GROUND WATER RESOURCES OF THE BEDROCK AQUIFERS OF THE DENVER BASIN COLORADO

2nd PRINTING

BY

JOHN C. ROMERO

OFFICE OF THE STATE ENGINEER
DIVISION OF WATER RESOURCES

Roy Romer
Governor

Jeris A. Danielson
State Engineer

GROUND WATER RESOURCES OF THE BEDROCK AQUIFERS OF THE DENVER BASIN COLORADO

2nd Printing

Preface to the 2nd Printing

Extensive utilization of Denver Basin bedrock aquifers as a source of water for municipal, domestic, commercial, and industrial purposes has resulted in a number of publications prepared specifically to meet that end. The first Ground Water Resources of the Bedrock Aquifers of the Denver Basin was a result of investigations which began in mid-1971 and extended into 1975. Published in 1976, it was the first report to describe the entire Denver Basin and its post-Pierre strata from a purely hydrogeologic standpoint. It also presented the first subdivision of the Dawson Formation into the Dawson, Denver, and Arapahoe aquifers by utilizing geophysical logs. When the report was published, it was realized that its main function would be to serve as a foundation upon which more detailed studies would be based.

Updates of the original bedrock maps were maintained and a second set was in use by early 1979. At the same time, the U.S. Geological Survey was expressing interest in the Denver Basin bedrock aquifers whereupon they agreed with the Colorado Division of Water Resources to jointly publish an updated version of the 1976 report. This was accomplished in 1981 as a series of USGS Hydrologic Investigations Atlases. Continuous demand upon the basins bedrock aquifers, a slow but steady influx of new data, frequent difficulties in identifying aquifer boundaries, and the passage of Senate Bill 5 in 1985 resulted in the need for a new revision. The resulting Colorado Division of Water Resources Denver Basin Aquifer Data Report was published in 1986 as part of the proceedings for hearings held to establish rules and regulations for the administration of ground water contained in the bedrock aquifers. This was followed by publication of four new Denver Basin Atlases (DBA-1,2,3,4) in 1988.

Even with the availability of the new maps, there remains a demand for the original Denver Basin report. This might be due to the presence of relatively lengthy formation and aquifer descriptions, a fair treatment of water quality and historical development concepts, and, most important, access to information and maps which are an integral part of the historical development of procedures by which the Division of Water Resources manages ground water in the Denver Basin aquifer system.

John C. Romero

TABLE OF CONTENTS

FIGURES

TABLES

ILLUSTRATIONS

8222I

INTRODUCTION

PURPOSE AND SCOPE OF THE INVESTIGATION

The extensive use of ground water for municipal, domestic, commercial and industrial supplies, the current intensified suburban and rural development and the perpetual search for supplemental water have resulted in the need for a thorough hydrogeologic appraisal of the bedrock aquifers of the Denver Basin. In the past, municipalities, industries, and other water users could depend upon existing surface and ground water supplies. Population increases east of the Front Range eventually required construction of storage reservoirs, diversions from streams and more recently transmountain diversion wherein water from the Western Slope is collected and diverted to the Eastern Slope for use in areas such as metropolitan Denver and Colorado Springs. At present there is a trend for population growth to occur along and beyond the periphery of the metropolitan areas to rural areas. This expansion of population is beginning to tax the capabilities of present water supply facilities. Although future demand may be in part satisfied by additional transmountain diversions and storage facilities, it is inevitable that ground water from the bedrock aquifers of the Denver Basin will be called upon to either supplement or furnish the entire water supply for some areas. As of this writing, the Denver Basin's bedrock aquifers furnish the sole supply of water to no less than 20 municipalities and an equal number of smaller water agencies. In addition, about 10 water agencies in the Denver Basin rely upon the bedrock aquifers to supplement surface water supplies. The current utilization trend is expected to continue.

The purpose of this investigation is to evaluate the hydrogeologic characteristics of the bedrock aquifers in the basin, and the origin, movement, quantity, availability, and use of the ground water. The chemical quality of the water and its suitability for different uses are also evaluated. Consideration is given to the present and probable future distribution of deep wells in the Denver Basin, and to the possible effects of long-term withdrawals from the various aquifers.

This investigation was conducted at the request of the Colorado State Engineer. It is intended for use as a guide in the administration of ground water withdrawals from the bedrock aquifers, for local planning agencies, municipalities, water distribution agencies, and private individuals interested in developing a supply of water from the bedrock aquifers of the Denver Basin.

All numerical data of this report are represented by both the metric and English (in parenthesis) systems (both rounded).

LOCATION OF THE STUDY AREA

The area described in this report consists of about 15,500 square kilometers (6000 square miles) and includes all or parts of Adams, Arapahoe, Douglas, Elbert, El Paso, Jefferson, Lincoln, Morgan and Weld

Counties, Colorado. The area is roughly oval in shape, has a north-south length of about 193 kilometers (120 miles) and a maximum width of about 112 kilometers (70 miles). Descriptively, the study area extends from Greeley south to a point about 40 kilometers (25 miles) southeast of Colorado Springs and from Golden east to about 19 kilometers (12 miles) east of Deer Trail (Fig. 1).

PREVIOUS INVESTIGATIONS

Much of the area investigated in this report has been studied by previous workers. The investigations are about equally divided between those of a strictly geologic nature and those of a strictly hydrogeologic nature. Investigations of a regional magnitude include those by McCoy (1893), Darton (1905), Lovering (1932), Kittlemen (1956), and McConaghy, et al (1964). The Denver Regional Council of Governments (1965, 1969) has produced many useful data on both ground water properties and water demands of the greater metropolitan Denver area. Emmons (1898), Johnson (1934), LeRoy (1946), Reichert (1954, 1956), Van Horn (1957), Smith (1964), Scott (1962, 1963), Bellew (1957), and Malek-Adani (1950) have provided a great amount of geologic information on the sedimentary and igneous rocks along the east flank of the "Foothills Belt" from the Golden area to Perry Park southwest of Castle Rock. Waage (1959) specialized in a Dakota group study and Wahlstrom (1947) dealt with the physiographic history of the Front Range. Richardson (1915) and Gabriel (1933) examined the Castle Rock area. Varnes and Scott (1967), Finlay (1916), Jenkins (1964) and Soister (1968) provided useful geologic data from the Air Force Academy area at the southern end of the Denver Basin. Dan and Pierce (1936) examined the Dawson and Laramie formations in a large portion of the southeastern part of the report area. McLaughlin (1946), McGovern and Jenkins (1966), Erker and Romero (1967), and Owens (1971) conducted hydrogeologic examinations in the southern part of the Denver Basin. Romero (1965), Duke and Longenbaugh (1966), and Owens (1967, 1971) cover ground water investigations in the Kiowa Creek, Bijou Creek and Lost Creek drainage basins. Kuhn (1968) and Bibby (1969) examined the relationship between the Laramie-Fox Hills aquifer and the Bijou Creek alluvium in the northeastern part of the Denver Basin. General information on the basin's bedrock geology have been presented by Bjorklund and Brown (1957), and Smith, et al (1964), and Romero and Hampton (1972).

METHODS OF INVESTIGATION

Work on the Denver Basin report began in late fall of 1970 with the collection and interpretation of electric logs obtained from the Colorado Oil and Gas Conservation Commission. Intervening stages involved the collection of all types of data and literature pertinent to the completion of this report. Because the outcrops of the bedrock formations have been previously mapped to an accuracy acceptable to this particular study, and due to the existence of a large volume of miscellaneous information, including water quality data, field work was held to a minimum. Major field investigations involved the collection of updated water level data for wells tapping the Dawson, Laramie, and Laramie-Fox Hills aquifers. It is hoped that a much larger ground water level monitoring network will

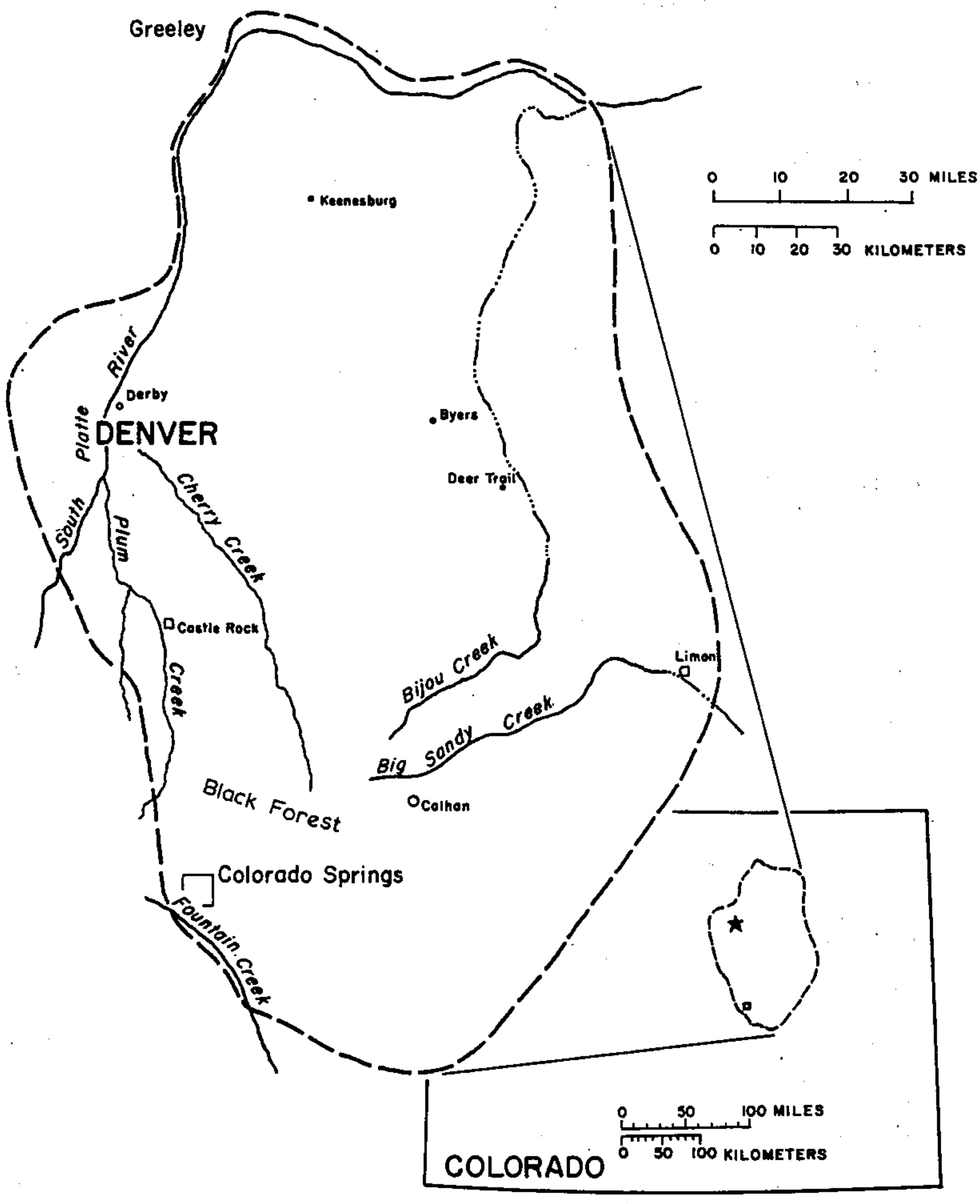

Figure 1. Index map of the Denver Basin study area

be operative by late 1976. This will be a part of a continuing investigation program scheduled for the Denver Basin.

