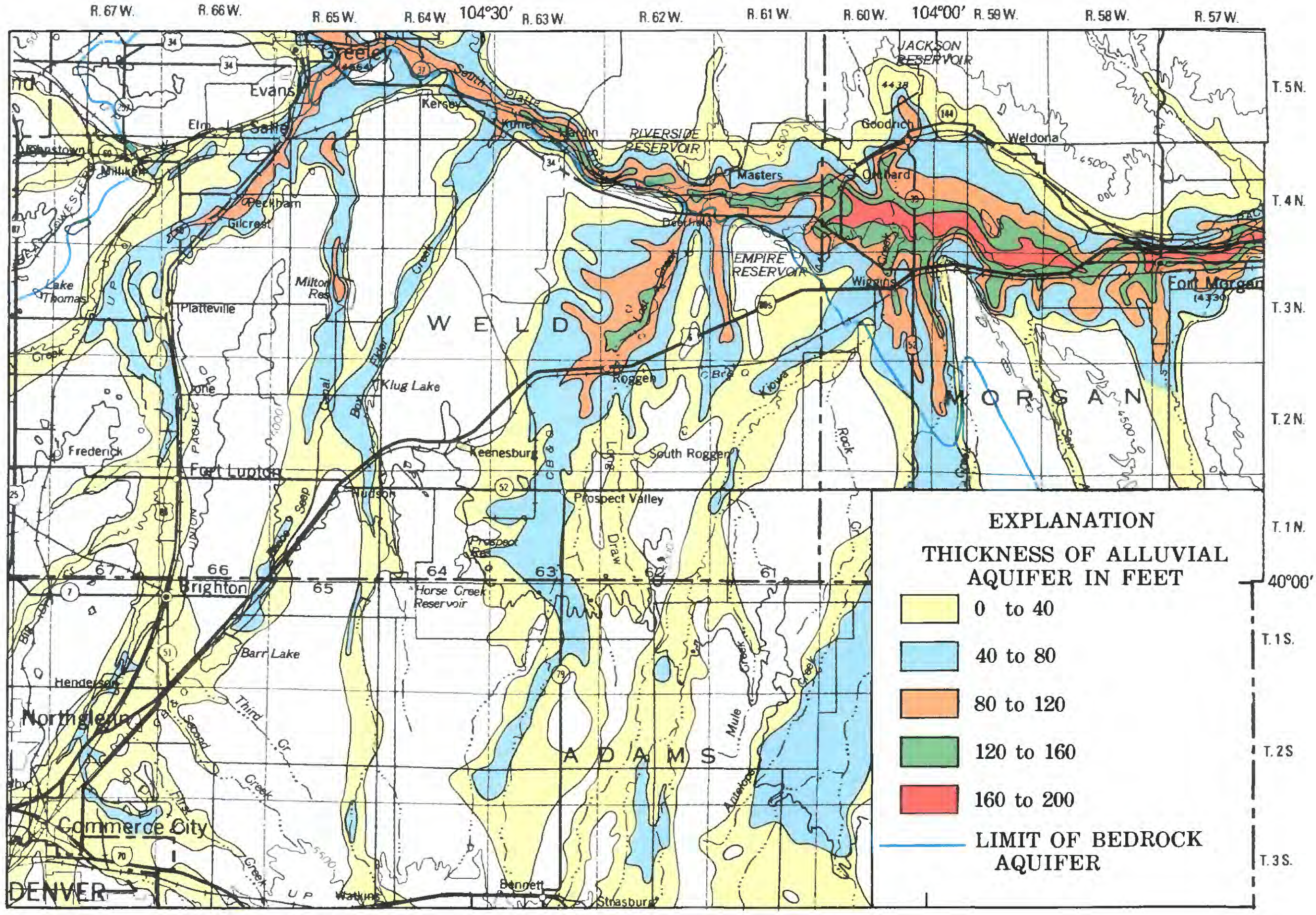


Figure 15. Geologic sections through the Denver basin (traces of sections located on fig. 17).



Base from U.S. Geological Survey, 1:500,000
Colorado State base map, 1969
Highways corrected to 1972

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Figure 16. Thickness of the alluvial aquifer.

margin of the bedrock aquifer to more than 3,000 feet in the area east of Monument (fig. 17). About 1,300 feet of this thickness consists of water-yielding sandstone and conglomerate; the remaining 1,700 feet consists of non-water-yielding shale.

WATER-YIELDING CHARACTER OF THE AQUIFERS

Porosity, Specific Yield, and Specific Retention

Ground water is contained in pore spaces between the adjacent grains of sediment that form the alluvial and bedrock aquifers. If the sediment grains are coarse, such as those of sand (fig. 18), relatively large pore spaces are present and water can move easily from one pore to another. Interconnected pore spaces allow water to move great distances, and sand and gravel formations readily yield water to wells. If the sediment grains are very fine, such as those of silt or clay (fig. 18), extremely small pore spaces are present and it is difficult for water to move from pore to pore. As a result, these sediments commonly form barriers to water movement, and they generally do not yield water to wells. Because grains of silt or clay are much smaller than those of sand, there are many more grains and intergranular pores in a given volume of silt or clay than in an equal volume of sand. The large number of pore spaces may compensate for the small size of the pores, and silt or clay may have a larger total pore volume than sand or gravel even though the silt or clay will not transmit water.

The measure of the volume of pore space in a material is *porosity*. If a sediment sample has a porosity

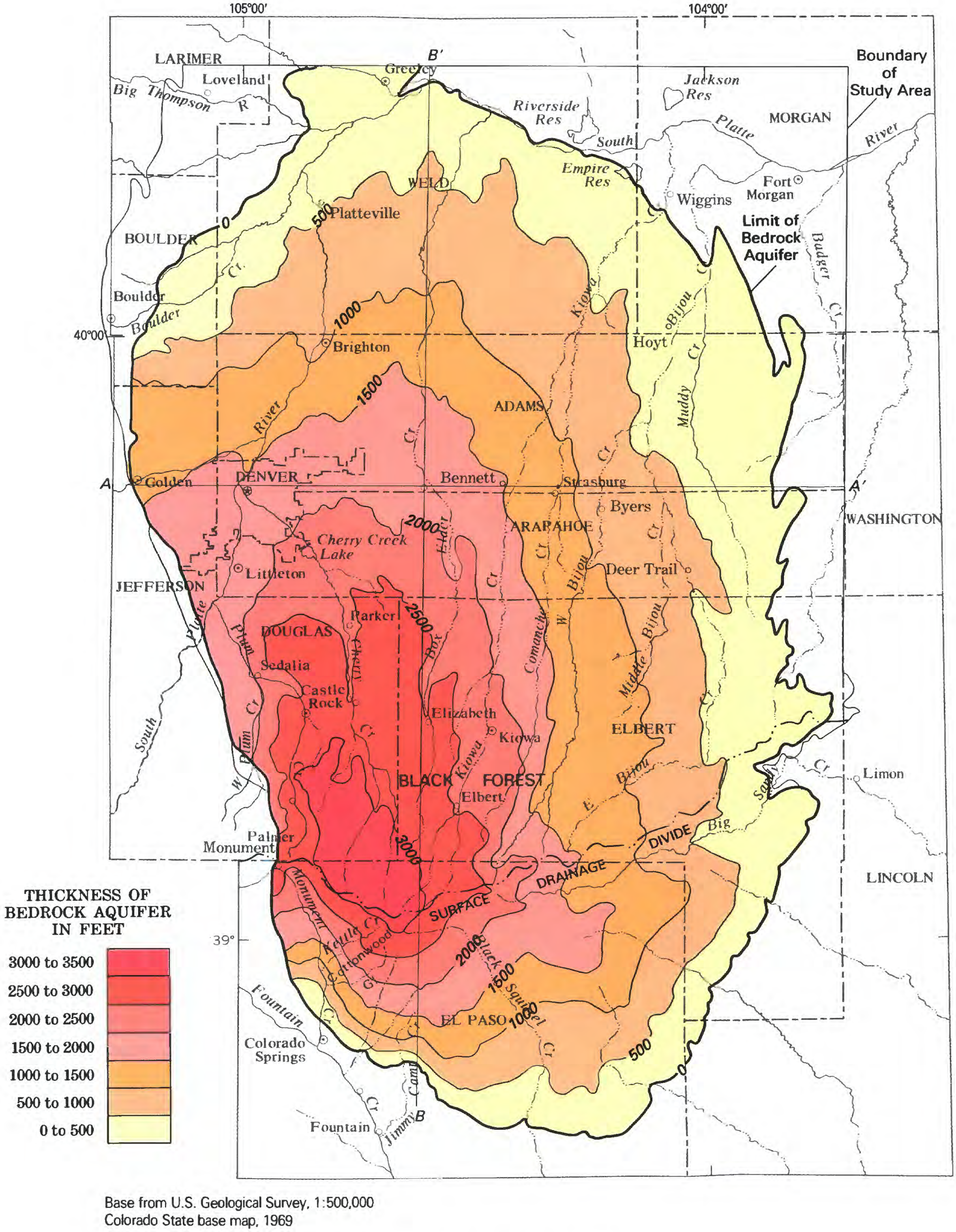


Figure 17. Thickness of the bedrock aquifer

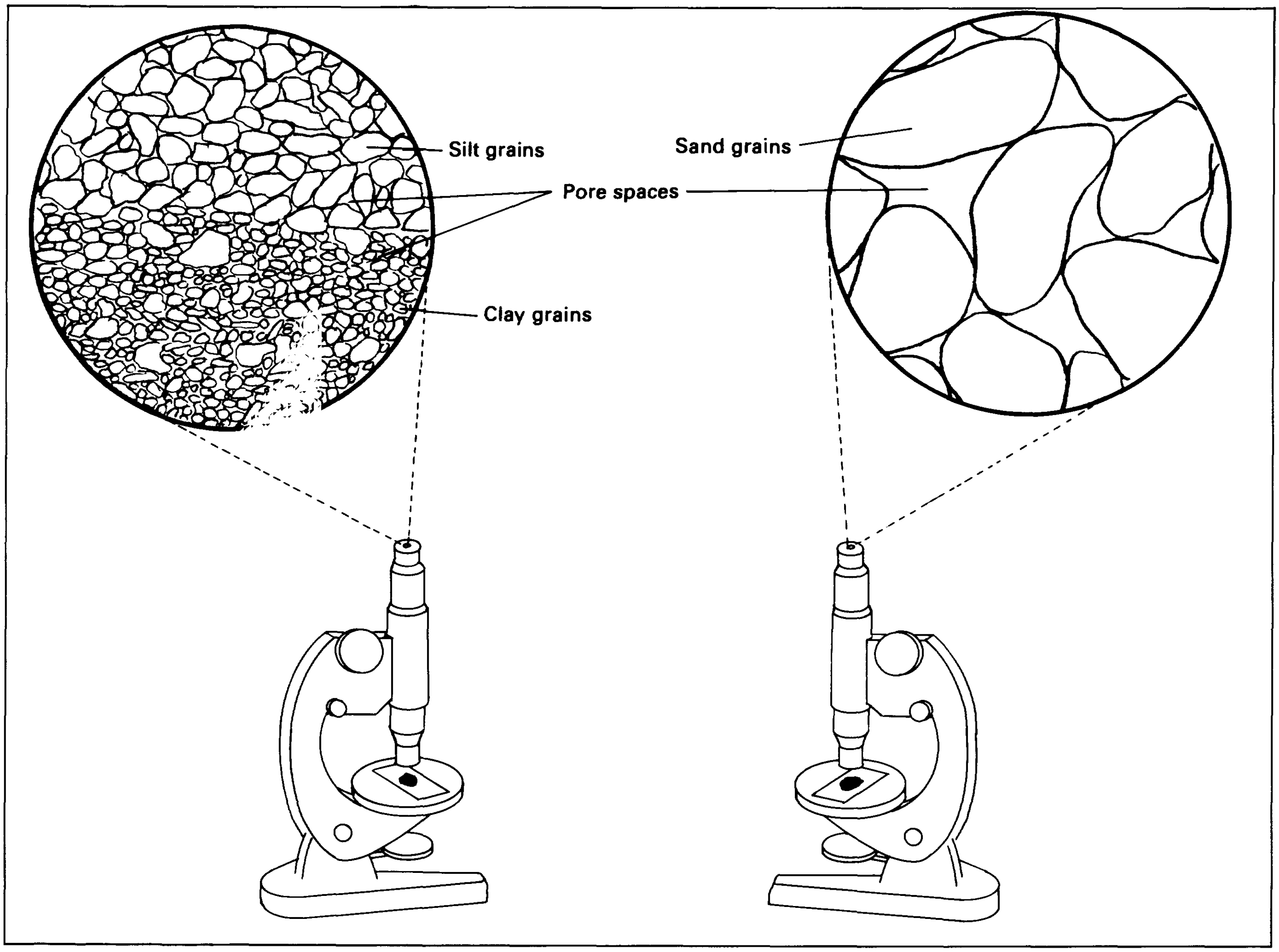


Figure 18. Diagram of sand, silt, and clay pore space.

of 20 percent, then 20 percent of the volume of the sample is intergranular pore space. Porosity of sand or gravel of the alluvial aquifer commonly ranges from 20 to 40 percent depending on the size and uniformity of sorting of the grains. Porosity of bedrock materials generally is less than that of comparable unconsolidated materials because pore space has been reduced by the geologic process that transformed the soft sediment into rock. Sandstone or conglomerate in the bedrock aquifer generally has a porosity of between 25 and 35 percent.