ACKNOWLEDGMENTS

Particular appreciation is extended to the Colorado Oil and Gas Conservation Commission, whose willingness to allow prolonged use of a large number of oil well logs was vital to the completion of this report. Appreciation is also extended to the many land owners and water users in the project area who were most cooperative in providing information about their wells and for allowing access for water-level measurements. Valuable hydrogeologic information was obtained from Willard Owens and Associates during the initial and final stages of the investigation. Hydrogeologic information was also provided by Gene Hampton and Tom Major of the U. S. Geological Survey, Hank Baski of Dames and Moore, and Curtis Wells of Curtis Wells and Associates.

Appreciation is also extended to personnel of the Cities of Arvada, Aurora, Denver, Byers, Castle Rock and Westminster, and Crestview South Adams County Water and Sanitation Districts for furnishing valuable information regarding the historic use of water in their areas of jurisdiction.

Personal appreciation is extended to Mr. E. H. Phillips of Vorhees, Trindall, and Nelson, whose advice and counsel contributed to the progress of the study, and to the staff of the Colorado Division of Water Resources who assisted in the preparation of the final report and accompanying maps.

GEOGRAPHY

TOPOGRAPHY AND DRAINAGE

The Denver Basin study area is defined by the outcrop-subcrop of the Pierre-Fox Hills formation contact as portrayed on Plate 1 and Figure 1, and which lies within the Colorado Piedmont Section of the Great Plains physiographic province. It is somewhat elliptical in shape with the long axis trending roughly north-south. It consists of three relatively distinct subdistricts: (1) a wide band which nearly encircles the basin and is marked by relatively wide stream valley lowlands separated by gently rolling uplands, (2) a relatively isolated area in the south-central part of the basin which is marked by relatively narrow stream valleys, separated by gently rolling to steep uplands (the latter exhibits a widespread growth of pine trees and is known as the Black Forest region), and (3) on the western side, a narrow band of steep, northwest trending hogback ridges that dip sharply away from the crystalline rocks of the front range. The hogback ridges mark the westernmost extent of the project area. Maximum topographic relief within the study area is about 975 meters (3200 feet); the altitude above mean sea level ranges from about 2340 meters (7690 feet) on Spruce Hill in the Black Forest region to about 1370 meters (4500 feet) near the junction of U. S. Highway 34 and U. S. Highway 6 in the northeastern portion of the study area.

The study area is drained by a large number of streams, most of whose headwaters are in the Black Forest region. The South Platte River enters the study area about 20 kilometers (12 miles) southwest of Denver, flows in a generally northward direction to Greeley where it swings toward the east. Plum Creek, and several streams entering the South Platte from the west, including Bear Creek and Clear Creek, begin in the Front Range. Most of the streams which drain the southern part of the study area have headwaters either in the Black Forest region or in the Rampart Range.

Major northward or eastward flowing streams in the South Platte drainage are Plum Creek, Bear Creek, Cherry Creek, Clear Creek, Box Elder Creek, Kiowa Creek, and Bijou Creek. Major streams in the Arkansas River drainage are Monument Creek, Jimmy Camp Creek, Black Squirrel Creek, Horse Creek, and Big Sandy Creek. Only a very few of the streams whose headwaters are in the Black Forest region can be considered perennial. Most are dry except during periods of snowmelt or during and after heavy thundershowers. Flow under such conditions is often short-lived, because after several kilometers of travel on the surface runoff, water generally percolates downward through the sandy stream beds and becomes ground water.

Most of the streams whose headwaters are in the Black Forest region occupy long, narrow drainage basins in which all parts of the drainage are close to the main streams and sub-basins are quite small. In such areas, surface runoff reaches the main stem in a short time after a storm and flooding is common. (Mundorff, 1964, p. 49). The gradients of most of the streams are about 66 meters per kilometer (350 feet per mile) in the Black Forest region and about 4 meters per kilometer (20 feet per mile) in the lowland areas.

CLIMATE

The area investigated is typical of the continental, semi-arid plains regions. The climate is relatively uniform from place to place with characteristic features of low relative humidity, abundant sunshine, generally light rainfall, moderate to high wind movement, and a large daily range in temperature (U. S. Department of Commerce, 1968).

Normal annual precipitation for the basin ranges from about 28 to 43 centimeters (11 to about 17 inches), the high value occurring in the higher elevations of the Black Forest region. About 70 percent of the precipitation occurs generally as thundershowers between May and September. The thundershowers are erratic, unevenly distributed and are often accompanied by strong winds and sometimes by destructive hail. The erratic nature and uneven distribution of precipitation results in some local areas experiencing extended dry periods. In general, the precipitation is sufficient to support native grasses, hay and some grains.

Normal monthly temperatures range from about -5 to 0 C (25 to 30 F) during the winter months to 30 to 40 C (60 to 70 F) during mid-summer. Annual precipitation and temperature for six weather stations are shown graphically in figure 2. The frost-free growing season ranges from about 120 days in the Black Forest region to about 140 days in the prairie lowlands.

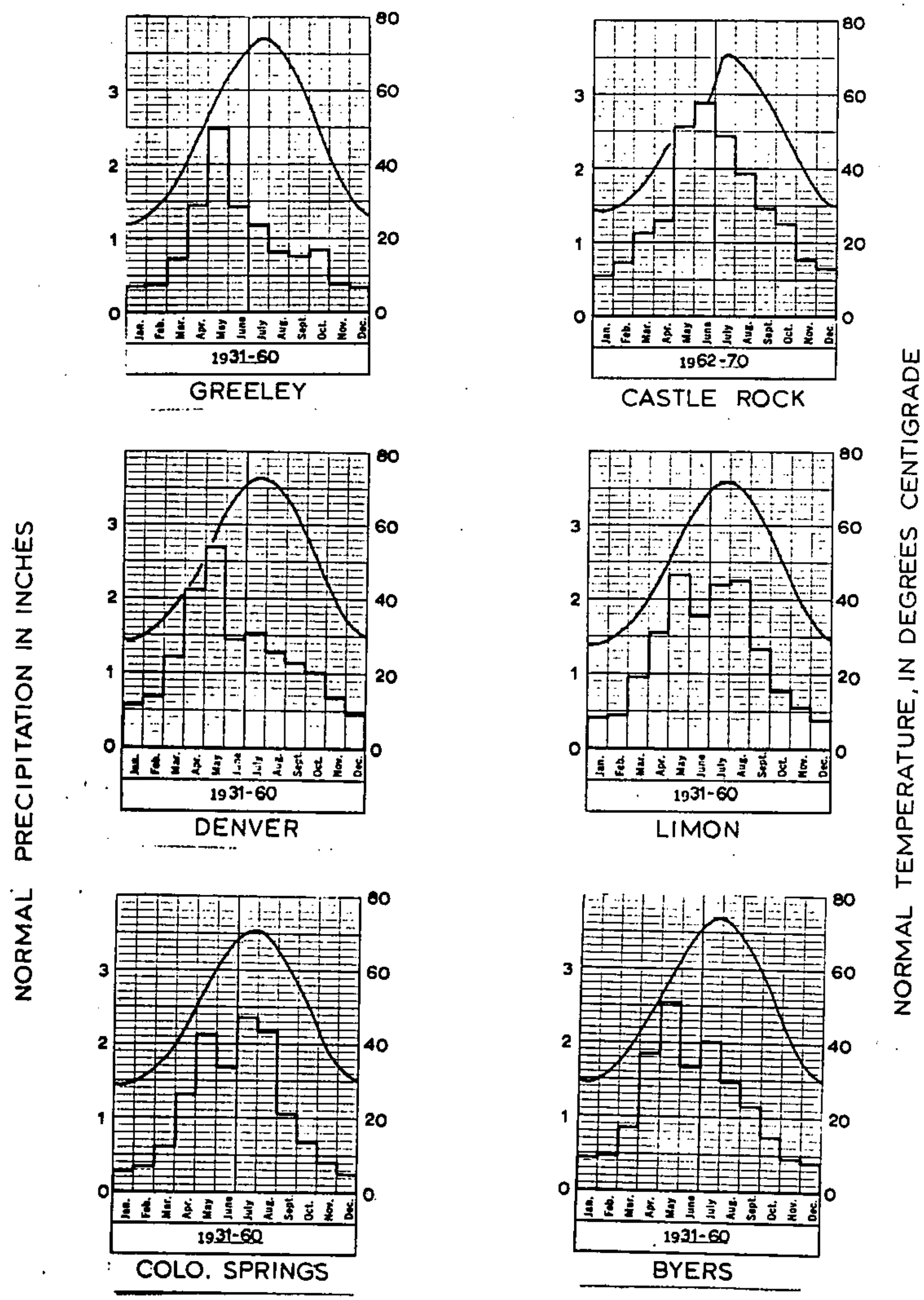

Figure 2. Normal monthly precipitation and temperature for the period 1931-60 at Byers, Colorado Springs, Denver, Greeley and Limon weather stations, and the period 1962-70 at the Castle Rock station. (Data from U. S. Weather Bureau). Multiply inches by 2.54 to find centimeters.

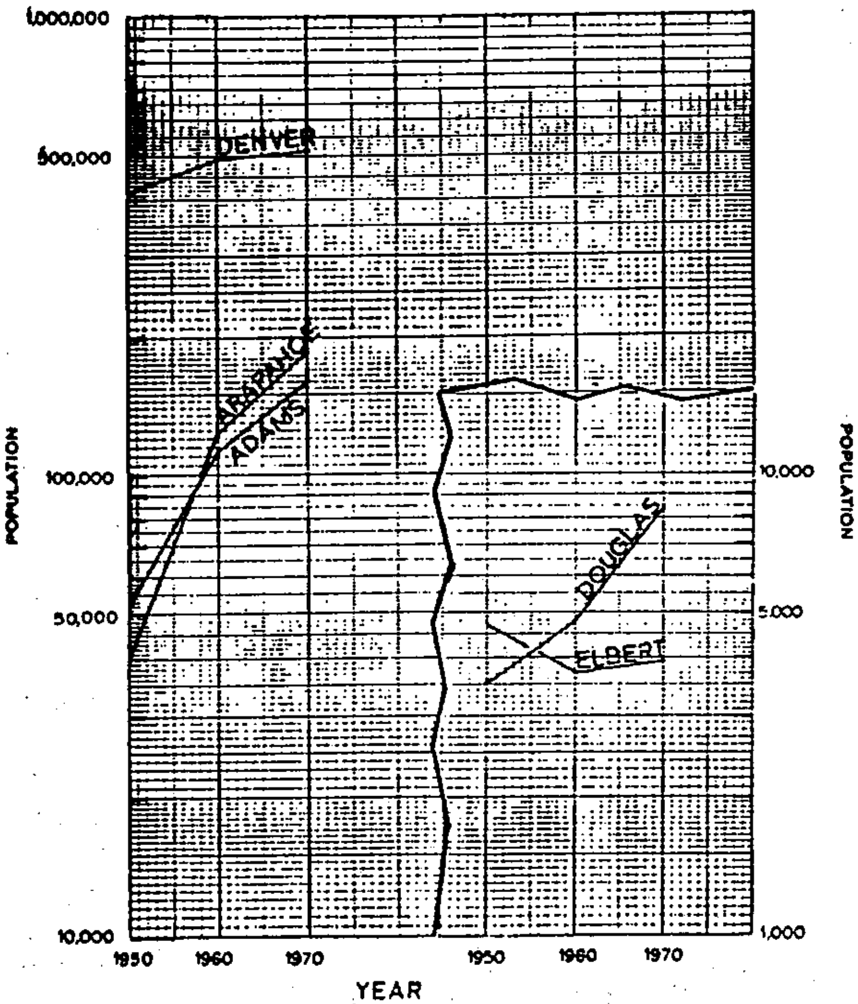

Figure 3. Population growth of typical counties in the Denver Basin.

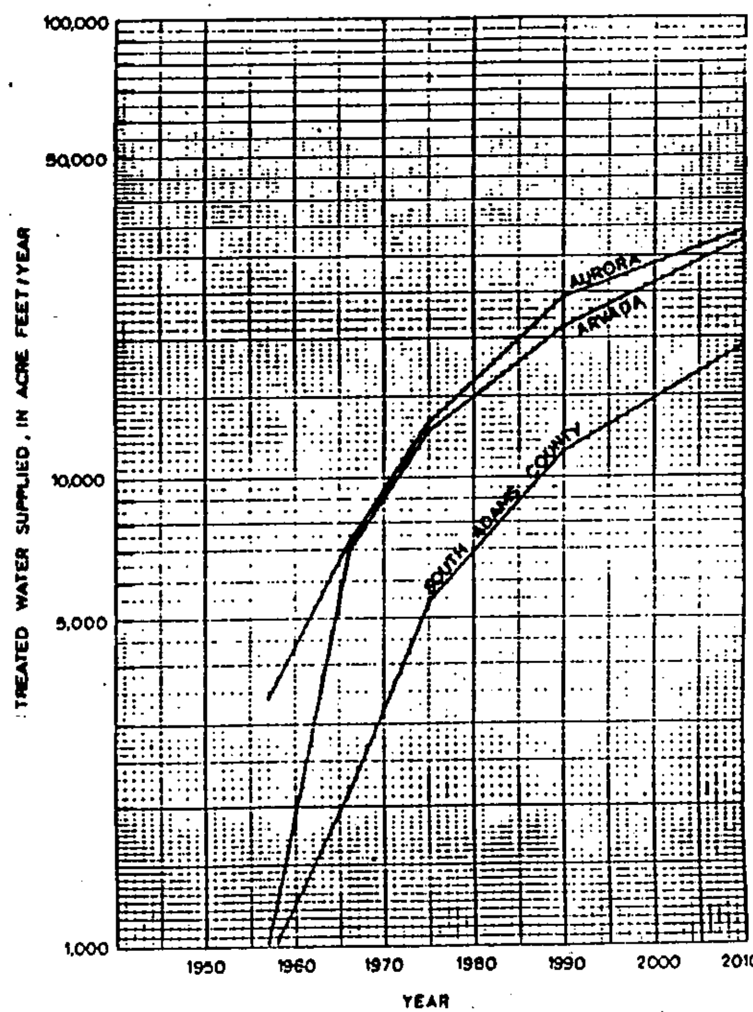

Figure 4. Graph showing present and projected demands for water by typical water supply agencies within the Denver Basin. Multiply acre feet by 1233.?2 to find cubic meters.

The combination of the project area's distance from major sources of moisture (the Pacific Ocean and the Gulf of Mexico), the rainshadow effect of the Rocky Mountains, and relatively high altitude results in low relative humidity throughout most of the basin. The average relative humidity for the Denver area is 36% during summer months and 42% during winter months. Low relative humidity and frequent wind results in a relatively high evaporation rate. The range of Class A pan-evaporation is from about 137 centimeters (54 inches) along the foothills and Black Forest region to about 162 centimeters (64 inches) in the eastern prairie lowlands.

AGRICULTURE AND INDUSTRY

The present agricultural economy of the study area is based on irrigated and dry farming, and stock raising. The principal irrigated crops are corn, sugar beets, alfalfa, potatoes, beans and truck garden vegetables. Dry-farmcrops are wheat and other small grain crops. Livestock raising includes beef and dairy cattle, hogs, sheep, and poultry.

The principal industries of the basin are agriculturally oriented. Widespread sand and gravel deposits are exploited for the manufacture of concrete products, home building and for road construction. There are also some local deposits of coal, oil and clay.

At present, most of the water used for irrigated crops is obtained from either surface water diversions or from shallow ground water supplies. There are a few isolated cases wherein small scale irrigation is accomplished by applying water pumped from bedrock formations. Water for stock is generally obtained from either shallow or bedrock aquifers. Water from bedrock aquifers is preferred in cases where certain types of livestock cannot tolerate hard water such as that found within the lower reaches of some of the basin's larger stream systems. Water for most industrial and municipal uses is primarily obtained from surface and shallow ground water supplies. A few industries and many water supply agencies either supplement such sources with bedrock water or rely totally upon bedrock water.

The basin is served by a system of federal and state highways, county roads and by the main lines of the Burlington-Northern, Denver and Rio Grande Western, Rock Island, Santa Fe and Union Pacific Railroads.

POPULATION AND GROWTH

The population within the boundary of the project area is about 1.5 million. About 75 percent of the total live near large population centers such as Metropolitan Denver, Castle Rock and Colorado Springs.

During the past quarter century the population of the study area has continued to grow. The greater percentage of this growth has occurred in the western and northern portions of the basin. The reasons for such growth are probably related to gradual reorientation from agricultural to industrialized areas. The brunt of the population increase has and is occurring in the greater Metropolitan Denver area, and between Denver and Colorado Springs along the so-called urban corridor. The average annual growth rate (1960 through 1970) for Adams, Arapahoe, Denver, Douglas and Elbert Counties is 3.6 percent.

As population growth continues, so does the demand for treated water. The annual increase in demand for treated water for many water supply agencies within the metropolitan area is roughly 10 percent.

Figure 3 illustrates population growth by counties lying 80 percent or more within the project area and figure 4 illustrates present and projected demands for treated water from typical water supply agencies. Water demand and supply will be given a more thorough treatment in later sections of this report.

GEOLOGY

REGIONAL GEOLOGIC SETTING

The Denver Basin is a structural basin which owes its existence to a long series of tectonic adjustments which began in Precambrian time and has continued intermittently to the present. The basin, which extends northward into Wyoming, is flanked on the west by the Southern Rocky Mountains and on the east by the High Plains. The west flank of the basin is marked by the steeply upturned sedimentary rocks which abut against the crystalline rock complex of the mountains and dip toward the east to the synclinal axis of the basin. The sedimentary rocks form hogback ridges and strike valleys along most of the western flank of the basin, but toward the south, abrupt displacement by the Rampart Range fault has prevented hogback formation except in the Perry Park and Colorado Springs areas. The northern, eastern, and southeastern parts of the basin are topographically flat to gently rolling. Plates 1 and 2 are generalized bedrock and surficial geologic maps of the basin and table 1A is a generalized composite section of the stratigraphic units of the Denver Basin. Table 1B is a more detailed section which briefly describes the unit's physical character and water-bearing properties.

SUMMARY OF GEOLOGIC AND PHYSIOGRAPHIC HISTORY

The following summary of the geologic and physiographic history of the Denver Basin project area is taken largely from McCoy (1953), Van Tuyl (1955) and Smith, et al (1964), and in part from field observations made previous to and during this investigation.

Pre-Pennsylvanian sedimentary rocks in the Denver Basin project area are not found north of Township 10 South. Along the foothills in the southernmost part of Township 10 South intermittently extending to and beyond Colorado Springs are found deposits of Cambrian, Ordovician, and Mississippian age. The rocks are composed primarily of shallow marine quartzitic sandstones, massive limestones, dolomites, and a few stringers of mudstone. The materials were deposited in a narrow east-west trending trough between the structurally positive elements called Siouxia (to the north) and Sierra Grande (to the south) (McCoy, 1953). The base of the series is the Sawatch Sandstone of Cambrian age and the top is the Madison Limestone of Mississippian age.

The beginning of the Denver Basin is thought to have occurred during Pennsylvanian time when the primeval makings of the north-south trending structural axis of the basin occurred. Uplift toward the west (North Park and Uncompahgre positive regions - often termed Ancestral Rockies) was accompanied by removal of existing pre-Pennsylvanian rocks north of Larkspur and resulted in the accumulation of 300-600 meters (1000-2000 feet) of coarse arkosic sand, gravel, and silt of the Fountain Formation. The period of aggradation was followed by a period of almost continuous deposition in the Denver Basin. That seas encroached and regressed is apparent in the nearshore dune environment of the Lyons Sandstone (Permian), shallow sea, landlocked basin and floodplain deposits of the Lykins Formation (Permo-Triassic), and subareal deposits of late Triassic age.

No record of the early Jurassic is present in the Denver Basin area. Late Jurassic and early Cretaceous is marked by a period of continental conditions during which the Ralston Creek and Morrison Formations and Lytle Formation of the Dakota Group were deposited. The Ralston Creek and Morrison Formations are of fresh water, lake, swamp, and fluvial origin, and the Lytle is a floodplain deposit. From early Cretaceous to Fox Hills time in late Cretaceous the Denver Basin experienced downwarping, encroachment of the sea and deposition of about 2100 meters (about 7,000 feet) of marine sandstone, siltstone, shale, and limestone. The sequence is represented by the South Platte Formation of the Dakota Group, the Benton Group, the Niobrara Formation, and the Pierre Formation. Withdrawal of the sea in late Cretaceous time was marked by deposition of the sandy-shale transition zone of the upper Pierre and the sandstones of the Fox Hills and lower Laramie Formations. Continuous regression of the sea and rise of the Laramide Rockies resulted in deposition of fresh water sandstone, claystone, shale, coal, and, during a geologically brief increase in the rate of mountain building, the deposition of 300 to 450 meters (about 1000-1500 feet) of coarse sandstone and conglomerate of the Cretaceous part of the Dawson Group. Mountain building slowed considerably by early Cenozoic time when the finer-grained sediments of the Paleocene part of the Dawson Group were deposited.

During middle Tertiary time the region encompassed by the project area was subjected to successive rejuvenations, erosion intervals, and climatic changes which resulted in the deposition of the Castle Rock Conglomerate (Oligocene). Later, during Miocene and Pliocene times, extensive blanket-like beds of clay, silt, sand and gravel were deposited as a vast pediment over most of the region extending from the mountain front to the Great Plains. It has been suggested by many investigators (e.g., Pearl, 1971) that the South Platte and Arkansas Rivers were occupying their present courses at the close of Pliocene time.

Regional uplift in late Tertiary time initiated the development of present major physiographic features by the development of numerous

Table 1A - Generalized composite section of the geologic units of the Denver Basin, Colorado.

Era	System or Period	Series	Geologic Unit	
Cenozoic	Quaternary	Recent and Pleistocene	Quaternary surficial deposits	Stream channel, flood-plain and terrace deposits; eolian sand, etc.
	Tertiary	Oligocene	Castle Rock Conglomerate	
			Tertiary intrusive and extrusive rocks	
Cenozoic and Mesozoic	Tertiary and Cretaceous	Paleocene ---?---- Upper Cretaceous	Dawson Group	Dawson Arkose
				Denver Formation
				Arapahoe Formation
Mesozoic	Cretaceous		Laramie Formation	Upper part
				B sandstone
				A sandstone
			Fox Hills Sandstone	Milliken Sandstone
				lower part
			Pierre Formation	
			Niobrara Formation	Smoky Hill Shale
				Fort Hayes Limestone
			Benton Formation	Carlile Shale
				Greenhorn Limestone
				Graneros Shale
		Lower Cretaceous	Dakota Group	South Plate Formation
				Lytle Formation
	Jurassic	Upper Jurassic	Morrison Formation	
			Ralston Creek Formation	
Palezoic	Triassic ? and Permian		Lykins Formation	Strain Shale
				Glennon Limestone
				Bergan Shale
				Falcon Limestone
				Harriman Shale
	Permian		Lyons Sandstone	
	Pennsyl- vanian		Fountain Formation	
			Glen Eyrie Formation	
	Mississi- pian		Madison Limestone	
			Williams Canyon Limestone	
	Ordovician and Cambrian		Manitou Dolomite	
	Cambrian		Sawatch Sandstone	
Precambrian			crystalline rocks	

tributaries to the South Platte and Arkansas Rivers. The tributaries worked headward and by early Quaternary time (Pleistocene and Holocene) had removed the middle and late Tertiary sediment deposits and an undetermined amount of older strata from the west flank of the Denver Basin (Van Tuyl, 1955).