The volume of ground water stored in an aquifer is controlled by the volume of pore space in the sediments. However, the volume of water that can be withdrawn from an aquifer is much less than the total volume in storage because not all the water can be drained from the pore spaces. Some of the water adheres to the surfaces of the grains or is held in small pores by capillary forces. *Specific yield* is a measure of the volume of water that gravity will drain from an aquifer, and *specific retention* is a measure of the volume of water that remains trapped in the aquifer (fig. 19). For example, a cubic foot of aquifer material may have a porosity of 40 percent, and if all the pore space is filled with water, it will contain 0.4 cubic foot of water. If the specific yield of the sample is 30 percent, then 0.3 cubic foot of this water will drain out of the sample. The remaining 0.1 cubic foot of water (10 percent specific retention) will not drain from the sample and remains

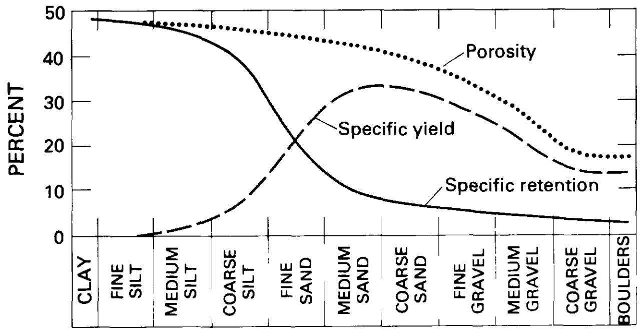


Figure 19. Relation of porosity to specific yield and specific retention. Modified from Todd (1967).

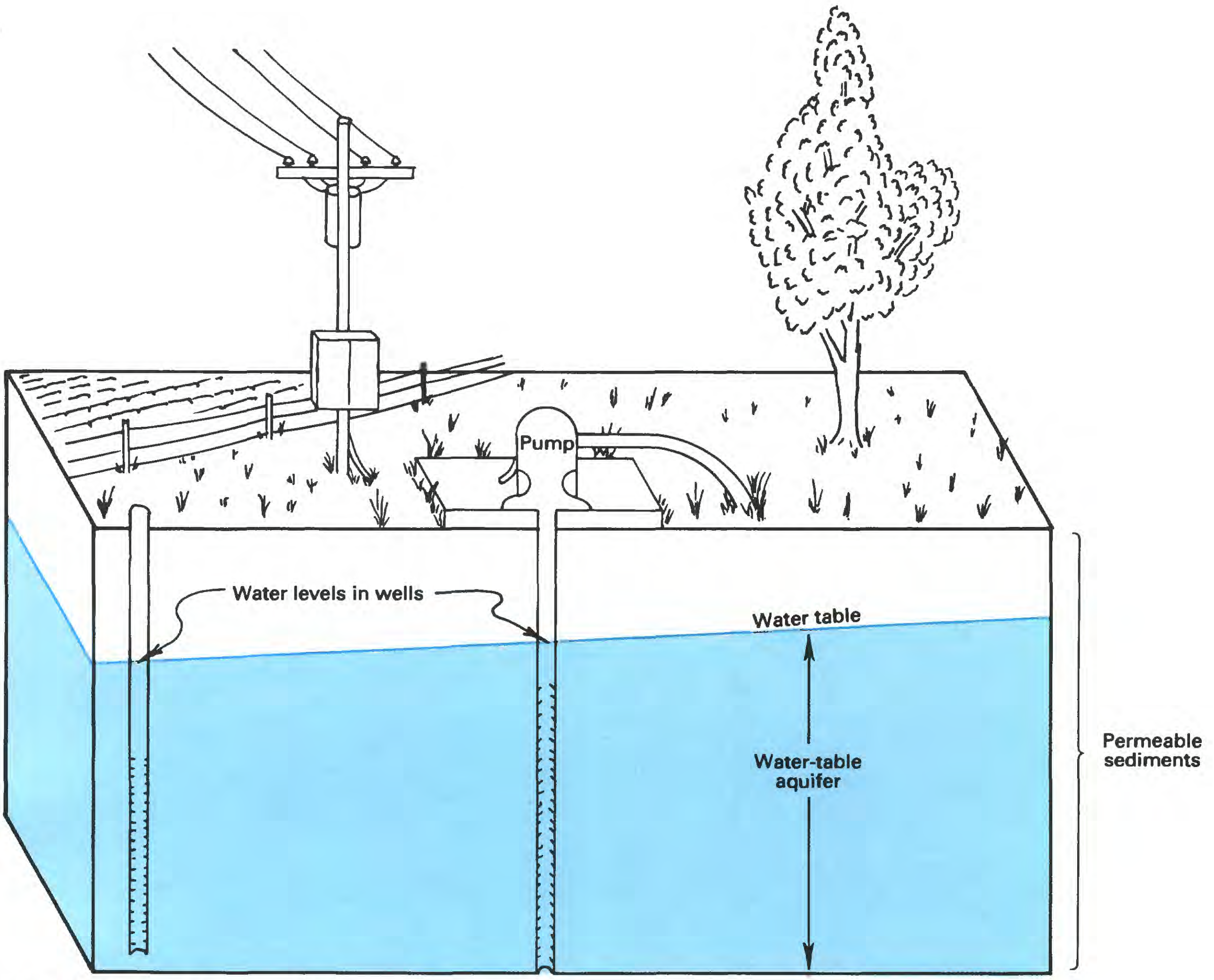


Figure 20. Diagram of a water-table aquifer.

trapped in the pores. The volume of water that drains from the sample plus the volume of water retained in the sample will equal the total volume of water originally contained in the sample; that is, specific yield plus specific retention equals porosity. The specific yield of the alluvial aquifer is about 20 percent, and the specific yield of the water-yielding materials in the bedrock aquifer ranges from about 14 to 20 percent.

This process of withdrawing water from storage in an aquifer is based on physically draining the water-filled pores of the sediments and applies only to *water-table aquifers.* A water-table aquifer is present where the standing water level in wells is located within the permeable sediments (fig. 20). The surface defined by the water levels in wells is called a *water table,* and it forms the top of the water-table aquifer. The alluvial aquifer is the principal water-table aquifer in the area, although water tables are present in some of the shallow parts of the bedrock aquifer. When the water table declines, as it does in response to the pumping of wells, for example, water drains from the sediment pores that are above the declining water table. Water is removed from storage in a water-table aquifer by this process.

Storage Coefficient

A water-table aquifer is present where the standing water level in wells is located below the top of the permeable materials. A *confined aquifer* is present where the standing water level in wells is located above the top of the permeable materials (fig. 21). A bed of clay or shale commonly forms a *confining layer* that restricts vertical movement of water. Confining layers are present at the top and bottom of confined aquifers. For example, near Aurora (fig. 1) the top of the Laramie-Fox Hills sandstones is at a depth of 1,500 feet, but the depth to water in wells completed in this sandstone is only about 250 feet. Southwest of Denver the pressure in this formation is large

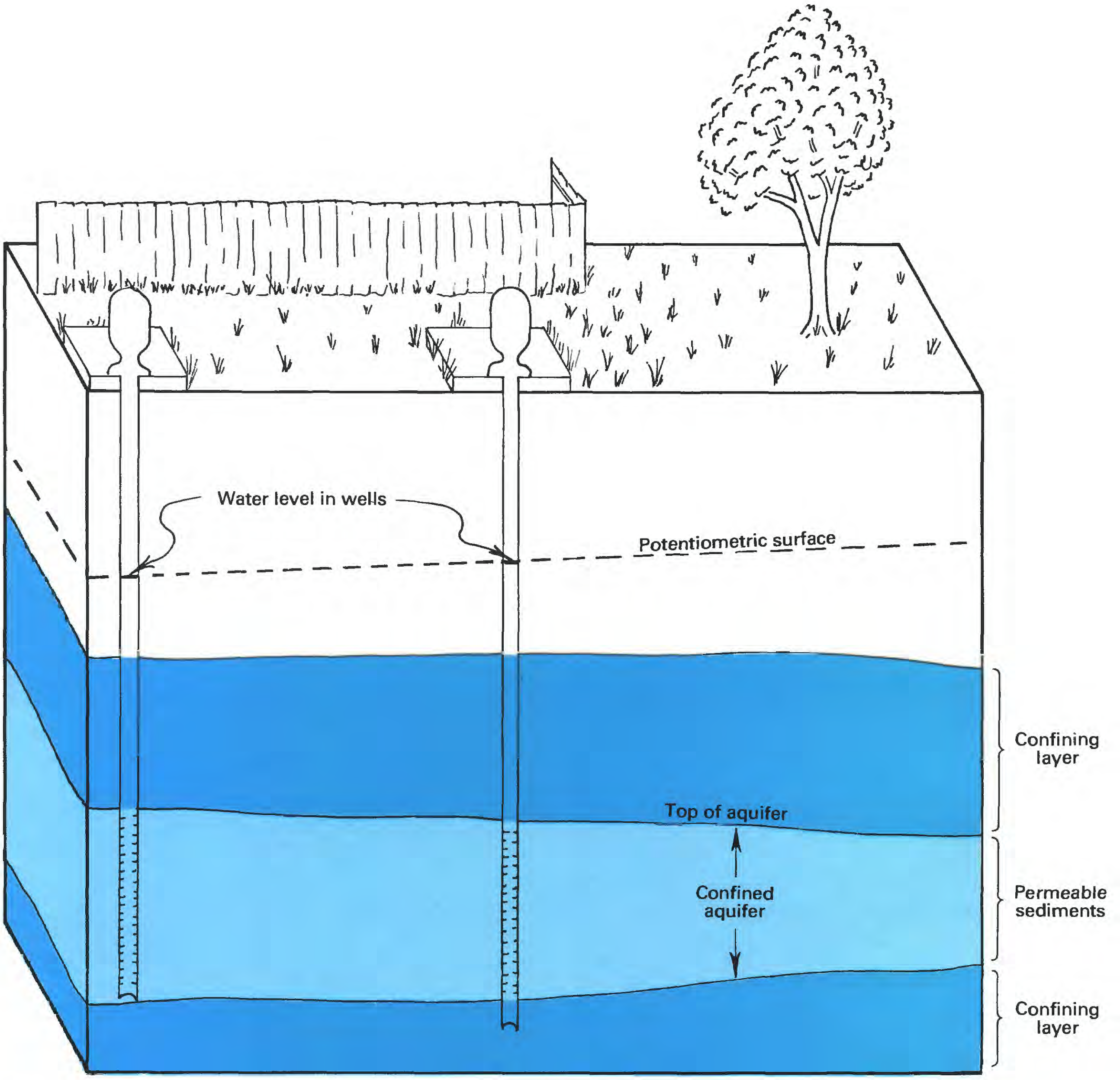


Figure 21. Diagram of a confined aquifer.

enough for the water level in wells to be above land surface (fig. 22). The water levels in both areas are above the top of the water-yielding sandstone, making this a confined aquifer. The theoretical surface defined by water levels in wells completed in a confined aquifer is called a *potentiometric surface* (fig. 21). The alluvial aquifer and the shallow parts of the bedrock aquifer contain the principal water-table aquifers in the area. In the deep parts of the bedrock aquifer, layers of shale commonly form confining layers and the water-yielding sandstone and conglomerate form confined aquifers.

A second process for withdrawing water from storage in an aquifer is associated with the elastic properties of water and sediments in a confined aquifer. In spite of their outward appearance, both water and rock can be compressed slightly when subjected to sufficient pressure. Conversely, water and rock that have been under pressure will expand slightly when the pressure is reduced. Water pressures in a confined aquifer may be reduced by pumping wells in the aquifer. The reduced pressure results in a small expansion of the remaining water in the aquifer and also in a small reduction in the porosity of the aquifer materials because of increased overburden load placed on these materials by the reduced water pressure. Both changes supply water that may be removed from storage in the confined aquifer without draining water from the

Figure 22. Well completed in a confined aquifer. The water level in this well is above land surface. If the well casing were not capped, the well would flow (an artesian well). The potentiometric surface at this well stands at the height of the liquid in the plastic tube.

pore spaces of the sediments. This phenomenon is somewhat similar to what occurs when a nozzle on a garden hose is turned on after the spigot at the house has been turned off: water briefly flows from the hose, yet the hose remains full of water.

The measure of the total volume of water that can be withdrawn from storage in an aquifer is the sum of these two processes and is called *storage coefficient*. In a water-table aquifer, the effects of the elastic properties of the water and sediments are insignificant compared with the magnitude of specific yield, and storage coefficient is approximately equal to specific yield. In a confined aquifer, no drainage of pore spaces takes place (hence specific yield is not involved), and storage coefficient is determined by the elastic properties of the water and sediments. The storage coefficients of water-table and confined aquifers thus are markedly different, and this difference is of critical importance.

A comparison of the volumes of water withdrawn from storage in a water-table aquifer and in a confined aquifer illustrates the significance of the difference in storage coefficient in the two aquifers. In a water-table aquifer, drainage of pore spaces can occur, and a 1-cubic-foot sample of aquifer material might yield about 0.2 cubic foot of water by drainage. In a confined aquifer, elastic release of water occurs, and a 1-cubic-foot sample of aquifer material would yield only about 0.000002 cubic foot of water (about one drop). Stated differently, this means that a 1-square-mile area of a water-table aquifer (assumed to be 100 feet thick) will yield 128 acre-feet of water if the water table is lowered 1 foot. To obtain the same volume of water from storage in a 1-square-mile area of a 100-foot-thick confined aquifer, the potentiometric surface would have to be lowered 1,000 feet. This large difference in the ability of a water-table and confined aquifer to yield water from storage indicates that larger water-level declines can be produced much more easily in the confined aquifer. In the study area, only 9 percent of the water pumped from wells is obtained from the bedrock aquifer; however, the water level in this confined aquifer has declined several hundred feet. By comparison, the alluvial aquifer, which supplies 91 percent of the water pumped from wells, has undergone water-level declines of only a few tens of feet. This difference in water-level decline is due in large part to the difference in storage coefficient between these two aquifers. The difference in storage coefficient thus has a dramatic effect on how the aquifers will respond to man's use of the ground-water resources.