Since the removal of the Tertiary pediment deposits from most of the Denver Basin, alternating episodes of valley development and pedimentation related to climatic changes have resulted in the development and partial destruction of gravel-capped terraces along important streams. Differential erosion of upturned sediments along the foothills resulted in the formation of hogback ridges and strike valleys, and increased the relief of erosion remnants such as North and South Table Mountain, Green Mountain, and many Castle Rock Conglomerate-capped buttes in southeastern Douglas County and southwestern Elbert County.

GEOLOGIC FORMATIONS

The Denver Basin project area is underlain by approximately 4570 meters (about 15,000 feet) of consolidated to semiconsolidated sedimentary rocks ranging in age from Cambrian to Recent. Rocks older than the Fountain Formation (Pennsylvanian-Permian) are discussed only briefly. Rocks younger than the Castle Rock Conglomerate are discussed because of their influence on natural recharge and discharge to the bedrock formations (tables 1A and 1B).

Precambrian Basement Rocks

The sedimentary rocks of the Denver Basin are upturned against the Precambrian crystalline rocks of the Front and Rampart Ranges. The Precambrian rock complex has yet to be completely deciphered. Both igneous and metamorphic rocks are present and consist primarily of batholithic and stocklike granitic rocks, pegmatite dikes, and a relatively large assortment of gneisses and schists. They are important only in that they form the western boundary of the study area and they have been intermittently fractured since Precambrian time (refer to Structure, this report).

In the northern part of the project area, a pronounced nonconformity separates the Precambrian rocks from the overlying Fountain Formation of Pennsylvanian age. Southward along the Rampart Range from Township 10 South, a series of early Paleozoic formations occur between the Precambrian rocks and the Fountain Formation.

Early Paleozoic Rocks

Rocks of early Paleozoic age are limited to a relatively small section of the southwestern part of the Denver Basin. The rocks range in age from Cambrian to Mississippian and are represented by the Sawatch Sandstone (C), Manitou Dolomite (O), Williams Canyon Limestone (M), and Madison Limestone (M). These rocks crop out only in widespread locations extending along the Rampart Range fault southward to and beyond Colorado

Springs. Work by MacLachlan (1961) indicates that many of the sediments extend southward as far as the Arkansas River and eastward as far as the Great Plains. Their combined thickness averages about 145 meters (about 475 feet).

Pennsylvanian, Permian, and Triassic Rocks

Glen Eyrie Formation - Developed only in the Colorado Springs area, the Glen Eyrie Formation rests unconformably upon the weathered surface of Mississippian and older rocks. The formation consists of about 30 meters (about 100 feet) of dark colored shales with thin interbedded sandstones. In the Colorado Springs area, the formation is interstratified with, and conformably overlain by, arkosic sandstone of the Fountain Formation.

Fountain Formation - Unconformably overlying the Precambrian basement rocks in the northern part of the Denver Basin and conformably overlying the Glen Eyrie Formation in the Colorado Springs area are the continental deposits of the Fountain Formation. The dominant constituents of the formation are red, pink, and gray, cross-bedded, poorly sorted micaceous and arkosic, sandstones and conglomerates. Unevenly distributed throughout the formation are micaceous shales and mudstones, and locally thin beds of fresh-water limestone. Particle size ranges from silt to cobbles up to 15 centimeters (about six inches) in diameter. The predominantly red color of the formation is due to iron oxide cement, hematite films on sand grains, pink feldspar, and red interstitial argillaceous material (Scott, 1963, p. 88). Silica and calcareous cement are present, but do not add to the formation's red color.

The Fountain Formation is generally poorly exposed - in spite of the fact that the formation is upturned sharply against the Precambrian basement rocks. The sandstone of which it is primarily composed is in most places, poorly cemented with iron oxide and carbonaceous material and forms numerous strike valleys between its contacts with underlying and overlying formations. The more resistant beds are probably the result of a higher content of silica cement. The difference in hardness of individual beds is the primary cause of the Fountain to weather and erode into picturesque shapes such as those at the Garden of the Gods in Colorado Springs, at Perry Park, Roxborough Park, Red Rocks Park near Morrison and the Flatirons near Boulder. The Fountain is not exposed along portions of the southwestern part of the project area where it has been sharply downfaulted along the Rampart Range fault.

The Fountain Formation ranges in thickness from about 240 meters (about 800 feet) near Golden to about 1340 meters (about 4,400 feet) in the Colorado Springs area. The reduction in thickness in the northern part of the project area is probably the result of thinning by one or more strike faults which occur along the foothills belt. The formation dips eastward at slopes ranging from 35 to 85 degrees.

The Pennsylvanian and Permian age of the Fountain is based on stratigraphic relationships with the Ingleside Formation to the north of the project area and with the Glen Eyrie Formation in the Colorado Springs area. The Fountain is unconformably overlain by the Lyons

Sandstone.

Lyons Sandstone - The Lyons Sandstone of Permian age overlies the Fountain Formation and forms a continuous resistant hogback that dips eastward at slopes ranging from 35 to 75 degrees. The formation consists of yellowish-gray (south) to brownish-yellow, tan and pink (north) fine to medium-grained, thin bedded to massive, quartzose sandstone. The Lyons is locally arkosic and cross laminated. Lenticular layers of coarse channel conglomerate occur near its base near the vicinity of Kassler (Scott, 1963, p. 90). Throughout most of the area where the Lyons is exposed, it is found to be friable. Predominant cementing materials are iron oxide and calcareous material. Iron oxide cement is more common in the lower portion of the formation and forms resistant sheets of maroon and dark reddish-brown sandstone.

The Lyons Sandstone ranges in thickness from about 30 meters (about 100 feet) in the Golden area to about 120 meters (about 400 feet) in the vicinity of Colorado Springs. Variations in thickness are likely to occur in those areas subjected to intensive faulting such as in the Golden-Morrison-Littleton area. The formation is generally well exposed except along the Rampart Range fault in the southwestern part of the project area.

The Permian age of the Lyons Sandstone is based on identification of reptile tracks and correlation with formations lying north and east of the project area. The Lyons Sandstone is in conformable contact with the overlying Lykins Formation.

Lykins Formation - The Lykins Formation of Permian and Triassic age is predominantly a reddish-maroon, thinly-bedded shale and siltstone with minor sandstone and limestone beds. The formation is relatively non-resistant and occupies a strike valley between the Lyons Sandstone and Dakota Group. Dips of the Lykins Formation average about 60° northeasterly; with exceptions occurring locally where it has been overturned by faulting, i.e., along southern extremities of the Jarre Canyon fault and along a branch of the Rampart Range fault in the southern part of the project area.

In the Golden-Morrison-Littleton area, the Lykins can be subdivided into five recognizable members (table 1). For a detailed description of these members, the reader is referred to LeRoy (1946, p. 30-42). Average thickness of the Lykins is about 138 meters (453 feet).

The Lykins Formation is generally poorly exposed except along road cuts and gullies, or where the Glennon Limestone forms a minor hogback. Locally, the Lykins has been thinned by the Golden and Rampart Range faults.

The Permian-Triassic age span of the Lykins Formation is based on stratigraphic relationships, lithologic affinities and weak paleontologic evidence. The Lykins Formation is unconformably overlain by the Ralston Creek Formation.

Jurassic Rocks

Ralston Creek Formation - The Ralston Creek Formation is composed of varicolored limestone, calcareous shale, gypiferous deposits and locally thin beds of fine-grained, light yellow sandstone. Thickness of the formation ranges from about 0.6 meters (about two feet) in the Colorado Springs area to about 33 meters (about 110 feet) in the Golden area. Near Colorado Springs the formation consists of about 0.6 meters of grayish-brown, fresh-water limestone. The formation thickens northward and becomes silty and locally gypsiferous. Near Kassler the formation is about 15 meters (about 50 feet) thick and consists of a series of yellowish-gray, ridge-forming limestone beds separated by thin-bedded sandstone and shale in the lower part and silty, calcareous shale in the upper part. Northwest of Golden, the formation is 30 meters (about 100 feet) thick and composed primarily of varicolored claystone, calcareous siltstone and thin-bedded limestone; the claystone is orange, red, green, and gray, and the limestone is commonly light gray and locally tinged with red or orange.

The Ralston Creek Formation is generally covered by surficial deposits except in water gaps and road cuts. It occupies part of the strike valley between the Lyons and Dakota hogbacks. Locally it has been thinned by the Golden and Rampart Range faults. Dips range from about 40° to 65° northeasterly.

The Jurassic age of the Ralston Creek Formation is based on paleontologic evidence and stratigraphic correlation.

Morrison Formation - The Morrison Formation of Late Jurassic age consists of a series of non-marine shale, siltstone, sandstone and marlstone. Thickness of the Morrison ranges from 60 meters (about 200 feet) in the Colorado Springs area to about 120 meters (about 400 feet) at Kassler and 91 meters (300 feet) at Golden. The lower part of the formation constitutes a series of greenish-gray and reddish, massive to thin-bedded, sandy shale interbedded with lithographic, fresh-water marlstone and occasional lenticular masses of cross-bedded, brownish-gray to light brown and yellow, calcareous sandstone. The base of the Morrison is marked by a relatively consistent bed of light-gray to brown, cross-bedded sandstone.

The upper part of the formation consists of red, brownish-red, and variegated, silty claystone, interbedded with reddish or yellowish-gray, fine to medium-grained sandstones. The sandstones become more numerous near the top of the formation.

The Morrison Formation crops out on the west slope of the hogback formed by the overlying Dakota Group. Most exposures are hidden by colluvial debris and vegetation. Dips generally range from 30° to 60° northeasterly; locally the beds stand vertically or are overturned due to structural movements along the Golden fault. The formation has been thinned locally by the Golden and Rampart Range faults.

Continental deposition within streams, lakes, and swamps is responsible for the nature of the Morrison Formation. It has been age dated primarily by fossil evidence. The Morrison is unconformably overlain by the Lytle Formation of the Dakota Group.

Lower Cretaceous Rocks

The Dakota Group - At present the rocks lying between the Morrison Formation and Benton Group that crop out along the Front and Rampart Ranges have been referred to by two different sets of names. In the Colorado Springs area (and southward) the rocks are referred to as the Purgatoire Formation (lower part) and the Dakota Sandstone (upper part). In the northern regions the rocks are referred to as the Dakota Group. In this report the term Dakota Group is preferred because of predominant usage of that term in the project area and because use of the word "Dakota" implies reference to a nearly unmistakable series of beds in the stratigraphic column.

The lower part of the Dakota Group is called the Lytle Formation. Early Cretaceous in age, the Lytle Formation is composed of 9 to 30 meters (30 to 100 feet) of yellowish-gray, lenticular, locally conglomeratic sandstone, irregularly interbedded with varicolored claystone. It is characterized by lenticularity of its sandstones, discontinuous extent of other units, and content of quartz pebbles, chert, quartzite, and logs of agatized wood. It is also locally cross-bedded and ripple marked. Most of the sandstones are relatively resistant to erosive processes, hence the Lytle and overlying South Platte Formation form a conspicuous hogback ridge.