Hydraulic Conductivity and Transmissivity

Hydraulic conductivity is a measure of how readily a water-bearing material can transmit water; it usually is measured in terms of the rate of flow of water past a given cross-sectional area of the water-bearing material. Coarse-grained materials such as sand or gravel have large hydraulic conductivities; fine-grained materials such as silt or clay have very small hydraulic conductivities. The ability of an entire aquifer to transmit water is determined by the hydraulic conductivity of the various sediments present in the aquifer and by the thickness of each of these layers. *Transmissivity* is the measure of this water-transmitting ability of an aquifer; it incorporates the effects of both hydraulic conductivity and thickness. Thus, an aquifer that readily transmits water will have a large transmissivity, and this may be due to the presence of materials of large hydraulic conductivity or to large thickness, or both.

Hydraulic Conductivity of the Aquifers

The average hydraulic conductivity of the sediments in the alluvial aquifer generally ranges from about 100 to 2,000 feet per day and is 200 to 300 times larger than the average hydraulic conductivity of the bedrock aquifer. The large hydraulic conductivity of the alluvial aquifer is produced by the coarse-grained, uncemented sediments that are prevalent in these deposits. Near Denver, the alluvium along the South Platte River has an average hydraulic conductivity of about 870 feet per day and the sediments are predominantly sand and gravel with little clay. The hydraulic conductivity decreases at greater distance downstream. Near Fort Morgan, the average hydraulic conductivity of the alluvial sediments is about 630 feet per day owing to the finer grain size of the sand and gravel and the more prevalent beds of silt and clay. Hydraulic conductivities in excess of 3,000 feet per day have been measured in the coarse gravel and boulder

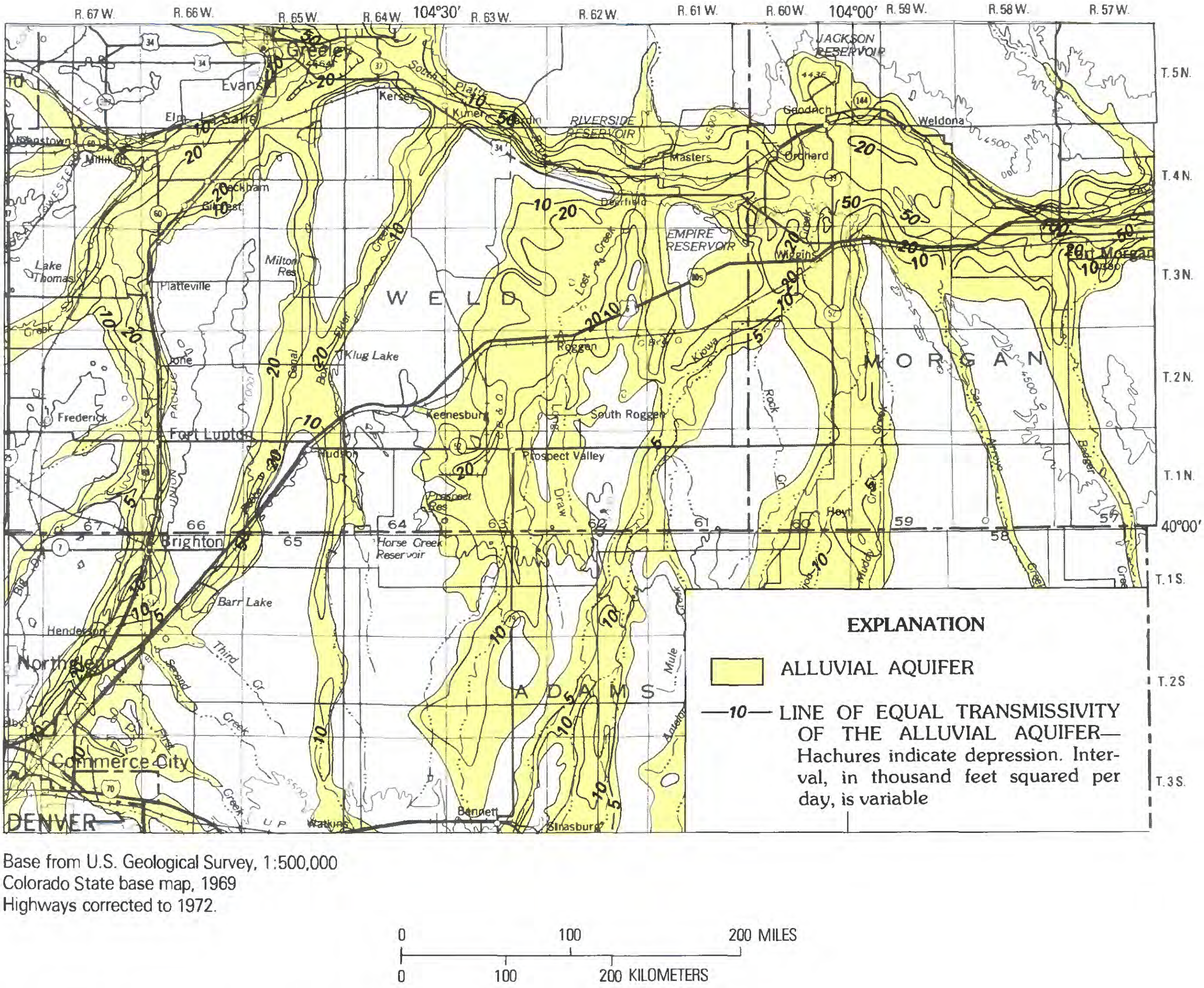


Figure 23. Transmissivity of the alluvial aquifer.

sediments found along parts of the aquifer near Beebe Seep. The smaller streams draining the south-central part of the study area have greater quantities of clay exposed in their drainage areas and are less able to wash the clay from the alluvial sediments than is the case with the larger South Platte River and its mountain tributaries. As a result, the hydraulic conductivity of the aquifer under most of these streams is 200 to 400 feet per day and is as low as 70 feet per day in the Bijou Creek drainage where clay is particularly prevalent.

The hydraulic conductivity of the water-yielding sediments in the bedrock aquifer generally ranges from 0.5 to 7 feet per day. Areas of relatively large hydraulic conductivity are present at varied locations in each of the five bedrock formations. The most important of these areas is located between Denver and Castle Rock and includes the southern part of the Denver metropolitan area. Here, hydraulic conductivities of 2 to 7 feet per day occur in the Denver, Arapahoe, and Laramie Formations and in the Fox Hills Sandstone. A zone of small hydraulic conductivity (0.05 foot per day) is present in the Laramie Formation and the Fox Hills Sandstone along the western margin of the Denver basin.

Transmissivity of the Alluvial Aquifer

The transmissivity of the alluvial aquifer is strongly affected by the thickness of the aquifer but also is affected by changes in hydraulic conductivity. Thickness changes cause transmissivity to be small near the edges of the aquifer and to increase toward the center of the valleys where the alluvial deposits are thickest. Thickness and transmissivity also increase in a downstream direction. Along the South Platte River, the downstream increase in transmissivity is moderated slightly by the downstream decrease in hydraulic conductivity. However, thickness effects are more pronounced, resulting in the general downstream increase in transmissivity (fig. 23).

Transmissivity of the Bedrock Aquifer

Differences in the transmissivity of the bedrock aquifer are caused primarily by changes in the hydraulic conductivity of the water-yielding materials because thickness of the bedrock formations is less variable. Areas of large transmissivity are present in various parts of each bedrock formation and generally correspond to areas of relatively large hydraulic conductivity. Small transmissivities caused by reduced thickness are most apparent around the northern, eastern, and southern margins of the bedrock aquifer (fig. 24). The combined transmissivity of the bedrock aquifer increases from zero at the edge of the aquifer to as much as 3,000 feet squared per day in the area of maximum transmissivity southeast of Littleton.

Transmissivity of the alluvial aquifer generally ranges from 10,000 to 80,000 feet squared per day; transmissivity of the bedrock aquifer generally ranges from 200 to 2,000 feet squared per day. Thus, the ability of the alluvial aquifer to transmit water is about 50 times greater than that of the bedrock aquifer, even though the alluvial aquifer is only about one-tenth as thick as the bedrock aquifer.

When both the transmissivity and the storage coefficient of the alluvial aquifer are compared with the same characteristics of the bedrock aquifer, it is evident that the alluvial aquifer has superior water-supply potential. The alluvium will transmit water to wells more readily than the bedrock and will yield water from storage with less water-level decline than the bedrock. This is part of the reason the alluvial aquifer is heavily used as a source of water supply (fig. 25).

WATER-LEVEL CONDITIONS

The marked difference in the geologic setting and character of the alluvial and bedrock aquifers produces major differences in the ground-water-level conditions in the aquifers. Water levels in the alluvial aquifer generally are near the land surface, or a few tens of feet below land surface, and are readily affected by percolation of surface water and by the altitude of the water in nearby streams. Water levels in the bedrock aquifer generally are one hundred to many hundreds of feet below land surface and are less readily affected by surface conditions.

Water Levels in the Alluvial Aquifer

Depth to water in the alluvial aquifer generally ranges from 0 to 40 feet. The shallow depth to water allows the water percolating downward from wet soil, irrigated fields, and lakes and ditches to easily reach the water table, thus providing recharge to the aquifer. The recharged water moves from areas of higher water-table altitude toward areas of lower water-table altitude. This produces a general downstream direction of ground-water movement in most valleys (fig. 26). However, in valleys having a perennial stream, such as the South Platte River, ground water also tends to move toward the stream and eventually may contribute to the surface flow. This is particularly common along the South Platte River because of the large expanse of irrigated land and numerous reservoirs and ditches along either side of the valley. Water from these sources recharges the aquifer and raises the water table sufficiently for the river to become a drain for the aquifer. Where the aquifer and the stream are well connected, the altitude of the stream affects the altitude of the water level in the aquifer. For example, if a pumping well lowers the water level in the aquifer, the water-level decline eventually will reach the stream and cause either a reduction in the rate of discharge from the aquifer to the stream or an increase in the flow of water from the stream to the aquifer. In either instance, pumping in the alluvial aquifer tends to decrease the rate of flow in the nearby stream, and the additional water recharged to the aquifer moderates the water-level declines in the aquifer.

Water levels in the alluvial aquifer range in altitude from about 4,250 feet near Fort Morgan to more than 5,400 feet along the South Platte River south of Denver and exceed 6,500 feet in the headwaters of Kiowa and Box Elder Creeks in southern Elbert County. These water levels fluctuate slightly during the course of a year in response to heavy pumping during the summer growing season and in response to recharge during periods of above-average precipitation. In addition, extended periods of drought can cause water-level declines to persist for several years and to be reversed only by the return of wetter climatic conditions (fig. 27). Pumping has produced large water-level declines in the aquifer to the east of Denver because perennial streams are uncommon in most of these valleys and the water-level changes are not moderated by the effects of surface water. In this area, water levels (wells 2, 6, 7, 8) have fluctuated 10 to 20 feet during a year, and declines have exceeded 30 feet during a 20-year period (fig. 27). Along the South Platte River valley, water levels (wells 1, 3, 4, 5) have fluctuated 5 to 10 feet during a year, and declines over a 20-year period have ranged from 0 to 20 feet.

Water Levels in the Bedrock Aquifer

Depth to water in the bedrock aquifer generally ranges from 0 to 250 feet, but water levels are 500 to 1,000 feet below land surface in the deep parts of the aquifer between Denver and Castle Rock. The great depth to water and the prevalent shale layers in the bedrock formations make it difficult for surface water to affect water levels

Figure 24. Transmissivity of the bedrock aquifer.

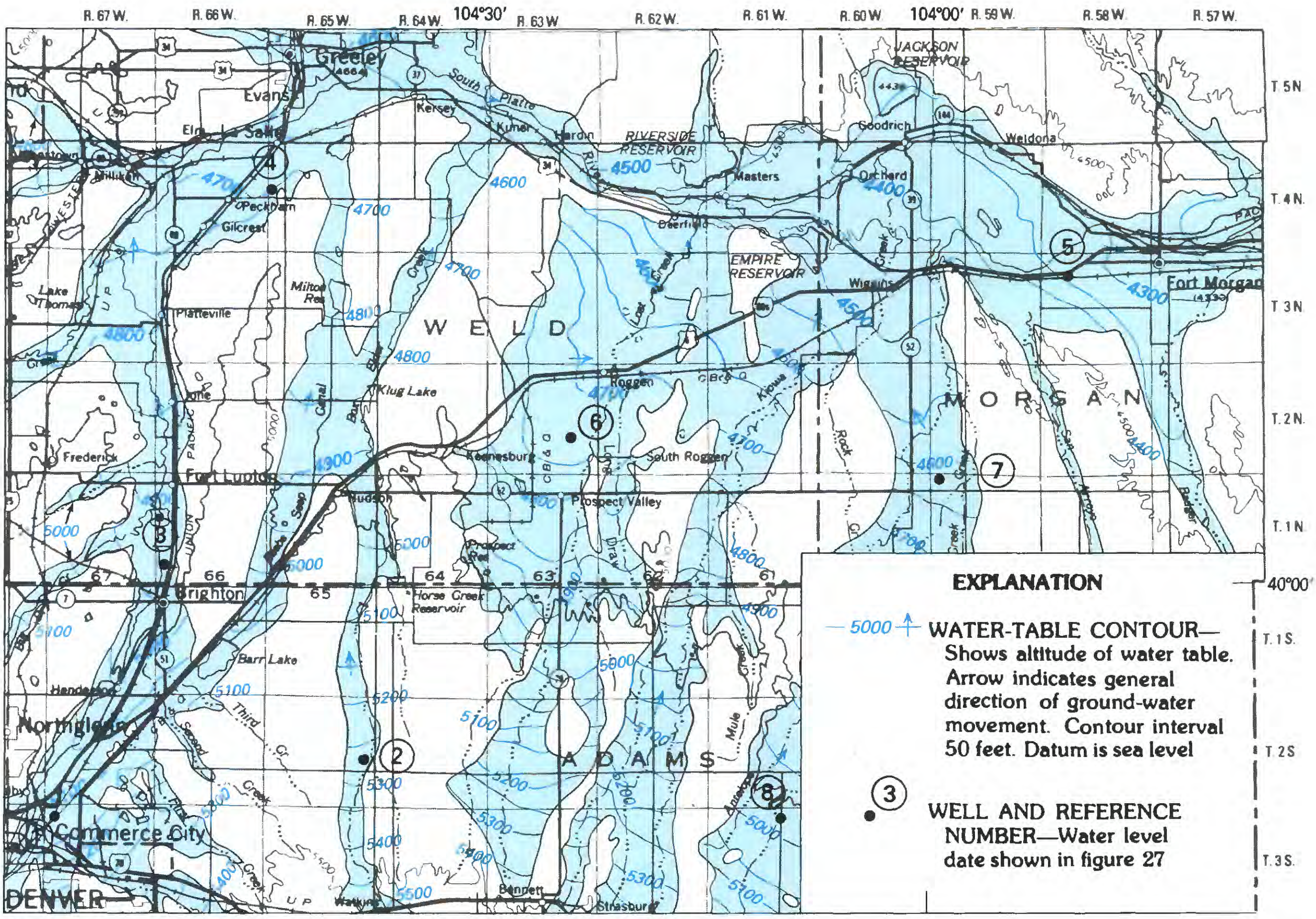
Figure 25. Large-capacity irrigation well pumping from the alluvial aquifer. Discharge rate is about 1,000 gallons per minute. (Photograph by Dawn Reed, U.S. Geological Survey.)

in the deeper parts of the bedrock aquifer. As a result, the potentiometric surface in a deep zone, such as the central part of the Laramie Formation and Fox Hill Sandstone, is of relatively uniform shape and slopes gently to the north in most areas (fig. 28). The shallow parts of the bedrock aquifer are more easily recharged by water percolating from the surface, and the potentiometric surface in these zones (the Dawson Arkose, for example) is very irregular because of water entering the aquifer from highland areas between stream valleys and water leaving the aquifer by moving into the streams or the alluvial aquifer (fig. 28).

In most places, water in the bedrock aquifer moves in the general direction of the surface flow in the streams. North of the South Platte-Arkansas Rivers drainage divide, ground water generally moves in a northerly direction. However, south of this divide ground water may move in either a northerly or southerly direction. A southerly direction of movement is common in the shallow parts of the bedrock formations as locally recharged water moves toward discharge areas along the southern margin of the formations. At greater depth, the water levels in the formations are less easily affected by surface recharge, and ground water moves to the north through the northward-dipping layers of sandstone and conglomerate. Thus, an unusual condition exists in this area: ground water in the deep and shallow parts of the bedrock aquifer may move in opposite directions.

Pumping from many of the estimated 12,000 wells drilled into the bedrock aquifer is the principal cause of water-level decline. Water-level declines began in the Denver area in 1884 when the first deep wells were constructed and it was found that the wells would flow without being pumped. This discovery led to a rapid increase in the number of wells and in the rate of discharge from the aquifer. The resulting water-level declines caused wells to stop flowing and required the installation of pumps to maintain the former rate of yield. By 1960, water levels had declined 400 to 500 feet near Denver. Since 1960, a reduction in pumping in this area has resulted in a reduction in the rate of water-level decline near downtown Denver. In some outlying suburban areas, municipally supplied water is not available and the bedrock aquifer is the principal source of supply. In these areas, the rate of pumping has steadily increased. Between 1958 and 1978, bedrock water levels in the suburban area declined by as much as 300 feet. These declines exceed 200 feet in an 80-square-mile area of the Laramie Formation and Fox Hills Sandstone near Brighton, in a 135-square-mile area of the Arapahoe Formation near Cherry Creek Lake, and in a 40-square-mile area of the Denver Formation east of Denver. Declines exceed 100 feet in a 70-square-mile area of the Dawson Arkose in northeastern Douglas County.

Computer models have been used to show how future water levels in the bedrock aquifer will change in response to projected rates of future pumping (Robson, 1987). For example, modeling results indicate that if the rate of pumping from the bedrock aquifer increases from about 50 cubic feet per second in 1985 to about 150 cubic feet per second in the year 2050, 1979-to-2050 water-level declines of 200 to 310 feet could occur in the Dawson Arkose near Parker. Water-level declines of as much as 420 feet could occur in the Denver Formation, and declines could exceed 200 feet in a 280-square-mile area extending from Denver to south of Castle Rock. In the Arapahoe Formation, a maximum decline of 1,000 feet could occur near Parker, with declines in excess of 600 feet in a 370-square-mile area extending from Cherry Creek Lake through most of northern Douglas County. The largest 1979-to-2050 water-level declines would occur in the Laramie Formation and Fox Hills Sandstone. Declines ranging from 1,500 to 1,830 feet are calculated for a 220-square-mile area extending from Cherry Creek Lake to southwest of Castle Rock. Although the exact future water-level decline is unknown because the rate of



Base from U.S. Geological Survey, 1:500,000
Colorado State base map, 1969
Highways corrected to 1972

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Figure 26. Water-table altitude in the alluvial aquifer.

future pumping is uncertain, these model results indicate that very large water-level declines may be produced in the bedrock aquifer if pumping continues to increase. Increasing pumpage has occurred historically and is probable in the future as the population increases and land development continues in the basin.

Effects of Water-Level Declines in the Aquifers

As water levels in the bedrock aquifer decline, the rate of yield of wells drilled into the aquifer also will decline. Age-related factors such as wear and corrosion of the well casing and pump are partly responsible for the reduced yield; however, reduction of the distance from the water level to the bottom of the well and increased distance from the water level to the land surface are principal factors affecting yield. As the yield of a well decreases, it may fail to supply enough water to meet the owner's requirements and a second well may be needed to supplement the decreasing yield of the first well. The following simple analysis demonstrates the general effects of declining water levels on the yield of wells and on the resulting cost of a ground-water supply.

Consider a hypothetical well site in the bedrock aquifer near Denver. Water levels are declining at a rate of 10 feet per year and the water level in a well is 1,000 feet above the base of the aquifer. At this rate of decline, the aquifer will be dewatered at the end of 100 years (in this simplified example). As the water level declines to zero at 100 years, the yield of the well is assumed to decline to zero at the same rate. In this example, the water-level decline is due to regional conditions and is unaffected by pumping from this or other nearby wells, and the yield

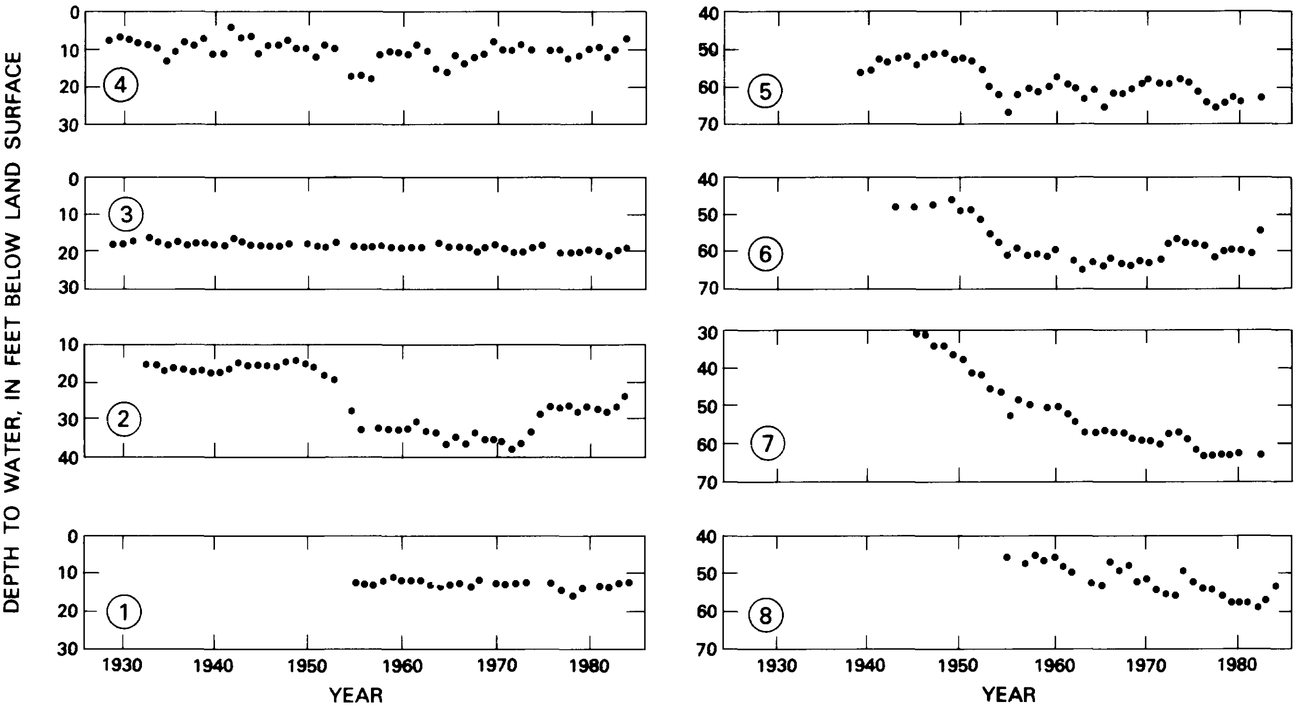

Figure 27. Water-level changes in the alluvial aquifer (see fig. 26 for location of wells).

of the well is determined only by the water level in the aquifer and not by other conditions, such as age of the well.

The hypothetical well yields 40 acre-feet per year at the time it is drilled (year 0, fig. 29); the owner has a minimum requirement for 30 acre-feet of water per year. Thus, at the time the well is drilled, the well yield is 10 acre-feet per year more than the owner requires (point A, fig. 29). However, as the water level declines during the 100-year period, the well yield will decrease, as indicated by the line connecting points A and Z. About 25 years after the well is drilled its yield will have decreased to the point of just supplying the minimum water requirements of the owner and a second well must be drilled to supplement the yield of the first. The combined yield of the two wells initially far surpasses the owner's water needs (point B, fig. 29), but the combined yield decreases more rapidly than that of one well. About 62 years after the first well is drilled, the combined yield of the first and second wells will have decreased to the point of just supplying the minimum water requirement. A third well now must be drilled, and it, and the first and second wells, will provide adequate water for another 13 years before a fourth well is needed.

This sequence is continued at increasing frequency even though the water level is declining at a constant rate. The time between construction of the second and third well is 37 years; the time between the third and fourth well is 13 years. The time between construction of the sixth and seventh well is only 3 years. The total volume of water pumped from each well is controlled by the pumping rate and the number of years the well is used. Thus, the first well produces 1,875 acre-feet during the 100-year period. The second well produces only 562 acre-feet during the 75 years of its use. If the cost of constructing and equipping each well is $50,000, then the cost of water produced by each well ranges from $27 per acre-foot for the first well to $1,300 per acre-foot for water from the sixth well (table 2), assuming no cost for power to run the pumps.

This simplified example illustrates that as water levels continue to decline in the bedrock aquifer, the cost of producing a constant supply of water will increase dramatically owing to the need for additional wells. Other factors, such as increasing pumping lift required to bring water to the surface, also would increase cost. As water cost increases, the conditions depicted in the example probably would be altered by political, social, and economic changes that would affect the use of ground water from the bedrock aquifer. Rapidly increasing cost of ground water likely would lead to water conservation, recycling, switching to other sources of water, or cessation of pumping because of legal restraints or adverse economic conditions. These alternatives could reduce the rate of water-level decline as the cost of water increases and would prolong the ground-water supply for the remaining users.

Similar increases in the cost of water would occur if the alluvial aquifer had large water-level declines.

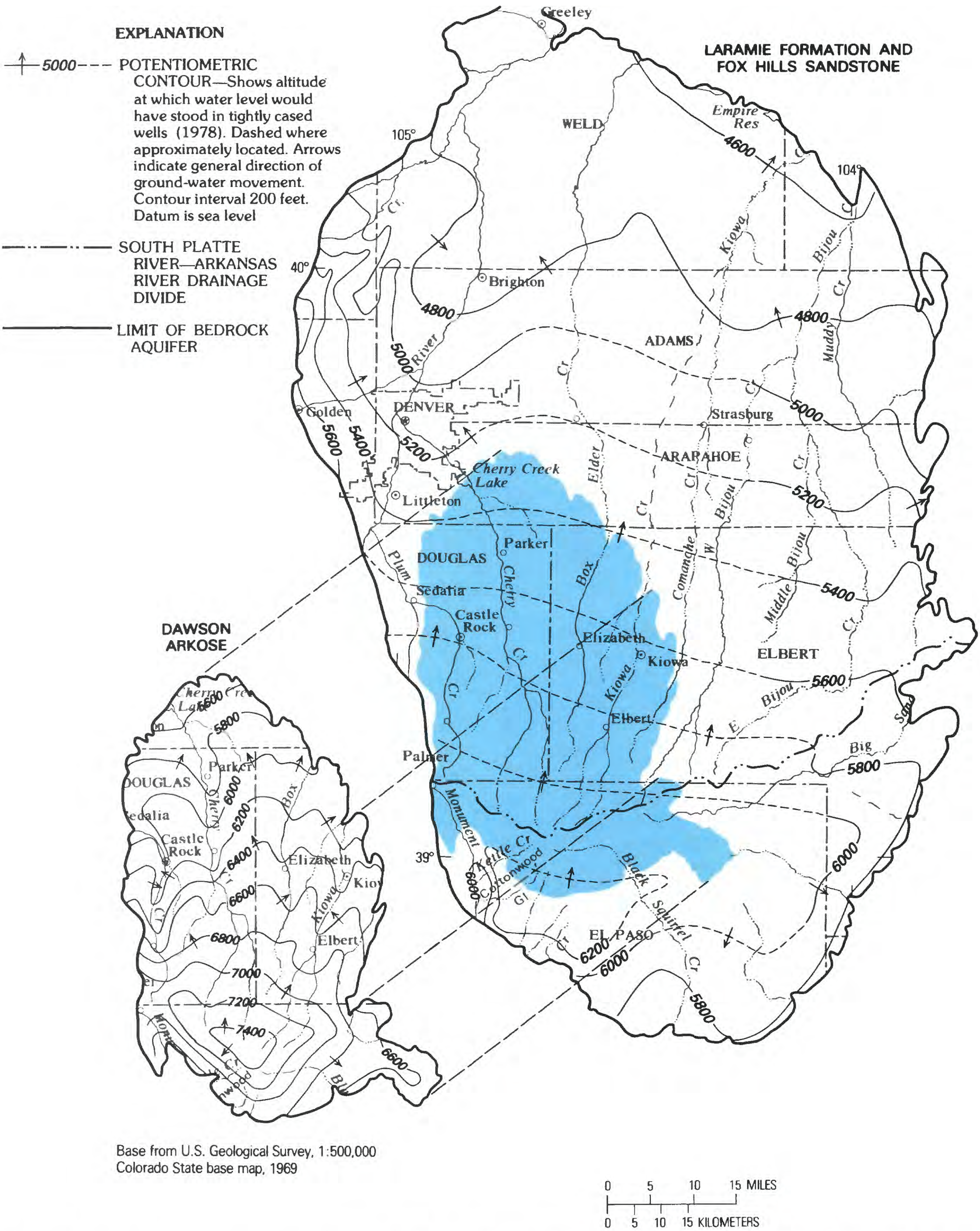

Figure 28. Altitude of the potentiometric surface in the shallow (Dawson Arkose) and deep (Laramie Formation and Fox Hills Sandstone) parts of the bedrock aquifer.