The upper part of the Dakota Group is referred to as the South Platte Formation and ranges from 60 to 106 meters (about 200 to 350 feet) in thickness (Waage, 1959, p. 119). The predominant rock type is a fine-grained, light-brown to tan-weathering, medium-bedded to massive, locally ripple-marked sandstone. Gray to black clay, shale, silty shale and siltstone are interlayed between the numerous sandstone beds. In the northern part of the project area, the shales are locally very pure and highly refractory and have been utilized in the ceramics industry.

The sandstones of the Dakota Group are generally indurated with limonitic, calcareous, and more commonly, silicious cement. The group is most conspicuous as a continuous hogback, locally scarred by clay mining activities, with dips commonly ranging from 40° to 60° easterly. These values are exceeded locally where the group has experienced overturning. The Dakota Group has been locally thinned by the Golden, Jarre Creek, and Rampart Range Faults. Ballew (1957, p. 70, 71) reports that the Dakota is about 2740 meters (about 9000 feet) below the surface in the Jarre Creek area.

LeRoy (1946, p. 75) attributes the deposits of the Dakota Group to a primarily near-shore, deltaic environment. The early Cretaceous age of the group is based upon paleontological evidence. The upper member of the Dakota Group is in transitional contact with the Benton Formation.

Upper Cretaceous Rocks

Benton Formation - The Benton Formation consists of a series of thin-bedded, dark-gray to gray-black, fissile marine shales, interbedded with bentonite, soft, platy, shaley limestone, and local beds of calcarenite. It ranges in thickness from 90 meters (about 300 feet) in the Colorado Springs area to 152 meters (about 500 feet) in the Golden area. The formation is often described in terms of three rock units which lie within the formation (table 1).

The Benton Formation is generally poorly exposed except in road cuts or water gaps. Topographically, the Benton tends to form a subdued valley between the Dakota hogback and the Fort Hays Limestone of the overlying Niobrara Formation. The formation dips from about 40° to 70° northeasterly. It has been locally cut out by the Golden fault and intermittently by the Rampart Range fault. Its age is based primarily on paleontological evidence. The Benton is unconformably overlain by the Niobrara Formation.

Niobrara Formation - The Niobrara Formation is composed primarily of marine limestone, chalk and chalky shale (Varnes, D. G., and Scott, G. R., 1967, p. 13 and Scott, G. R., 1962, p. 14). Thickness of the formation ranges from 106 meters (about 350 feet) in the Golden area to about 160 meters (about 530 feet) in the Colorado Springs area. The Niobrara has been subdivided into two members; the lower member is termed the Fort Hays Limestone, the upper is termed the Smokey Hill Shale (table 1).

The Niobrara Formation dips toward the northeast at values ranging from 30° to 70°. It is generally poorly exposed and has been locally cut out by the Golden fault and intermittently by the Rampart Range fault. The Late Cretaceous age of the formation is based upon paleontological evidence. It is conformably overlain by the Pierre Formation.

Pierre Formation - The Pierre Formation consists essentially of 1520 to 2130 meters (about 5,000 to 7,000 feet) of medium to light and olive-gray, clayey, marine shale. The shale contains zones of hard, calcareous, locally fossiliferous concretions. Two thick siltstone beds and several thin ones occur in the section (Van Horn, 1957). Scott (1963, pp. 99-104) identified five major groups of strata within the Pierre Formation (table 1).

In the western part of the basin, the Pierre is upturned sharply against older sedimentary rocks. Dips average between 30° and 70° except where local structural conditions caused the formation, or at least parts of it, to stand vertically or exhibit overturning. Surface exposures of the Pierre have been thinned by the Golden fault and intermittently thinned by the Rampart Range fault.

To the north, south, and east, the Pierre Formation dips about one half of one degree toward the central part of the Denver Basin. Throughout the entirety of the study area, the Pierre is poorly exposed except in road and stream cuts. The age of the Pierre is based on paleontological evidence. It is in transitional contact with the overlying Fox Hills Formation.

Fox Hills Formation - The boundaries of the Fox Hills Formation have been a subject of controversy for many years. Because this report is ground water oriented, it in no way intends to solve stratigraphic problems. Instead, there is more or less agreement with statements by Lovering and others (1932, pp. 702-703) which involve a sand-shale sequence which represents a final phase in the transition from marine to continental deposition.

The Fox Hills Formation consists of a sequence of sandy shales interbedded with thin sandstone layers near its base and thick layers near the top. Thickness of the sequence ranges from a feather edge in the outcrop areas to about 61 meters (about 200 feet). The lower part of the Fox Hills consists of an average of about 45 meters (about 150 feet) of relatively soft, yellowish-brown to olive-brown, sandy shale interbedded with thin layers of limey sandstone which are locally fossiliferous and concretionary. The upper part of the formation consists of an average of 15 meters (about 50 feet) of medium-bedded to massive, soft to medium hard, olive-brown to tan sandstone interbedded with very thin layers of silty shale. This sandstone is often referred to as the Milliken Sandstone Member of the Fox Hills Formation. Lenticular ferrugenous concretions are common. Kuhn (1968, p. 7) observed silty shale layers several meters thick in the northeastern part of the project area. Faunal and floral fossils are common throughout the series. Emmons and others (1896, p. 71) state that the upper sandstone is noteworthy because of its position as a cap to the great thickness of Cretaceous clays and shales below it, its wide areal extent, abundant fossil remain, and its marked lithologic difference from the overlying basal sandstones of the Laramie Formation.

In the northern part of the project area, the Milliken Sandstone is locally separated from the basal Laramie sandstone by 6 to 30 meters (about 20 to 100 feet) of generally dark-gray, sandy, foraminiferal, locally lignitic shale (LeRoy, 1946, pp. 87-88).

The average dip of the Fox Hills Formation in the western part of the project area is about 70° toward the northeast. Locally, dips are near vertical to overturned. Throughout most of the eastern portion of the area, the formation dips 6 meters per kilometer (approximately 30 feet per mile) toward the deepest part of the Denver Basin. The formation is generally poorly exposed except in highway and railway cuts and along the banks of certain streams. Typical exposures of the Fox Hills Formation and the basal sandstone of the Laramie formation include: a Denver and Rio Grande Railroad cut in SW$\frac{1}{4}$, Sec. 21, T2S, R70W (somewhat north of the project area); a road cut along Alameda Parkway in SE$\frac{1}{4}$ of Sec. 23, T4S, R70W; in the W$\frac{1}{2}$, Sec. 21, T14S, R64W; along the east bank of Black Squirrel Creek in Sec. 18, T15S, R62W; in the vicinity of Cedar Point in Sec. 12, T8S, R58W; in the vicinity of Poison Springs, Adams County in Secs. 17 and 18, T8S, R58W; and on Wildcat Road in Sec. 27, T4N, R67W.

The Fox Hills Formation is dated on the basis of both paleontologic and lithologic evidence. It is unconformably overlain by the basal sandstone facies of the Laramie Formation.

Laramie Formation - The Laramie Formation, of late Cretaceous age, includes those strata occupying the interval between the Fox Hills Formation and the basal sandstones of the Dawson Group. The Laramie consists of a thick series of predominantly olive-gray and pale yellowish-brown, clayey shale, interbedded with frequently iron stained, light-gray, tan and dark-brown, fine to medium-grained quartzose sandstone, carbonaceous shales, claystone, and sub-bituminous to lignitic coal seams. The coal seams range in thickness from several centimeters to about 3 meters (about 9 feet) and are present in several stratigraphic horizons. The sandstones are locally white, contain a small amount of argillaceous matrix, and near the base and top contain irregularly shaped, generally iron oxide cemented concretions. Minute particles of black chert give the sandstones a "salt and pepper" appearance. The sandstones of the formation are generally loosely to moderately compacted and cemented with calcium carbonate or silica; locally the cementing material is limonitic, and result in the formation of ridges and hogbacks (Reichert, 1954, p. 15) Fossils are abundant throughout the formation. Thickness of the formation ranges from a feather edge in the outcrop areas to 152 meters (about 500 feet).

The Laramie Formation is considered by most investigators to consist of two parts, a lower part composed predominantly of sandstone and an upper part composed largely of shale (Smith and others, 1964, p. 23), (table 1, pl. 3). The lower 30 to 80 meters (100 to 260 feet) of the Laramie consists of a series of thin-bedded, white to yellowish-orange and tan, quartzose sandstone interbedded with seams of lignitic shale and coal, and two generally prominent beds of yellowish-brown to tan and light-gray, medium-grained, quartzose sandstones. The two sandstone beds form the base of the Laramie and from the base upward are termed the A and B sandstones. An intervening thickness of about 2 to 6 meters (about 5 to 20 feet) of shale commonly separates the two sandstones. The A and B generally range in thickness from 12 to 30 meters (about 40 to 100 feet); B is generally thicker than A by about 60 percent. Kuhn (1968, p. 9) reports that the B sand is capped by as much as two meters (about six feet) of hard carcareous sandstone. The cap is said to be locally responsible for the very prominent deflection on electrical resistivity logs (pl. 3).

A third sandstone, C, has been reported to exist 10 to 18 meters (about 30 to 60 feet) above B (Emmons and others, 1906, p. 74) but its small size, 2 to 3 meters (about 8 to 10 feet) thick, and its position with respect to other sandstones in the same general horizon make identification per se difficult.

The upper part of the Laramie Formation consists of 90 to 120 meters (about 300 to 400 feet) of bluish-gray to olive-gray and pale yellowish-brown, clayey shale, interbedded with siltstone, lignitic shale, workable coal seams and lenticular beds of medium to fine-grained quartzose sandstone. Irregularly shaped, iron oxide-cemented concretions occur in the upper sandstone layers. Electric logs of the Laramie reveal that certain sandstone layers near the middle of the formation can generally be traced throughout much of the central portion of the project area. In this report, the top of the Laramie is identified as that horizon below which is 90 to 120 meters of predominantly shale with interbedded sandstone and coal, and above which is a zone of quartzitic sandstones generally 30 to 60 meters (about 100 to 200 feet) thick and a basal conglomerate of the overlying Arapahoe Formation.

Laramie outcrops are widely distributed throughout the mountain front and only sparsely in the eastern prairie lands. Along the mountain front, the Laramie exposures occur in highway and railroad cuts, in clay pits, and locally as prominent topographic features where some of the sandstones are cemented with ferruginous meterial. The formation has been locally thinned by the Golden fault and intermittently by the Rampart Range fault. In the prairie lands east of the foothills, the Laramie is covered by soil except along the steep sided valleys and banks of certain stream systems in the southern and eastern parts of the project area. Of particular interest are exposures in the vicinity of Section 32, T14S, R64W; Sec. 18, T15S, R62W; and in the general vicinity of T8S, R58 and 59 West.

Along the foothills belt, the Laramie Formation dips toward the east at slopes generally ranging between 60 and 75 degrees. Locally the formation is vertical to overturned. In the prairie lands, the Laramie dips toward the deep part of the Denver Basin at about 9 to 18 meters per kilometer (about 50 to 100 feet per mile).

The age of the Laramie Formation is based on paleontological evidence. It is unconformably overlain by the basal conglomerate of the Dawson Group.

Upper Cretaceous and Lower Tertiary Rocks

Dawson Group - Use of the term "Dawson" for most of the strata overlying the Laramie Formation has been a subject of controversy for many years. This report is inclined to agree with Emmons and others (1896, pp. 151-2-1), Reichert (1956, pp. 107, 111), and McConaghy and others (1964, p. 5) in that the strata can be subdivided on the basis of lithology and mapped in areas of outcrop.