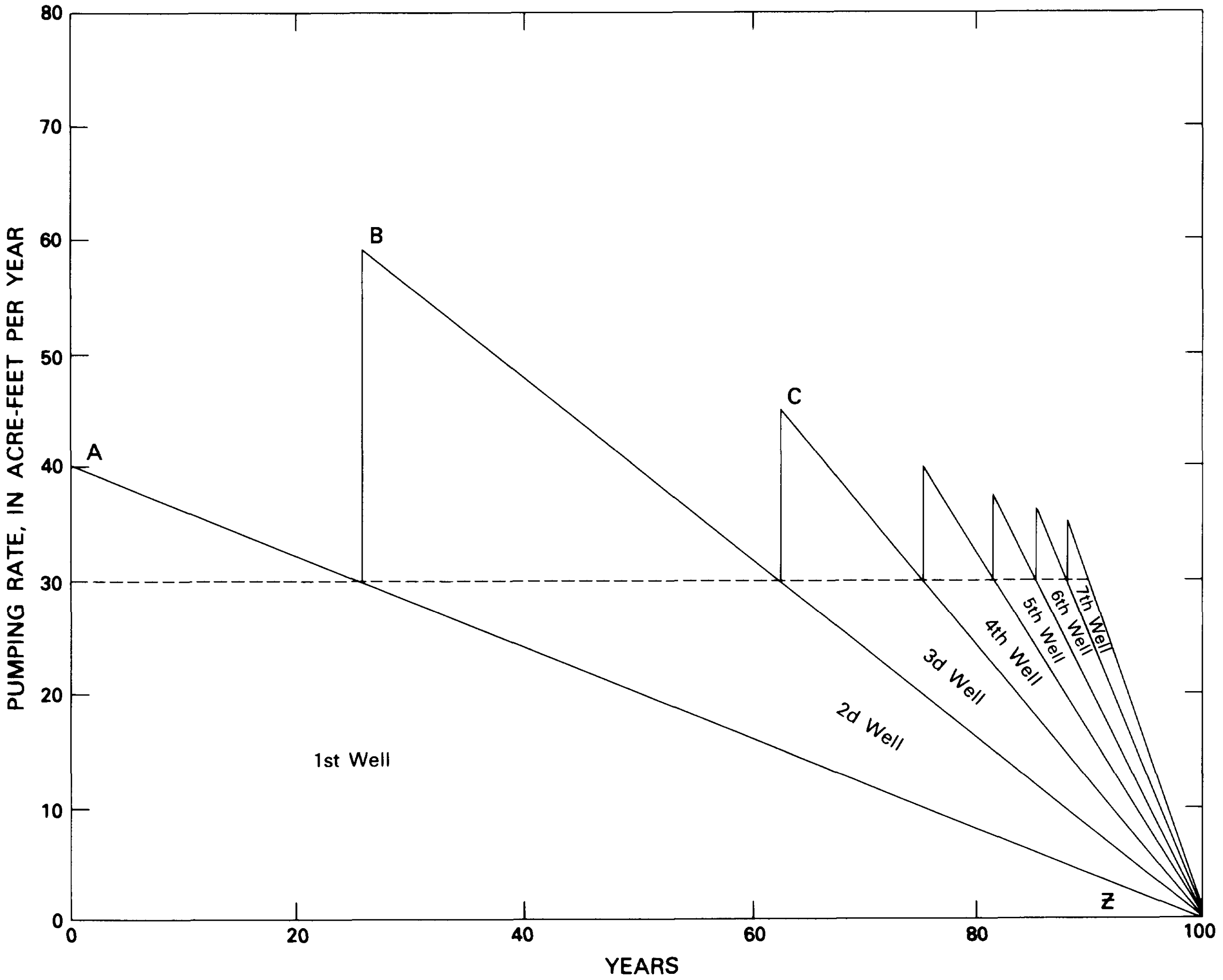

Figure 29. Number of wells required to maintain a constant supply of water as individual well yields decrease.

Table 2. Increase in water cost caused by declining water levels

Well sequence	Volume of water pumped from well (acre-feet)	Well cost	Water cost (dollars per acre-foot)
1	1,875	$50,000	$ 27
2	562	50,000	89
3	188	50,000	270
4	94	50,000	530
5	56	50,000	890
6	37	50,000	1,300

However, recharge from irrigated fields, lakes, canals, and streams tends to offset water-level declines in the alluvial aquifer, and increased cost resulting from water-level declines is much less.

GROUND-WATER BUDGETS

A ground-water budget is an itemized list of the sources and quantities of water recharging an aquifer, the volume of water in storage in the aquifer, and the sources and quantities of water discharging from the aquifer. The water budgets for the alluvial and bedrock aquifers are markedly different because of differences in the size of the aquifers and differences in the way surface water affects the aquifers.

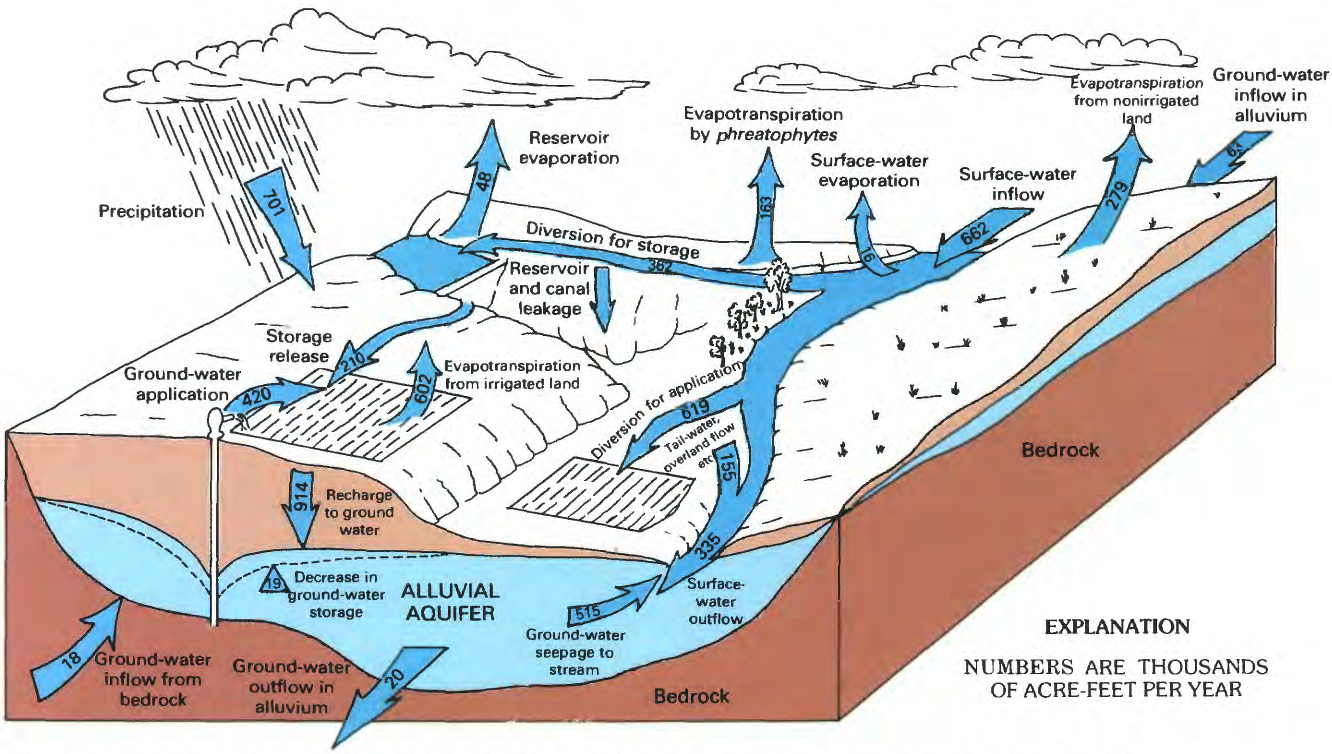

Figure 30. Average annual 1947–70 water budget for the alluvial aquifer. Modified from Hurr and others (1975).

Budget for Alluvial Aquifer

A water budget for the alluvial aquifer in the reach of the South Platte River from Denver to Julesburg, presented by Hurr and others (1975), indicates the complexity of the hydrology of the alluvial aquifer. This water budget represents average conditions for 1947–70 for a longer reach of the river than is considered in this study. However, the components of the water budget are identical with those in this study area, and the budget provides considerable information about the functioning of the hydrologic system in this area even though the volumes of water shown are probably slightly different from those for this area.

The water budget (fig. 30) indicates that precipitation (701,000 acre-feet per year) and surface-water inflow (662,000 acre-feet per year) are the two principal sources of water entering the area. Surface-water inflow is supplied by the South Platte River upstream from Denver, transmountain diversions, the Big Thompson, St. Vrain, Cache la Poudre Rivers, and numerous other tributaries. Ground-water inflow from adjacent alluvial aquifers (63,000 acre-feet per year) and bedrock aquifers (18,000 acre-feet per year) supply the remaining part of a total inflow of 1,444,000 acre-feet per year.

Evaporation from wet soil and water surfaces and transpiration of water by vegetation combine to produce a total evapotranspiration loss of 1,108,000 acre-feet per year. This is the largest means of water loss from the area. Surface-water outflow (335,000 acre-feet per year) and ground-water outflow in the alluvial aquifer (20,000 acre-feet per year) contribute to the total outflow of 1,463,000 acre-feet per year. Water-level declines between 1947 and 1970 caused a decrease in the volume of ground-water storage that averaged 19,000 acre-feet per year. This decrease is the difference between the total inflow and outflow for the area.

Recharge to the alluvial aquifer totals about 1,099,000 acre-feet per year in the water budget area and primarily is the result of infiltration of precipitation and irrigation water applied to fields (914,000 acre-feet per year). Between 45 and 50 percent of the water applied to fields percolates to depth and ultimately recharges the alluvial aquifer. Thus, about twice as much water is applied to the fields as the crops require for growth. Leakage from reservoirs and canals contributes about 104,000 acre-feet per year to the alluvial aquifer, and underflow from adjacent bedrock and alluvial aquifers supplies an additional 81,000 acre-feet per year.

Discharge from the alluvial aquifer has two principal components. The largest (about 515,000 acre-feet per year) occurs through ground-water seepage to the South Platte River and is due primarily to recharge from irrigation. Prior to the onset of irrigation in about 1860, water levels in the alluvial aquifer were not high enough to maintain flow in some reaches of the river throughout the year.

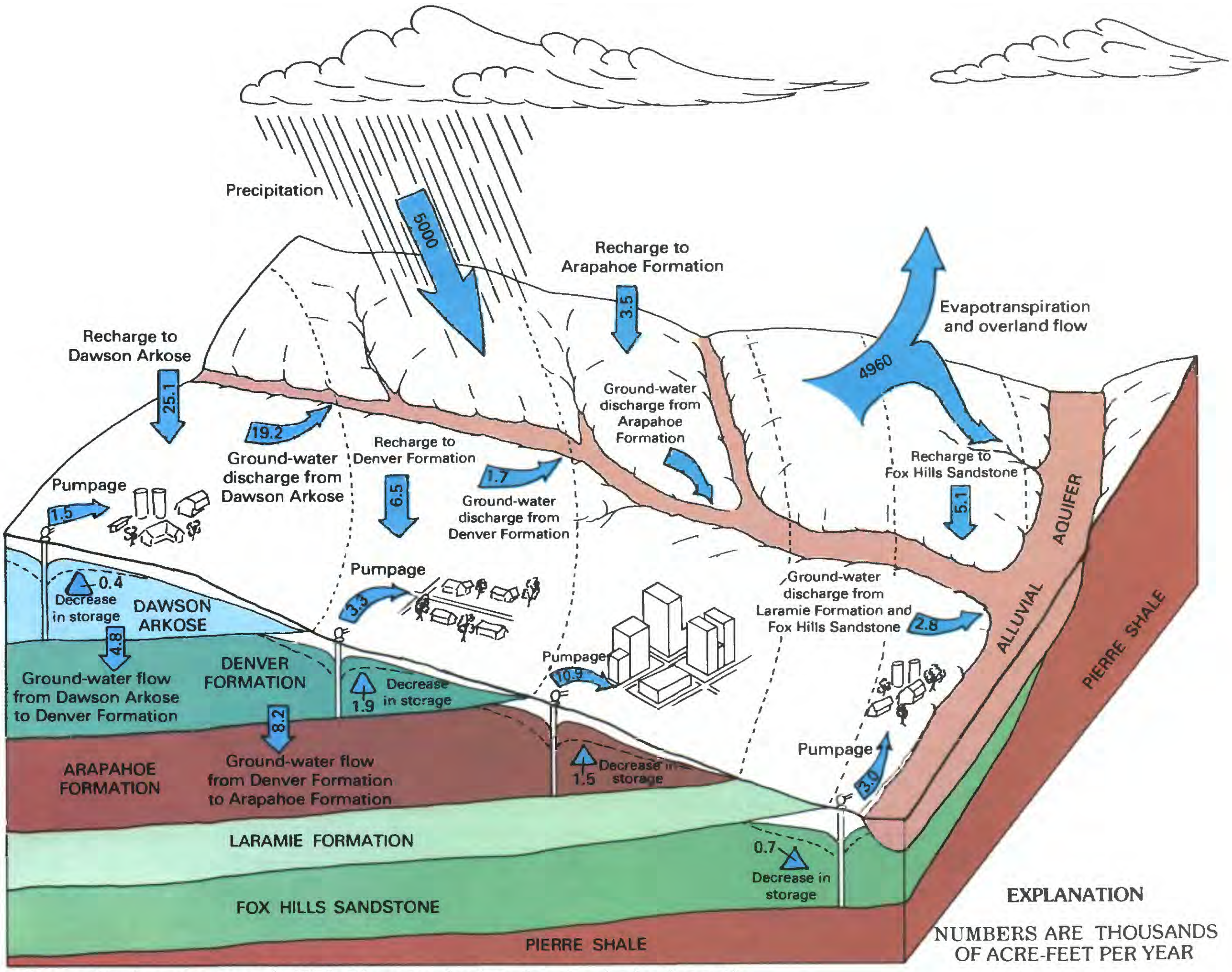

Figure 31. Average annual 1958–78 water budget for the bedrock aquifer.

Irrigation provided recharge to the aquifer, which raised water levels and increased ground-water discharge to the river. The river is now the principal drain for the alluvial aquifer. Pumpage is the second largest discharge component (420,000 acre-feet per year) for the alluvial aquifer. An additional 163,000 acre-feet per year is lost by evapotranspiration from vegetation and wet soil in areas of shallow water table, and 20,000 acre-feet per year discharges as outflow from the alluvium. Total discharge from the alluvial aquifer is about 1,118,000 acre-feet per year, which is 19,000 acre-feet per year more than the estimated total recharge. This difference represents an average decrease of 19,000 acre-feet per year in the volume of ground water in storage from 1947 to 1970.

The alluvial aquifer in the study area underlies 1,890 square miles and contains about 8,850,000 acre-feet of ground water in storage. About 46 percent (4,030,000 acre-feet) of the ground water is stored in the alluvium along the South Platte River between Denver and Fort Morgan. The part of the alluvial aquifer underlying the northward-draining tributaries on the plains east of Denver contains about 48 percent (4,230,000 acre-feet) of the stored ground water. The remaining 6 percent (585,000 acre-feet) is contained in the part of the aquifer underlying the plains tributaries entering the South Platte River near Denver and the tributaries originating in the Rocky Mountains.

Budget for Bedrock Aquifer

The water budget for the bedrock aquifer differs from that for the alluvial aquifer primarily because of the larger area of the bedrock aquifer and the lesser ability of the aquifer to accept surface recharge. The bedrock aquifer underlies an area of 6,700 square miles, compared with the 1,900-square-mile area of the alluvial aquifer. As a result, precipitation on the larger area of the bedrock aquifer supplies about 5,000,000 acre-feet of water per year to this area (fig. 31). Of this huge volume of water, only about 40,000 acre-feet percolate to depth each year

Table 3. Volume of water stored in the bedrock formations in the Denver basin

Formation	Volume of water in storage (acre-feet)
Dawson Arkose	48,000,000
Denver Formation	89,000,000
Arapahoe Formation	150,000,000
Laramie Formation and Fox Hills Sandstone	180,000,000

and recharge the bedrock aquifer. The vast majority of the precipitation is lost through evaporation, transpiration by plants, overland runoff, or recharge to the alluvial aquifer and, thus, does not reach the bedrock aquifer. By comparison, the alluvial aquifer receives about 701,000 acre-feet of precipitation per year and perhaps as much as one-half of this recharges the aquifer.

The large area of the bedrock aquifer, combined with its great thickness, enables it to contain much more water in storage than the alluvial aquifer. The bedrock aquifer contains about 470,000,000 acre-feet of water in storage; the alluvial aquifer contains about 8,850,000 acre-feet of water in storage. By comparison, Lake Erie of the Great Lakes contains about 390,000,000 acre-feet of water. Thus, the bedrock aquifer in the Denver basin contains 20 percent more water than is held in Lake Erie. Of the bedrock formations in the basin, the Dawson Arkose contains the smallest volume of water in storage, and the Laramie Formation and Fox Hills Sandstone contain the largest volume of water in storage (table 3).

Recharge to the bedrock aquifer occurs primarily through infiltration of precipitation in the highland areas between stream channels. The water moves from the recharge areas through the aquifer to natural discharge areas along the stream valleys or to pumping wells. Total discharge from the bedrock aquifer was about 45,000 acre-feet per year during 1958–78. Water that naturally flows out of the bedrock aquifer may evaporate or be consumed by vegetation growing near the discharge site, or it may form a spring that flows into a stream, or the water may become part of the water moving through the alluvial aquifer. Discharge by these processes was about 26,000 acre-feet per year during 1958–78; pumping wells discharged 18,700 acre-feet per year during this period (fig. 31). Thus, just as the South Platte River and nearby vegetation serve as a drain for the adjacent alluvial aquifer, the alluvial aquifer and associated streams and vegetation serve as a drain for the underlying bedrock aquifer. The alluvial aquifer drain receives about 678,000 acre-feet of water per year. The bedrock drain receives about 26,000 acre-feet of water per year.

Although the bedrock aquifer contains more than 50 times as much water in storage as does the alluvial aquifer, it receives only about one-tenth as much natural recharge as the alluvial aquifer and discharges only about one twenty-fifth as much to the natural drain as does the alluvial aquifer.

Pumping has lowered the water level in parts of the bedrock aquifer, and the resulting decrease in the volume of ground water in storage averaged about 4,500 acre-feet per year during 1958–78. The average volume of water pumped (18,700 acre-feet per year) is larger than the decrease in storage because storage is not the only source for the pumped water. As water levels decline, additional recharge is drawn into the bedrock aquifer and the rate of natural discharge is reduced. These two sources in addition to the decrease in volume of ground-water storage supply the pumped water.

LEGAL CONSTRAINTS ON USE OF WATER FROM THE ALLUVIAL AND BEDROCK AQUIFERS

Colorado water law is based on the doctrine of prior appropriation. According to this doctrine, the earliest historical diversion of water from a stream has the most senior right to surface flow in the stream. If subsequent diversions intercept water needed by a more senior diversion, flow in the junior diversion may be reduced to allow more water to continue downstream to the senior diversion. Diversion priorities date from 1852 in Colorado; priorities later than 1900 generally are too junior to ensure a year-round supply of surface water. An example of a diversion structure on the South Platte River is shown in figure 32.

Ground-water use could affect streamflow, and thus these water laws may also control ground-water pumping. A pumping well in a tributary aquifer could cause a reduction in the volume of water in the stream by increasing water movement from the stream to the aquifer or by intercepting water moving from the aquifer to the stream. In either instance, the flow in the stream could be reduced, thereby infringing on water rights of other users. Most wells in eastern Colorado have been drilled since 1940, and those tapping tributary aquifers, such as the alluvial aquifer in the report area, have very junior priority dates. These wells may be subject to pumping regulation or shutdown if surface flow is not adequate to meet the needs of the numerous more senior surface-water diversions. Such regulation could severely limit development of the ground-water resources in tributary

Figure 32. Surface-water diversion structure on the South Platte River near Platteville.

Figure 33. Well-drilling rig constructing a well 2,000 feet deep in the bedrock aquifer near Castle Rock.

aquifers if it were not for augmentation plans. Augmentation plans are designed to supply additional water directly to the stream in order to offset the reduced streamflow caused by pumping. In areas where augmentation is not feasible, new development of tributary ground-water supplies has been prohibited since about 1965.

Aquifers that are considered legally nontributary have little effect on the surface flow in streams and are not regulated by the doctrine of prior appropriation. These aquifers include much of the bedrock aquifer in the report area. Water use from a nontributary aquifer is governed by laws that allow a landowner annually to pump as much as one one-hundreth of the recoverable volume of water under his property. If, for example, a landowner has 5,000 acre-feet of potentially recoverable water in a bedrock aquifer under his land, he would be permitted to pump no more than 1 percent, or 50 acre-feet of water, per year. This water is available to him without concern for priority dates; however, augmentation plans may still be required if the bedrock well is located near a stream. The relative availability of water from the nontributary bedrock aquifer makes it an attractive source of supply for rapidly developing areas near Denver (fig. 33).

Another means of regulating ground-water use applies to wells located in certain designated ground-water basins. Two of the seven designated basins in Colorado are located in the drainage areas of Lost, Kiowa, and Bijou Creeks. In these basins, development is governed by the Colorado Ground Water Commission. Applications for new wells are evaluated on the basis of the water-level decline the new pumping would cause in a 25-year period. Construction of new large-capacity wells in the bedrock aquifer generally is permitted, but similar new wells in the alluvial aquifer generally are disallowed. Construction of small-capacity domestic or stock wells in either the alluvial or bedrock aquifer is allowed throughout the study area. However, restrictions may be placed on the rate of annual withdrawal from some of these wells.

The presence of large volumes of water in an aquifer does not indicate that this water can be developed without causing harm to other users. When such harm is recognized under State law, additional development may be restricted or precluded. This regulation has the effect of saving such water for existing users even though their wells may not directly tap the aquifer containing the water being protected.

CHEMICAL QUALITY OF GROUND WATER

Alluvial Aquifer

Water in the alluvial aquifer is derived primarily from recharge by surface water in streams, irrigation canals, reservoirs, and irrigated fields. As a result, the chemical quality of water in the alluvial aquifer is affected significantly by the chemical quality of these sources. In the upstream reaches of the South Platte River and its western tributaries, the surface water is of very good chemical quality and the level of mineralization, as measured by dissolved-solids concentrations, generally is less than 300 milligrams per liter. Adjacent ground water is of similar quality. In comparison, the U.S. Environmental Protection Agency (EPA) (1976, 1977) recommends that dissolved-solids concentration not exceed 1,000 milligrams per liter in public water supplies. As the water in the South Platte River flows past Denver, outfall from municipal sewage treatment plants and other inflows degrade the river quality; water at Henderson, just downstream from Denver, has about 400 milligrams per liter dissolved solids. About one-half of the surface water diverted for irrigation is lost to evaporation and transpiration. This concentrates the dissolved minerals in the remaining water that ultimately returns to the stream by percolating through the soil and moving through the alluvial aquifer to the stream. This process primarily is responsible for a downstream increase in dissolved-solids concentrations in the South Platte River (table 4).

The downstream increase in dissolved-solids concentrations in the surface water contributes to a general downstream increase in concentrations in the alluvial aquifer. The distribution of dissolved solids in the alluvial aquifer is more complex than that of the surface water because water in the aquifer is derived from diverse sources and because water pumped from wells is used for irrigation. Part of the pumped irrigation water is lost to evaporation and transpiration and the dissolved minerals are concentrated in the remaining water, which recharges the alluvial aquifer. Leaching of the soil also carries agricultural chemicals and soluble natural minerals from the soil into the alluvial aquifer. These two processes degrade the chemical quality of water in the aquifer. The degraded water then may be pumped from other wells and further degraded as the process is repeated many times. This leads to marked changes in the chemical quality of the aquifer both with distance downstream and across the stream valley. Dissolved-solids concentrations in the alluvial aquifer commonly range from less than 500 milligrams per liter in local areas close to sources of good-quality recharge to more than 3,000 milligrams per liter in areas where soluble minerals are more prevalent in the soil and good-quality recharge is not available (fig. 34).

Most of the water in the alluvial aquifer is not well suited for use as public or domestic supplies because of its large dissolved-solids concentrations, hardness, or localized large concentrations of iron, nitrate, or sulfate. Dissolved minerals commonly present in significant concentrations include compounds of calcium, sodium, iron, magnesium, bicarbonate, sulfate, and nitrate. Calcium and bicarbonate compounds are more prevalent in the less mineralized upstream parts of the aquifer; sodium and sulfate compounds are more prevalent in the more mineralized downstream parts of the aquifer. The ground water generally is classified as very hard. Hard water is objectionable because it leaves scaly deposits on the inside of pipes and water heaters, requires more soap to make a good lather while leaving behind a soapy scum, and roughens washed clothing and skin. Dissolved iron, sulfate, or nitrate concentrations commonly exceed those recommended by the EPA for public drinking water. Dissolved iron can produce black to reddish-brown discoloration in the pumped water, and the water may stain and discolor porcelain fixtures, laundry, and cooking utensils. Dissolved sulfate in excess of the limit of 250

Table 4. Average dissolved-solids concentrations in surface flow of the South Platte River

Sample site	Dissolved-solids concentration (milligrams per liter)
At mountain front southwest of Denver	200
Henderson	400
Fort Lupton	700
Kersey	1,100
Masters	1,000
Weldona	1,000

milligrams per liter recommended by the EPA for drinking water may tend to produce a laxative effect in those unaccustomed to drinking the water. Nitrate concentrations in excess of 10 milligrams per liter may be harmful to infants who drink the water. These adverse effects, plus the general disagreeable taste of most of the water, make the alluvial aquifer a less than ideal source of public supply, although several rural communities and many rural residents have used this water as their only source for many years.