In the past, investigators have applied the terms Arapahoe Formation, Arapahoe Conglomerate, Denver Formation, Arapahoe-Denver Formation, Dawson Arkose and Dawson Formation to the strata. Because the units more or less exhibit the same general lithologic personality and because the terms Arapahoe, Denver, and to a certain extent, Dawson, are assigned to specific horizons, the use of the term "Dawson Group" is proposed to encompass the entire section.

In this report, the term Dawson Group embraces in ascending order: the Arapahoe Formation, Denver Formation, and Dawson Arkose. Observations in the field, investigation of the literature and examination of a large number of electric logs lead to the belief that such nomenclature is not only warranted, but also workable.

Arapahoe Formation - The Arapahoe Formation, of Late Cretaceous age, varies in thickness from feather edge in the outcrop to generally 150-180 meters (about 500 to 600 feet) within the inner parts of the basin. The lower 30 to 60 meters (100 to 200 feet) of the formation consists of light-tan to light-brown and locally yellow to reddish-brown conglomerate and conglomeratic sandstone interbedded with coarse, quartzitic sandstones and beds of clay 3 to 10 meters (10 to 30 feet) thick. Large, sandy, ferruginous concretions up to several feet in diameter are common in the eastern prairie lands. The lowermost sandstones of the Arapahoe Formation might be of Laramie age, but are included in the Arapahoe Formation for hydrogeologic purposes. Locally, the sandstone and conglomerate of the lower Arapahoe are unevenly developed and assume the nature of a coarse lenticular sandstone (Emmons and others, 1896, p. 153).

The lower Arapahoe is known locally as the basal Arapahoe, Arapahoe Conglomerate, and Arapahoe sands. Surface recognition of the lower Arapahoe is relatively easy in the western and southern parts of the Denver Basin in areas of relatively high erosional relief. Throughout most of the remaining prairie land east of the Foothills the lower Arapahoe is covered by surficial deposits; good exposures occurring along the steep-sided banks of only a few streams.

The upper 122 to 152 meters (400 to 500 feet) of the Arapahoe Formation locally differs from the lower part in that textures are finer and colors are generally darker. Reichert (1953, p. 19) reports that shales, siltstones, and sandstones contain detrital hornblende and augite in increasing amounts toward the top of the formation.

Subsurface identification of the Arapahoe Formation is facilitated by use of E-logs (pl. 3), high quality geologic sample logs, and correlation with logs of surrounding wells.

Along the foothills, the Arapahoe Formation dips steeply eastward at slopes generally ranging from 40° to 70°, and is locally vertical to overturned. In other parts of the project area, the formation dips gently toward the center of the Denver Basin at slopes of about 3 to 11 meters per kilometer (15 to 60 feet per mile).

The late Cretaceous age of the Arapahoe Formation is based on paleontologic evidence. The Arapahoe is overlain by a thick sequence of predominantly dark-colored shales and sandstones of the Denver Formation.

<u>Denver Formation</u> - The Denver Formation consists of a series of poorly-bedded to cross-bedded, predominantly light-gray to dark-brown, silty claystones and shales, and tan through light-brown and greenish, andesitic and basaltic sandstones and conglomerates. Workable coal seams are present throughout much of the project area. Along the foothills west of Denver, the upper part of the Denver Formation includes 76 meters (about 250 feet) of basalt flows which cap North and South Table Mountains. Remnants of the flows continue southward for several miles.

The materials of the Denver Formation include considerable debris derived from the erosion of basaltic and andesitic lavas which gives the Denver Formation a pronounced lithology generally recognizable throughout the study area. The nearly complete absence of granitic and metamorphic debris imparts a generally pronounced darker color to the formation; as opposed to the lighter color of the underlying Arapahoe and overlying Dawson Arkose.

The base of the Denver Formation is taken as the top of a "buffer zone" of 15 to 30 meters (50 to 100 feet) of shale at the base of the 120 to 240 meter (400 to 800-foot) section of sedimentary debris, which because of its overall textural characteristics, can be identified on spontaneous potential and resistivity logs (pl. 3), and on geologic sample logs of the highest quality. The buffer zone provides hydraulic separation between the Arapahoe and Denver aquifer systems. In application, if this hydraulic separation is to be maintained, it is suggested that no water wells be perforated in the buffer zone.

Thickness of the Denver Formation ranges between 120-240 meters (about 400 and 800 feet) throughout most of the basin. The best exposures of the Denver Formation occur along the banks of steep sided valleys and in stream cuts. Except along the east flank of the foothills, the Denver Formation dips very gently toward the structural center of the Denver Basin at 2-3 meters per kilometer (about 10 to 15 feet per mile).

The sediments of the Denver Formation were deposited by aggrading streams as alluvial fans, and as lake deposits on an extensive piedmont plain. The age of the Denver is late Cretaceous in the lower part and early Tertiary (Paleocene) in the upper part. A complete discussion of the dispute surrounding the age and extent of the Arapahoe and Denver Formations is beyond the scope of this report.

The Denver Formation is disconformably overlain by light-colored arkosic sandstones, conglomerates and clays of the Dawson Arkose.

Dawson Arkose - In this report the Dawson Arkose includes all of the predominantly quartzose sedimentary debris above the predominantly dark-colored sequence of andesitic, micaceous, carbonaceous sandstones and shales of the Denver Formation lying below the cliff-forming Castle Rock Conglomerate. In this report, the Green Mountain Conglomerate of the Golden-Morrison area is considered as being a member of, or at least stratigraphically equivalent to, the lower part of the Dawson Arkose.

The Dawson Arkose is of Paleocene age: Eocene strata are possibly present in the upper part (Welsh, 1969, p. 33) but fossil evidence is lacking. Thickness of the Arkose ranges between 240 and 330 meters (about 800 and 1,000 feet) in the deeper parts of the Denver Basin. Additional subsurface data might extend the range appreciably. The "base" of the formation is marked in most areas by a significant quantity of light-colored quartzose debris overlying a 120 to 240 meter (400 to 800 feet) section of predominantly finer-grained, darker colored, and carbonaceous sediments of the Denver Formation.

The bulk of the Dawson Arkose consists of a thick sequence of light-gray to yellowish-gray and orange to pale-reddish and moderate-brown conglomerate, sandstone, and clayey shale with local beds of pale-green shale and lenses of lignitic coal. Much of the sandstone is micaceous and arkosic with grain sizes averaging that of very coarse sand. Individual beds range in thickness from less than one meter to 60 meters (1 foot to 200 feet). They are commonly extremely lenticular and are difficult to trace at distances exceeding one or two kilometers (about one mile). Locally, some sandstone beds are cemented by ferruginous material at their tops thus causing the formation of pedestal-like erosion remnants. These are common along the foothills south of Castle Rock. Some conglomerate beds are cemented with a hard, dense siliceous material. Such beds are highly resistant to erosion, and when broken, the fracture plane cuts across constituent quartz pebbles. Scott (1967, p. 15) reports that the two most common rocks of the Dawson are arkosic, micaceous sandstones and light-reddish-brown and light-green, sandy siltstone and claystone. Constituents common to most of the upper part of the formation include pebbles of chert, rhyolite, quartzite sandstone, chalcedony, granite fragments and scoria. Petrified wood and bone and leaf fragments are found locally in the lower part of the formation.

In the southern part of the Denver Basin, the lower Dawson contains distinctive beds of white, pink, yellowish-orange and light-reddish-violet clay, and white sandstone. The clays are utilized in the ceramics industry. The white color of the sandstone is possibly due to the chemical alteration of feldspar.

In this report, the Green Mountain Conglomerate, outcropping only on the top of Green Mountain west of Denver, is assigned to the basal part of the Dawson Arkose on the basis of a marked erosional disconformity between it and the underlying Denver Formation, and lithologic composition. Although the basal 15 to 45 meters (about 50-150 feet) of the conglomerate contains an abundance of basaltic and andesitic debris, the upper 82 to 113 meters (270-370 feet) is composed predominantly of light-colored Precambrian rocks. The basal basalt-andesite member thins southeastward where it grades into arkosic sandstones and conglomerates.

The top of the Dawson Arkose is marked by an average thickness of 8 meters (about 25 feet) of dense, brittle, locally porphyritic, pink, brown or gray rhyolite (Kittlemen, 1956, p. 50). The rhyolite, which might be more correctly classified as a welded tuff, caps isolated buttes over a 1,036 square kilometer (400 square mile) area between Palmer Lake and Sedalia. Kittlemen refers to this volcanic material as the Douglas Creek Rhyolite Member.

The Dawson Arkose covers about 4660 square kilometers (1800 square miles) of the central part of the Denver Basin. It is exposed in most deep stream and road cuts along the steeper flanks of pediments. In areas where it is not directly exposed, it is generally covered by only very thin soil.

The regional dip of the Dawson Arkose is 1 to 3 meters per kilometer (about 5 to 15 feet per mile) toward the east. Where the arkose abuts against the Rampart Range fault, dips of about 20 degrees are locally attained.

Castle Rock Conglomerate - The Castle Rock Conglomerate is a hard cliff, forming pink to brown conglomeratic arkose. Measured thicknesses range from a feather edge to nearly 90 meters (300 feet).

Kittlemen (1956, p. 54) divided the Castle Rock Conglomerate into two parts. In summary, the lower part is a tan to brown, hard, very coarse conglomerate with interbedded, hard, arkosic sandstone. The upper part is a light-tan to light-brown, moderately-hard, coarse grained, arkosic sandstone containing thin lenses of quartz pebble conglomerate.

The lower conglomerate is unique in that the size range of the constituent particles is extreme; from a fraction of a centimeter to about 1 meter (about 3 feet) in diameter. It also contains a substantial quantity of debris from the Douglas Creek Rhyolite Member of the Dawson Arkose.

The Castle Rock Conglomerate caps pine-tree-covered buttes and mesas in the south-central part of the project area. The outcrop pattern occurs in a lineation roughly paralleling the longitudinal axis of the Denver Basin structural trough. The Castle Rock is the youngest of the bedrock formations considered in this report.

Tertiary Intrusive and Extrusive Rocks - In several places throughout the Denver Basin project area, intrusive and extrusive igneous bodies have invaded or capped older sedimentary rocks. North of Golden, along the Ralston dike, several irregular intrusive bodies of mafic monzonite intrude a faulted block of the Pierre shale. Capping North and South Table Mountains are about 90 meters (300 feet) of dark-colored, latitic lava flows, in part interbedded with tuffaceous sediments. These were given partial treatment in the Denver Formation narrative. In the south-central portion of the project area, the upper part of the Dawson Arkose is marked by a bed of light-colored rhyolite approximately 8 meters (about 25 feet) thick.

Quaternary Rocks

Quaternary Surficial Deposits - Although the purpose of this report is to examine the hydrogeology of the bedrock aquifers of the Denver Basin, a cursory examination of the surficial deposits of the area is necessary. At least 90 percent of the area investigated is covered by a thin veneer of unconsolidated, predominantly water and wind-deposited, sedimentary debris. This material is important not only because of its vast areal extent, but also because it might have local influence on rate and quality of natural recharge of ground water to underlying bedrock formations. Plate 2 shows the areal distribution of the surficial deposits discussed in this report. Outcrops of bedrock geologic units have been partially subdivided.

Pediment Gravel - Pediment gravels of different ages have been recognized at scattered outcrops along the foothills from Jarre Canyon southward to the southern part of the U. S. Air Force Academy. Areally, the deposits resemble irregular alluvial fans extending outward from the crystalline rocks of the foothills. The deposits occur from slightly above modern streambeds to heights approaching 120 meters (about 400 feet). Particle size of the gravels' components ranges from silt to boulders 6 meters (20 feet) in diameter (Scott, 1967, p. 20). Rocks belonging to the Dawson Group are exposed along the steeper slopes of the dissected remnants of the pediments.

Loess - The loess shown on plate 2 is a predominantly yellowish-brown and locally olive-gray, sandy or clayey, locally calcareous silt. It has a well developed columnar structure and generally weathers as vertical banks. It occurs sporadically in the southern one-half of the project area within some of the large stream valleys and on gentle slopes. In the northern one-half of the project area, the loess and the brown soil developed upon it occupy at least 60 percent of the land surface.

Colluvium - Colluvium is the geologic material deposited near the base of steep slopes by the action of water and/or gravity. It includes earth flows and slumps in soft sedimentary rocks and rockfalls in hard, ridge-forming sandstones. Colluvium is undoubtedly more widespread than indicated on plate 2. The occurrences within the steep-sided strike valleys along the foothills are mapped because they exhibit both earth-flow and rockfalls.

Older alluvium, eolian sand, etc., undivided - Extensive, undivided deposits of older alluvium, eolian sand, loess, and colluvium occur along the foothills and south of Township 5 South in the remainder of the project area. The older alluvium is the most widespread deposit in the southern half of the project area. It is generally moderate-reddish-brown along the foothills area and light brown to yellowish-brown in the prairie lands. The older alluvium exhibits a coarse texture, good stratification and is locally deeply weathered. It is generally interstratified with small lenses of gravel and loess. In many of the wide valley bottoms and along many gentle slopes, the alluvium is mantled by deposits of loess and eolian sand. On most slopes developed on members of the Dawson group, the alluvium includes lithosols. Because of the small scale of the surficial geologic map, the alluvium necessarily includes stream channel and terrace deposits in small valleys. Colluvium and older alluvium are hydrogeologically important because their water transmitting capabilities affect the rate and quantity of natural recharge to bedrock formations throughout most of the southern one-half of the Denver Basin.

Eolian sand - Deposits of pale-yellowish-brown to brown, clayey and silty, predominantly fine to medium-grained, quartz sand, mantle younger deposits throughout much of the northern part of the project area and sporadically in the southern part. Topographically, the sand forms both flat surfaces and low mounds. Although stabilized by plant growth in most areas, blowouts have occurred in areas subjected to long periods of high wind velocities. Eolian sand is hydrogeologically important because its high infiltration rate and poor water retaining capabilities facilitate natural recharge of ground water to geologic formations below it.

Higher terrace deposits and colluvium - In this report, the term "higher terrace deposits and colluvium" refers to generally well developed terrace deposits occurring above the floodplains of the principal stream systems. They are composed of coarse to fine-grained, poor to well-sorted, generally well-stratified deposits of gravel, sand and silt. Colors are predominantly dark-brown to yellowish-brown and gray-brown. The deposits are locally iron and/or manganese-stained, calcareous and fossiliferous. Colluvial debris is present in the steeper valleys. Because of the scale of the geologic map, the deposits include stream channel and flood plain deposits of several stream systems.

Recent stream channel and floodplain deposits - The bottoms of all recent stream systems in the Denver Basin are filled with unconsolidated channel and floodplain deposits. The floodplain deposits are flat-topped and composed of humic clay, silt and sand with interbedded zones of clay and cobbles. Colors are generally brown, through yellowish-gray and gray-orange. Roots, tree branches, and occasional fossil fragments are found within the deposits. In most large valleys, the floodplain deposits contain a rich alluvial soil. The channel alluvium of the recent stream systems is generally coarser and lighter in color than the floodplain deposits. Particle size ranges from coarse sand through gravel and boulders. The terrace, stream channel and floodplain deposits are possibly a major contributor of ground water recharge to bedrock formations. Recharge obviously occurs along the contact between two types of formations in areas where bedrock formations will accept water.

STRUCTURE

Much of the material presented in this section is taken from the Guide to the Geology of Central Colorado: Colorado School of Mines Quarterly, Vol. 43, No. 2, and from Varnes, D. J., and Scott, G. R. (1967), General and Engineering geology of the Air Force Academy site, Colorado: U. S. Geological Survey Prof. Paper 551. Figure 5 is a map showing the major structural features of the Denver Basin.

The Denver Basin is a structural basin whose axis plunges northerly from east-central Pueblo County and attains a maximum depth in the Denver area. From Denver the axis swings northeastward, rises to a saddle in the La Salle-Greeley area, then plunges northward into a trough centered near Cheyenne, Wyoming. The Denver Basin is bounded on the west in Colorado by the Rampart and Front Ranges. The northern and eastern structural boundaries extend beyond the state line into Wyoming, Nebraska, and Kansas. The southern boundary is formed by the Apishapa and Las Animas arches in southeastern Colorado (Moody, 1953, p. 1873, 1874). Sedimentary formations from the Cambrian through the Tertiary are upturned along the mountain front on the west flank of the basin (figs. 6, 7). At many places such as in the Golden-Morrison area, Jarre Creek and Perry Park, many beds are vertical or overturned. Hogback ridges and strike valleys that resulted from such folding can be seen at Boulder, Red Rocks Park, Roxborough Park, Perry Park, and the Garden of the Gods near Colorado Springs. The upward and eastward pressure of the mountains ruptured the strata from Boulder southward beyond Colorado Springs and caused a series of large faults; mainly thrust faults, which parallel the mountain front. Southward from Golden the faults are named the Golden fault, Jarre Creek fault (possibly a continuation of the Golden fault) and the Rampart Range fault. Additional disruptions of strata are caused by numerous branch faults in the form of reverse faults, tear faults, and sliver blocks. The faults bring Precambrian rocks into contact with all the formations up to and including early Tertiary beds. Locally, the faulting has caused sedimentary beds to undergo extensive thinning, dragging and displacement. Vertical displacement of sedimentary rocks ranges from 1524 meters (5,000 feet) in the Golden area to about 3,048 meters (10,000 feet) in the Air Force Academy area north of Colorado Springs (Varnes, D. G. and Scott, G. R., 1967, p. 10). The fault planes of the major thrust faults of the area dip toward the west at values generally ranging from about 45 to 75 degrees.

East of Boulder and in the north Metropolitan Denver area is a group of northeast trending faults which extend from the Precambrian basement to the surface. The possibility that the faults extend as far east as the Derby area has been demonstrated by earthquake activity.

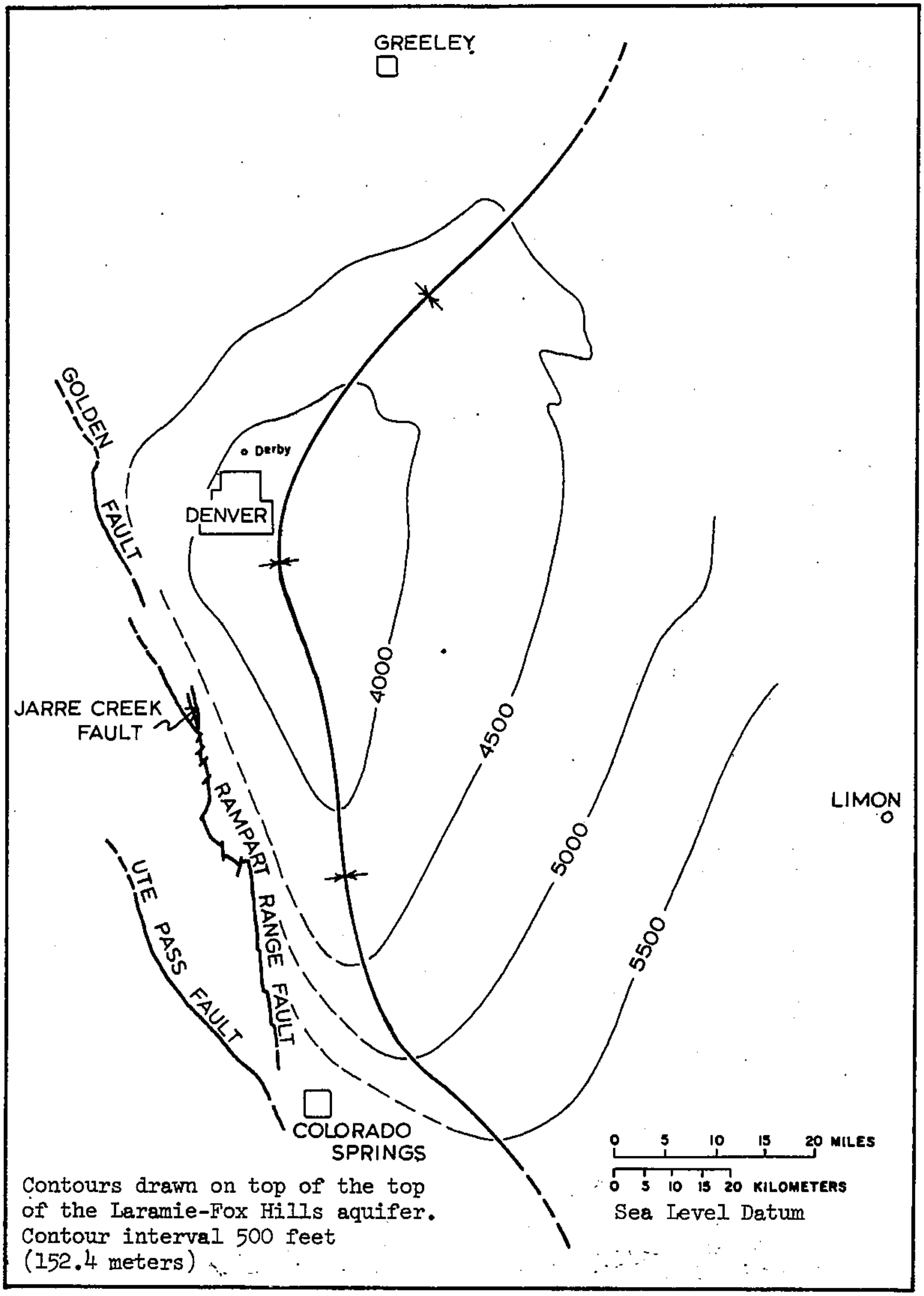

Figure 5. Map of Denver Basin showing major structural features

Numerous small folds are reported to exist along the foothills belt (Stewart, W. A., 1955, p. 29). Examination of existing information suggests that the folding does not extend east of the foothills belt and has only a minimal effect on the overall structure of the basin.

Folding is suggested in the northeastern part of the project area by the irregular nature of the contours on the top of the Laramie-Fox Hills aquifer (plate 4). However, the sinuous nature of the contours is probably due to the differences in elevations of the "picks" for the top of the L-F aquifer. In some wells, the basal Laramie sands were significantly developed above the B sand and warranted picks above the normal top. The probability that this area is not folded is in part substantiated by a structure contour map of the base of the lowermost potential aquifer sand in the Fox Hills Formation (plate 5).

GROUND WATER IN THE BEDROCK FORMATIONS

OCCURRENCE AND CLASSIFICATION OF THE AQUIFERS

By definition, an aquifer is a geological formation, group of formations, or part of a formation containing sufficient saturated permeable material that can yield a sufficient quantity of water thay may be extracted and applied to beneficial use.

In the Denver Basin study area, several of the previously discussed bedrock formations meet the above requirements. In ascending order from the Precambrian basement, the principal aquifers are the Fountain and Lyons Formations, the upper and lower parts of the Dakota Group, the Laramie-Fox Hills aquifer (the combined thickness of the Milliken Sandstone Member of the Fox Hills Formation and the A and B sandstones of the Laramie Formation), the middle part of the Laramie Formation and the Arapahoe, Denver, and Dawson Formations. Surficial geologic formations and the crystalling rocks of the Front and Rampart Ranges are not considered in this report.