Irrigation water supplied from mineralized ground water must be carefully managed, in some areas, to prevent crop-damaging salts from accumulating in the soil. However, in most areas the alluvial aquifer provides water that is of suitable quality for irrigation of crops, and the dissolved minerals that can make the water objectionable for public and domestic uses are not a serious problem for irrigation use.

Bedrock Aquifer

Unlike the alluvial aquifer, the bedrock aquifer generally contains water that is of good chemical quality for public supply and domestic use. The dissolved-solids concentrations of water in the bedrock aquifer generally are less than 200 milligrams per liter in the upper part of the bedrock formations (such as the Dawson Arkose) (fig. 35). In this area, the bedrock aquifer is recharged directly from precipitation, and the ground water is of excellent chemical quality. At greater depth in the bedrock formations (such as the central part of the Laramie Formation and the Fox Hills Sandstone), water quality has been degraded somewhat by prolonged contact with the

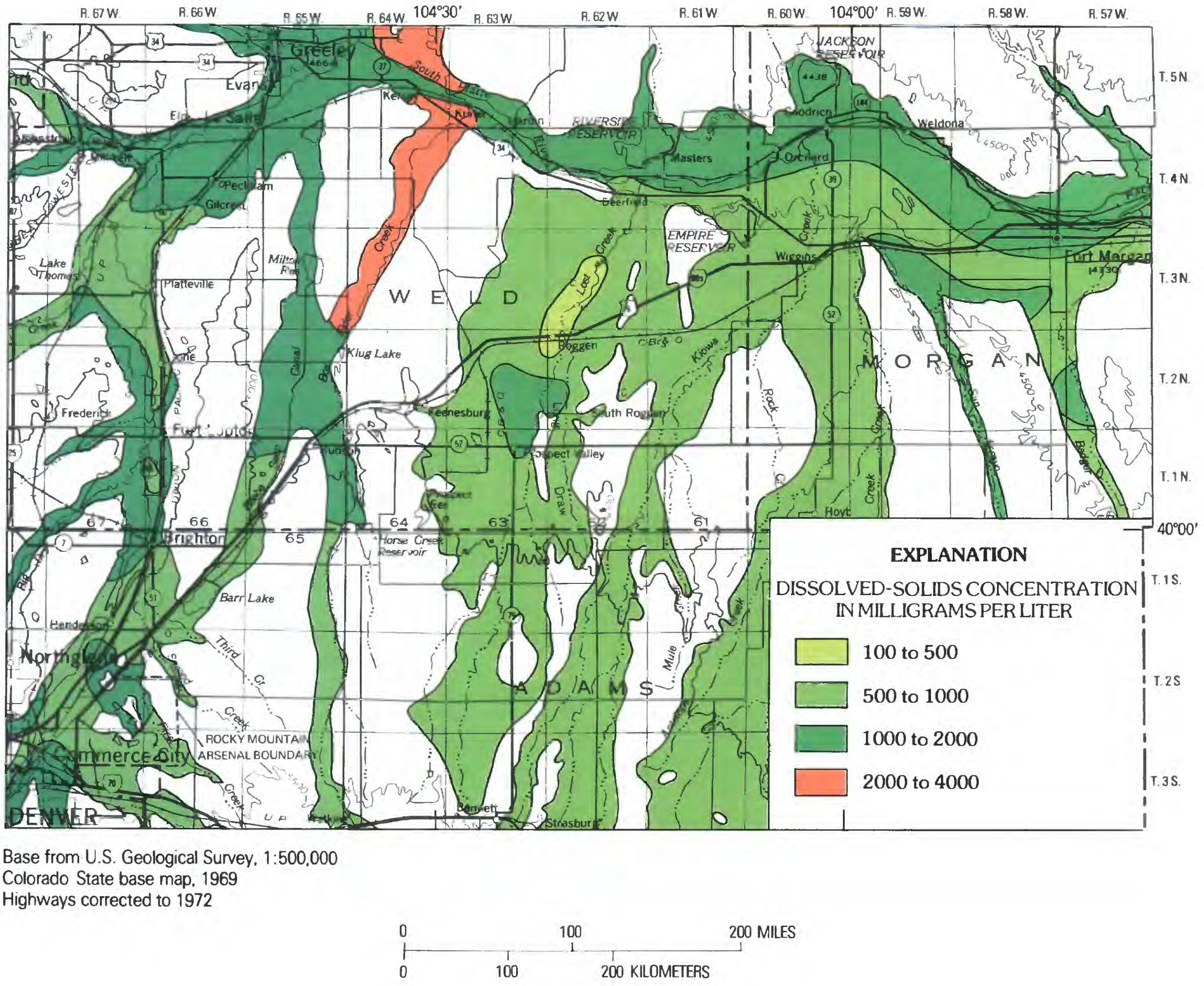

Figure 34. Dissolved-solids concentrations in the alluvial aquifer.

geologic materials (fig. 35). Water in this part of the aquifer generally contains 400 to 600 milligrams per liter of dissolved solids. Near the shallow margins of the bedrock formations, water may discharge from the bedrock aquifer to streams or to the alluvial aquifer, or may be consumed by evaporation and transpiration. Evaporation and transpiration, coupled with leaching of soluble minerals from the soil into the aquifer, produces local increases in dissolved-solids concentrations around the margin of the formations. Along the margin of the Laramie Formation and Fox Hills Sandstone, for example, dissolved-solids concentrations commonly range from 800 to 1,200 milligrams per liter and the water may contain 25 to more than 250 milligrams per liter of dissolved sulfate.

Nitrate concentrations in the bedrock aquifer are small because little irrigated land directly overlies the aquifer. Both the bedrock and alluvial aquifers contain areas where concentrations of dissolved iron are large. In the bedrock aquifer, concentrations of dissolved iron commonly range from 20 to 200 micrograms per liter, which is less than the limit of 300 micrograms per liter recommended by the EPA for public water supplies. The distribution of dissolved iron is extremely varied. A few bedrock wells have iron concentrations ranging from 6,000 to 85,000 micrograms per liter. However, the affected area is local; nearby wells of similar depth may not have unusually large iron concentrations.

Dissolved gases are a problem unique to the bedrock aquifer. In deeply buried parts of the aquifer near Denver, oxygen-deficient (reducing) conditions may occur, and organic material such as coal and lignite, as well as sulfate minerals, may be reduced to methane and hydrogen sulfide gases. When these gases are present in significant

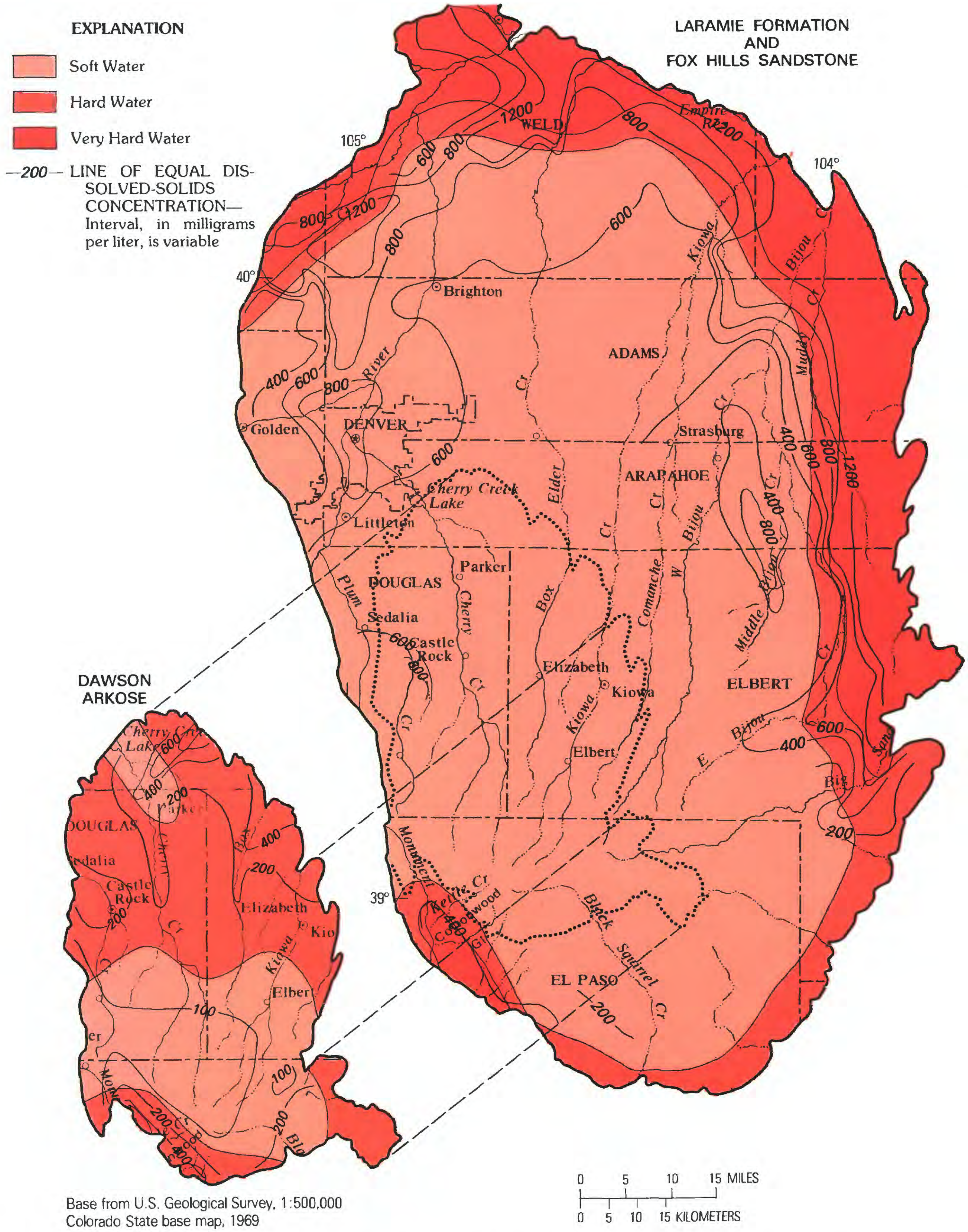

Figure 35. Dissolved-solids concentrations and hardness in the shallow (Dawson Arkose) and deep (Laramie Formation and Fox Hills Sandstone) parts of the bedrock aquifer.

concentrations, water pumped from deep wells may effervesce, have a putrid odor, and be of marginal value for many uses.

The bedrock aquifer generally is not used as a source of irrigation water. Near the margins of the aquifer, water that has large dissolved-solids concentrations and is of a sodium bicarbonate or sodium sulfate type has a high salinity hazard. This water is unsuitable for most irrigation because it could inhibit normal crop growth or cause a buildup of salts in the soil to a level that would be toxic to crops. However, in most areas of the bedrock aquifer, the smaller well yields and the greater cost of producing the bedrock water are more important in limiting irrigation use than is the water quality.

GROUND-WATER CONTAMINATION

Ground-water contamination can result from improper waste-disposal practices that allow pollutants to enter the soil and percolate to an underlying aquifer. The alluvial and bedrock aquifers are markedly different in their susceptibility to such contamination. In the alluvial aquifer, the shallow depth of the water table and the permeable nature of the soil allows pollutants to easily enter the aquifer, where they are spread throughout large areas by the moving ground water. In the bedrock aquifer, deeper water tables and relatively impermeable clay and shale layers above the water table restrict downward movement of contaminants, and slow rates of ground-water movement retard the spread of contaminated water. This difference in the susceptibility to pollution is well illustrated by two case histories involving contamination of the alluvial and bedrock aquifers.

Contamination of the Alluvial Aquifer

An example of alluvial-aquifer pollution is provided by contamination that occurred on the Rocky Mountain Arsenal between 1953 and 1956 (Robson, 1979). During this time, the U.S. Army was discharging effluent from the manufacture of chemical munitions to a series of unlined ponds located on the alluvium near the northern city limits of Denver. Computer-model studies of one organic chemical, called DIMP (diisopropylmethylphosphonate), contained in the effluent, indicate how this contaminant spread through the alluvial aquifer.

Concentrations of DIMP in the aquifer were assumed to be zero in 1952 prior to discharge of the DIMP-contaminated effluent. During the following 4 years, DIMP was disposed of in the five unlined ponds shown in figure 36. Computer-model calculations indicated that by 1956 DIMP-contaminated water had moved about 3 miles through the alluvial aquifer from near the ponds to the South Platte River. Water having DIMP concentrations of more than 200 micrograms per liter was shown to be present on the arsenal and adjacent property to the northwest (fig. 36*A*). After completion of a lined waste-storage reservoir in 1956, effluent was no longer released into the unlined ponds and the recharge of DIMP-contaminated water was halted. By 1960, DIMP concentrations began to decrease near the northern unlined ponds (fig. 36*B*). However, DIMP-contaminated water still was flowing into the South Platte River, and DIMP concentrations in excess of 200 micrograms per liter had spread farther to the northwest off the arsenal (fig. 36*B*). By 1964, 12 years after DIMP contamination first occurred and 8 years after the discharge ceased, DIMP concentrations in the ground water that was flowing into the South Platte River had increased to more than 200 micrograms per liter (fig. 36*C*). This process continued during the next 4 years, and by 1968 the last part of the 200-microgram-per-liter water was just entering the river (fig. 36*D*). By 1972, the only remaining areas of the alluvial aquifer with DIMP concentrations in excess of 200 micrograms per liter were near the northern boundary of the arsenal and near the unlined ponds (fig. 36*E*). Very small ground-water velocities in these areas retard the movement of this contaminated water. Ground-water velocities in the alluvial aquifer ranged from less than 1 foot per day near the northern boundary and the unlined ponds to more than 15 feet per day in the area northwest of the arsenal.

During 1953–56, about 50 tons of DIMP percolated into the aquifer. By 1975, about 34 tons of DIMP had been discharged to the surface flow in the South Platte River; 6 tons were discharged at springs, seeps, and pumping wells, and 10 tons remained in the aquifer. Computer-modeling results indicate that the maximum rate of DIMP discharge to the South Platte River occurred during 1958 through 1960. This discharge would have produced an average DIMP concentration of about 30 micrograms per liter in the river when its mean annual flow was about 200 cubic feet per second. DIMP concentrations in the river decreased to less than 1 microgram per liter in 1976. By 1976, 20 years after discharge of DIMP-contaminated effluent ceased, trace concentrations of DIMP were still present in a 28-square-mile area of the alluvial aquifer, and water in the South Platte River, several irrigation canals, and numerous irrigation and domestic wells had been affected by the pollutant. This contamination resulted from a 4-year exposure of the alluvial aquifer to industrial wastes in five small unlined ponds on the arsenal.

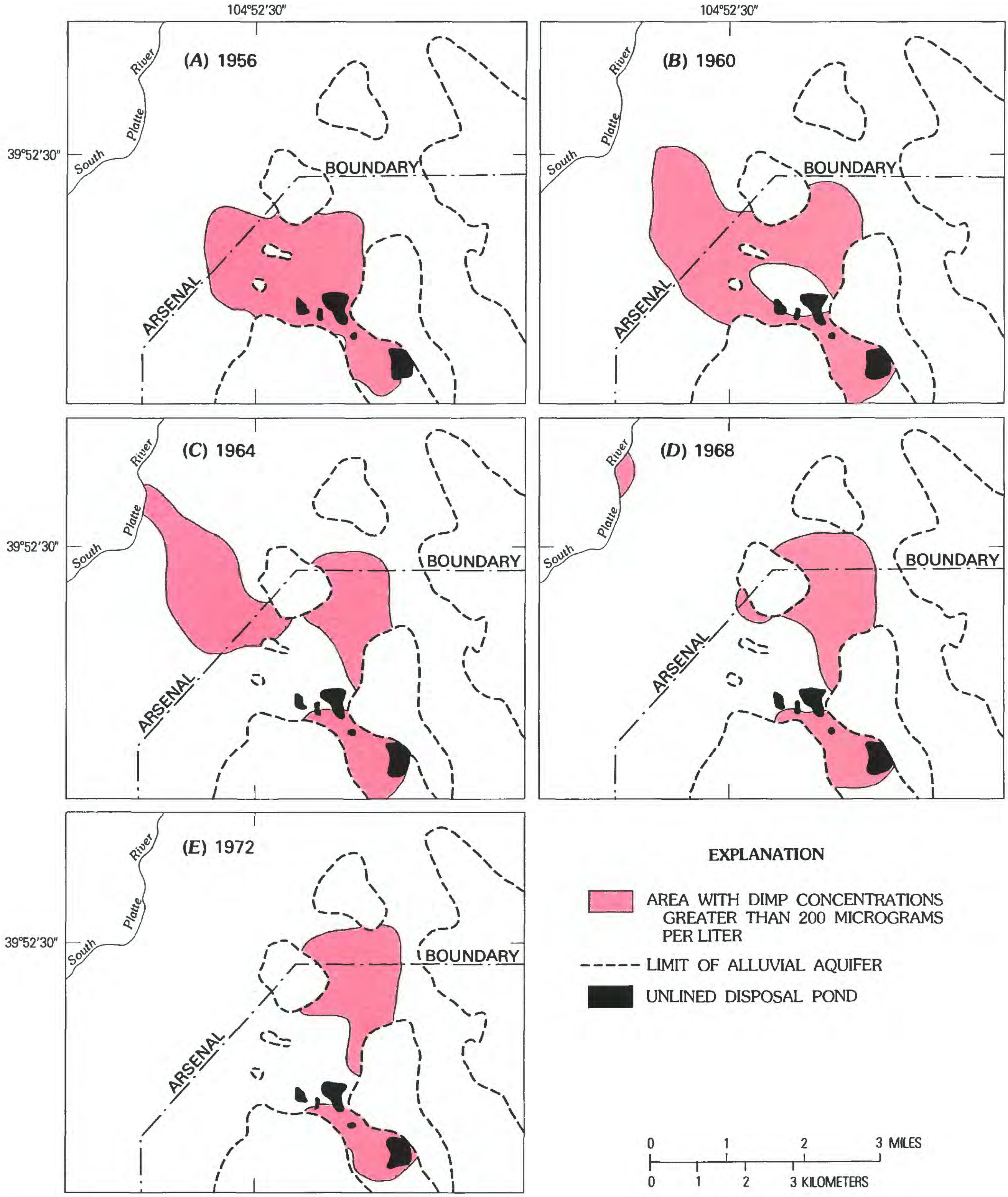

Figure 36. Historical movement of DIMP in the alluvial aquifer.

Figure 37. Liquid-waste-disposal trenches at the Lowry Landfill, May 1976. Dark liquid in center of scene is industrial waste in active trench. To the right, a new trench was being excavated; to the left, an old trench had been nearly filled with municipal refuse.

Contamination of the Bedrock Aquifer

From 1968 to 1981, industrial waste was disposed of in unlined trenches at the Lowry Landfill, which is located about 15 miles southeast of downtown Denver. The trenches were excavated 8 to 15 feet deep into the claystone and silty sandstone bedrock materials of the Denver Formation and Dawson Arkose. Industrial waste was poured into a trench until several hundred thousand gallons of liquid accumulated, at which time the trench was filled with municipal trash and covered with a layer of earth (fig. 37). Little attempt was made to monitor the chemical wastes dumped into the trenches, and adverse chemical reactions and several fires occurred in the trenches while they were used. Approximately 3 million gallons of industrial waste was placed in trenches during 1972, and the rate of disposal increased to about 15 million gallons per year by 1980. Between 1968 and 1981, about 90 million gallons of liquid waste may have been placed in the upper part of the bedrock formations at the Lowry Landfill.

The 14 years of large-scale industrial waste disposal at the landfill have resulted in degradation of ground-water quality in the shallow part of the bedrock aquifer underlying the area. However, unlike contamination of the alluvial aquifer near the Rocky Mountain Arsenal, which has affected a 28-square-mile area, contamination of the bedrock aquifer at the Lowry Landfill is confined to an area of less than 0.5 square mile. Organic chemicals have been detected in water from only a few of the 21 bedrock monitoring wells at the site, and most of the polluted wells are located within 0.2 mile of the former waste-disposal trenches.

The chemical composition of the industrial waste disposed of at the Lowry Landfill is unknown, but if a particular chemical was present in the waste at a modest concentration of 1,000 milligrams per liter, about 370 tons of that chemical would have been placed in the bedrock formation during the 14-year period of operation of the trenches. About 50 tons of the organic chemical DIMP were carried into the alluvial aquifer during a 4-year period of disposal at the Rocky Mountain Arsenal. Thus, the volume of a contaminant disposed of at the Lowry Landfill could be many times larger than the volume of DIMP disposed of at the arsenal, yet the extent of contamination in the bedrock aquifer is almost insignificant in comparison with the DIMP contamination in the alluvial aquifer.

These two case histories illustrate how the alluvial and bedrock aquifers were affected by pollution at the two sites. However, the geology of both aquifers is varied; at different sites, differences in geology could alter the extent, rate, and direction of movement of the polluted ground water. In the bedrock aquifer, for example, the predominantly clayey geologic materials present near the Lowry Landfill restrict ground-water movement and polluted water remains in a local area. If the bedrock aquifer had consisted of sandstone, more rapid and widespread migration of polluted water would have been possible and municipal and domestic ground-water supplies might have been affected. In spite of local differences in geology, marked differences exist in the susceptibility of the alluvial and bedrock aquifers to the spread of contaminants. Because of these differences, most monitoring of ground-water quality near suspected sources of contamination has been done on the alluvial aquifer rather than the bedrock aquifer. The differences in susceptibility to pollution and existing water quality are additional factors affecting the development and use of the two aquifers.

GROUND-WATER USE

The management and use of water from the alluvial and bedrock aquifers is affected by climatic conditions, surface-water availability, geologic and hydrologic characteristics of the aquifer materials, water-level conditions, legal and economic constraints, and water-quality conditions in the aquifers. These factors can ultimately affect the cost of producing ground water of acceptable chemical quality. The resulting economic constraints, together with existing legal constraints, dictate the use of the aquifers. The cost of producing large volumes of ground water from the alluvial aquifer is relatively small because of shallow well depths, small pumping lifts to bring the water to the surface, minimal water-level declines, and large well yields. Well yields of 200 to 1,000 gallons per minute are common in large-capacity wells in the alluvial aquifer, and yields of 2,000 to 3,000 gallons per minute have been attained in some wells. The cost of producing water from the bedrock aquifer generally is much larger because deep wells must be drilled, pumping lifts are sometimes as much as 500 to 1,000 feet, water levels are declining rapidly in some areas, and well yields are relatively small. Yields of 50 to 500 gallons per minute are common in large-capacity wells in the bedrock aquifer; yields of 600 to 800 gallons per minute have been attained in a few such wells. The greater cost of water from the bedrock aquifer makes it an unattractive source of supply for large-volume, low-profit uses such as irrigation of most commercial crops (fig. 38). However, water in the bedrock aquifer usually is of better chemical quality than that in the alluvial aquifer; this makes it the preferred source for domestic and municipal uses (fig. 39), where the cost of the water may be of lesser importance and water-quality considerations may be of greater importance.

The larger volumes of less expensive water produced from the alluvial aquifer are well suited for irrigation uses. As a result, about 90 percent of the water pumped from wells in the report area is supplied by the alluvial aquifer

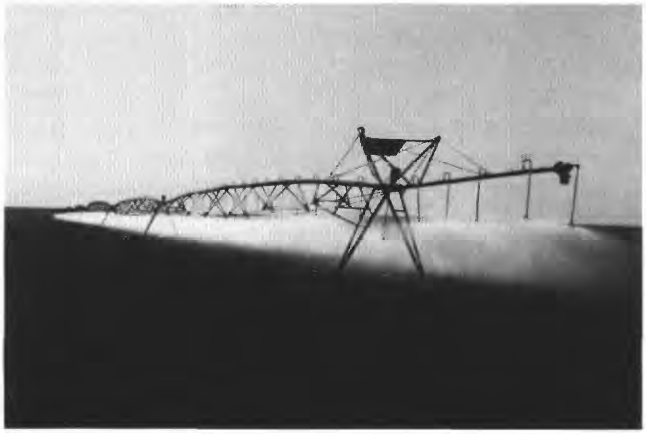

Figure 38. Center-pivot irrigation of cropland. The alluvial aquifer supplies water to many such systems.

Figure 39. Well completed in the bedrock aquifer used to supply water to the surrounding urban area.

for irrigation of nearby fields. An estimated 450,000 acre-feet per year of water is pumped from more than 2,000 irrigation wells in the alluvial aquifer and is supplemented with surface water diverted from the South Platte River and its tributaries to supply the 380,000 acres of irrigated farmland in the report area.

Water from the bedrock aquifer commonly is used as a domestic or stock supply for farms and ranches because of its superior chemical quality or because no other source is available. The largest use of the bedrock aquifer is in the outlying suburban areas near Denver, where rapid urbanization has exceeded the ability of municipal systems to supply surface water to the developing areas. As a result, water pumped from the bedrock aquifer is the principal source of supply. In 1985, about 36,000 acre-feet per year of water was pumped from the bedrock aquifer to supply domestic, municipal, industrial, and commercial requirements. In addition, a few parks, golf courses, and turf farms are irrigated with water from the bedrock aquifer. As many as 12,000 wells have been drilled into the bedrock aquifer; most of these are small-capacity wells used for domestic or stock supplies.

CONCLUSIONS

Many times it is erroneously assumed that if large volumes of water are present in an aquifer or lake, then this water can be used to easily satisfy the water requirements of the area. Commonly, it is further assumed that future increases in water demand can be met simply by drilling more wells or diverting more water. These simple solutions were adequate when the Nation was expanding westward and was first developing its western water resources from abundant, pure, and untapped supplies. As our Nation enters its third century, most of these readily available pristine sources of water have long since been developed, heavily used, or, in some places, nearly exhausted. The easy solutions to water problems that served us well in the past may no longer be suitable for dealing with the complex and often conflicting water needs of various segments of our society.

In the Denver basin for example, the bedrock aquifer contains 1.2 times as much water as Lake Erie of the Great Lakes. However, scientific knowledge, legal and economic constraints, and practical experience has shown that the largest supplies of ground water are best obtained from the alluvial aquifer even though it contains only one-fiftieth as much water as the bedrock aquifer. Many factors other than the volume of water in storage affect the use of an aquifer. Climatic conditions, precipitation runoff, the geology and water-yielding character of the aquifers, water-level conditions, volume of recharge and discharge, legal and economic constraints, and water-quality conditions all have an important bearing on the decision of how best to use the ground-water supplies.

As water demand exceeds currently available supplies, more costly sources of water of possibly poorer chemical quality may need to be used. Ground-water pollution by agricultural chemicals or industrial wastes already has occurred in the Denver basin and may become an increasingly important consideration in development of future water supplies from the two aquifers. The complexity of these aquifers makes a thorough understanding difficult, but essential, if wise use is to be made of their valuable water resources.

SELECTED REFERENCES

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METRIC CONVERSION FACTORS

The inch-pound units used in this report may be converted to the International System (SI) units by the following conversion factors:

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot	1233	cubic meter
acre-foot per year	1233	cubic meter per annum
degree Fahrenheit (°F)	5/9 (°F-32)	degree Celsius (°C)
foot	0.3048	meter
foot per day	0.3048	meter per day
foot per year	0.3048	meter per annum
foot squared per day	0.0929	meter squared per day
cubic foot	0.0283	cubic meter
cubic foot per second	0.0283	cubic meter per second
gallon	3.785	liter
gallon per minute	3.785	liter per minute
gallon per year	3.785	liter per annum
inch	2.540	centimeter
mile	1.609	kilometer
mile per hour	1.609	kilometer per hour
square mile	2.590	square kilometer
ton	907.2	kilogram

National Geodetic Vertical Datum of 1929: A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, and formerly called mean sea level, is referred to as sea level in this report.