The pre-Pennsylvanian sedimentary rocks described in the geology section of this report are not considered as being principal aquifers even though one or more of the units might contain water. The outcrop area of the formations is limited to a very narrow, discontinuous strip along the Rampart Range fault between Perry Park and Colorado Springs. At Colorado Springs, the outcrop area expands and swings southwestward toward the Ute Pass fault; an area which is considered out of the sphere of interest of this report. Eastward from their outcrops along the Rampart Range fault, the formations are too deep to consider them as economic sources of ground water.

Numerous post-Pennsylvanian formations which occur within the bounds of the study area are not classed as principal aquifers even though they might contain water. These formations are predominantly limestone, shale, and clay and are generally incapable of transmitting sufficient quantities of water to wells. Frequent reference can be found in the literature concerning the limited water-bearing characteristics of such strata. Perhaps limited quantities of water can be withdrawn from the formations, but the supplies are local, probably short lived, and generally of substandard quality. Strict application of the definition of an aquifer is sufficient to disqualify most of the strata in question.

The Pennsylvanian and younger rocks which are classed as principal aquifers are assigned varying degrees of importance depending on areal extent, depths to the water-bearing horizons, and quality and quantity of water available for withdrawal.

The Fountain Formation, Lyons Sandstone and Dakota Group are known to yield generally small quantities of water to wells drilled in or near the outcrop area. They are important aquifers only within and near their outcrops along the westernmost edge of the project area.

The massive sandstone of the Fox Hills Formation and the basal sandstones of the Laramie Formation are known to yield small to moderate quantities of water to most wells in an areal extent of about 12,950 square kilometers (5,000 square miles). The sandstones, which are collectively referred to as the L-F aquifer are, therefore, classed as a major aquifer. Sandstones in the upper part of the Laramie Formation have been locally utilized for sources of water to small capacity water wells throughout most of the Denver Basin.

The basal sand unit of the Arapahoe Formation has proven to be a reliable source of water for all purposes throughout the Denver Basin, hence its classification as a major aquifer. The Denver Formation should be classed as a major aquifer because of the areal extent of the sandstones within it and because of the generally good quality water that is obtained from it. The coarse arkosic sandstone of the Dawson Arkose is a reliable source of water for all purposes throughout most of its areal extent and is considered a major aquifer. Table 1b is a condensed summary of the hydrogeologic characteristics of the formations discussed in this report.

HYDROGEOLOGIC PROPERTIES OF THE PRINCIPAL AQUIFERS

Fountain Formation and Lyons Sandstone

The Fountain Formation and Lyons Sandstone are treated as a unit because they have similar hydraulic properties and are in juxtaposition from a regional standpoint. In the past, the Fountain and Lyons aquifers were frequently developed together as one source of water. Current practice is to develop each aquifer separately.

Natural and artificial recharge. Natural recharge to the Fountain and Lyons aquifers occurs as seepage from precipitation and as seepage from the many eastward flowing streams which breach strike valleys and hogbacks in which these formations are exposed or lying near the surface.

Annual precipitation on the outcrop area of the Fountain and Lyons aquifers averages 41 centimeters (about 16 inches). Normal May -

September precipitation is 46 centimeters (about 18 inches). Since much of the winter (October - April) precipitation occurs when the area's surficial deposits are partially frozen and are subjected to high wind movement, it is suggested that the "effective" precipitation occurs during May - September. Although detailed hydrogeologic investigations are required in order to determine whether recharge occurs and its quantity, estimates have been made by assuming the annual recharge can be approximated by the annual withdrawals of water from the estimated 25-35 wells penetrating the aquifers. Annual recharge from precipitation in the northern half of the basin, therefore, ranges from near zero in the cemented portions, to 0.05 to 0.13 centimeter (0.02 to 0.05 inch) in the friable zones and in faulted areas. This would amount to 18,500 to 37,000 cubic meters (about 15 to 30 acre-feet) per year.

The precipitation recharge rate in the southern outcrops is probably in the same range as that in the north, or from near zero to possibly 0.13 centimeters (0.04 to 0.05 inch). This would amount to 20,970 to 25,900 cubic meters (17 to 21 acre-feet) per year in the southern part of the outcrop area. It is possible that since the Fountain and Lyons aquifers have not been extensively utilized as aquifers in the southern part, much of the potential recharge is rejected. In other words, the aquifer might be "full" and no recharge can occur until withdrawals take place. The validity of this suggestion will probably be tested sometime in the near future when the area becomes developed and more detailed data is acquired.

Additional recharge to the Fountain and Lyons aquifers possibly occurs where streams cut the formations along the east flank of the foothills. The recharge occurs where water saturated sand and gravel of the stream bottom contact permeable, unsaturated sand and gravel horizons of the subject formation. Major stream systems which might contribute to such recharge include Clear Creek, Bear Creek, Turkey Creek, Deer Creek, West Plum Creek and the South Platte River. Because the area over which such direct recharge can occur is so small, it is suggested that this quantity of the recharge is minimal when compared to other sources.

The Fountain and Lyons aquifers are possibly artificially recharged by the infiltration of water through water diversion and storage works which are in contact with those formations. Sites where such recharge could occur include the Golden, Welch and Church Ditches near Golden, the Highline Canal, Platte Canyon Ditch and the Denver Water Board filtration ponds near Kassler. That significant recharge to the Fountain and Lyons aquifers occurs along streams and water diversion works is only a possibility. Detailed hydrogeologic investigations are required to either support or oppose the suggestions regarding such recharge.

A small quantity of water is probably recharged to the Fountain and Lyons aquifers as infiltration of sewage and excess lawn and garden irrigation water at homesites and commercial establishments.

<u>Natural and artificial discharge</u>. The only apparent discharge of water from the Fountain and Lyons aquifers occurs through well pumpage. Well records at the Colorado Division of Water Resources indicate that 20-25 wells penetrate the Fountain and Lyons aquifers. Unregistered wells may total 5 or 10. The number of wells penetrating the aquifer,

therefore, ranges between about 25 and 35. Most of the wells are classed as domestic . . . . four are registered for commercial use. If the number of people utilizing Fountain-Lyons water lies between 80 and 160 and the daily per capita consumption of water ranges between 190 and 380 liters (50 and 100 gallons), the annual withdrawal of water ranges between 6,170-22,200 cubic meters (5 and 18 acre-feet). Withdrawals approaching 37,000 cubic meters (30 acre-feet) per year are not unrealistic when lawn-garden requirements and modern household luxuries are considered.

Hydraulic properties of the aquifer. The artesian nature of the Fountain and Lyons aquifers is evident in wells by the rise in water level above the bottom of the upper confining beds. The major upper confining bed is the Lykins Formation (predominantly shale and limestone). The lower confining bed is the Precambrian basement in the northern half of the Denver Basin and the Glen Eyrie Formation or Sawatch Sandstone in the southern half of the basin. Confining beds within the aquifers have been formed by thorough cementation of sandstones by ferruginous and siliceous matter.

Logs of existing water wells indicate that depth to water in the Fountain and Lyons aquifers ranges from 0 to about 76 meters (250 feet). Minimal depths to ground water generally occur near the base of the Fountain strike valley. Depth to water increases in an eastward direction as the Dakota hogback is encountered. Static head ranges from zero to 91 meters (300 feet) along the foothills (fig. 6).

Most of the wells which tap the Fountain and Lyons aquifers are used for domestic purposes since well yields are relatively small. The range of well yields is 0.1 to 4 liters per second (1 to 60 gallons per minute) with an average of about 0.3 to 0.6 liters per second (5 to 10 gallons per minute). Wells producing an excess of 0.6 liters per second (10 gpm) are probably more likely to occur in the vicinity of faults. Potential water users in such areas should investigate their property in such light, as the presence of a fault could make the difference between a poor, fair, or an excellent well.

The Fountain Formation and Lyons Sandstone have not been extensively developed as aquifers; consequently, aquifer properties are imperfectly understood. Pump test data are available for several wells which tap the beds and are used to estimate the aquifer parameters. It is believed that the water-yielding parts of the aquifer occur generally in beds or zones from 1.5 to 6 meters (5 to 20 feet) thick.

Specific capacity, the ratio between discharge and drawdown, of existing wells ranges between 6.2×10^{-4} and 0.207 liters per second per meter of drawdown (0.003 and 1.0 gallon per minute per foot of drawdown) with an average of about 0.01 liters per second per meter (0.05 gallon per minute per foot). The transmissivity of the aquifer was found by emperical methods to lie in the range of about 0.62 to 1.24 square meters per day (50 to 100 gallons per day per foot width of aquifer). Hydraulic conductivity of the aquifer is estimated to range between 0.205 and 0.41 meters per day (5 and 10 gallons per day per square foot of aquifer). Although data are lacking, estimates of the storage coefficient and specific yield are assigned as follows: Storage coefficient 0.0001, specific yield 2 to 5 percent. The figures are subject to re-evaluation as more data become available.

Quantity of water available for withdrawal. The quantity of water stored within the Fountain and Lyons aquifers is probably considerable. However, the quantity which can be recovered is limited by the aquifer's steep eastward dip, hydraulic properties, and displacement by faulting.

The following estimate of stored and recoverable water in the Fountain and Lyons aquifers is based on maximum well depths in the range of 300 to 460 meters (1,000 to 1,500 feet), and treatment of the exploitable part of the aquifers as wedge-shaped solids. In the northern part of the basin (Golden to Kassler) the quantity of water stored in the Fountain Formation is estimated to range between 78.9×10^6 and 360×10^6 cubic meters (64,000 and 292,000 acre-feet); the quantity in the Lyons Formation is estimated to range between 36.4×10^6 and 90×10^6 cubic meters (29,500 and 73,000 acre-feet). In the southern part of the basin, the quantity of water stored in the Fountain Formation ranges between 149.3×10^6 and 372.5×10^6 cubic meters (121,000 and 302,000 acre-feet); the quantity stored in the Lyons Formation ranges between 37×10^6 and 93.8×10^6 cubic meters (30,000 and 76,000 acre-feet). About 30 percent of the above values is estimated to be recoverable.

The Dakota Group

Water from the Dakota Group is obtained from sandstones in the upper 30 meters (100 feet) of the South Platte Formation and the Lytle Formation. The shale separating the water-bearing sandstones commonly does not yield water to wells. Wells which successfully tap the Dakota are generally located a short distance east of the outcrop and range in depth from 30 to 305 meters (about 100 to about 1,000 feet). Because of the group's steep eastward dip and displacement by faulting, and an eastward deterioration of water quality, only a fraction of the Dakota can be utilized as a source of water (fig. 6).

Natural and artificial recharge. Natural recharge to the water-bearing horizons of the Dakota Group originates as downward percolation of precipitation and as seepage from streams which cut the Dakota hogback.

The average annual precipitation which falls on the area occupied by the Dakota Group is about 40 centimeters (about 16 inches). Average May - September precipitation is about 20 centimeters (8 inches). For reasons suggested previously (Fountain-Lyons analysis), the effective precipitation is believed to occur during May - September. Much of the precipitation which falls on the Dakota Group is probably lost as runoff on the east and west flanks of the hogback, and as evapotranspiration. The recharge is probably considerably less than 0.2 centimeters (about 0.1 inch) throughout the project area.

The water-bearing sandstones of the Dakota Group are possibly recharged by seepage of water through stream channels at water gaps in the hogback. Like the Fountain-Lyons aquifer, the permeability of the Dakota is so low that most of the potential recharge is rejected. Major stream systems which might contribute to such recharge include Bear Creek, Turkey

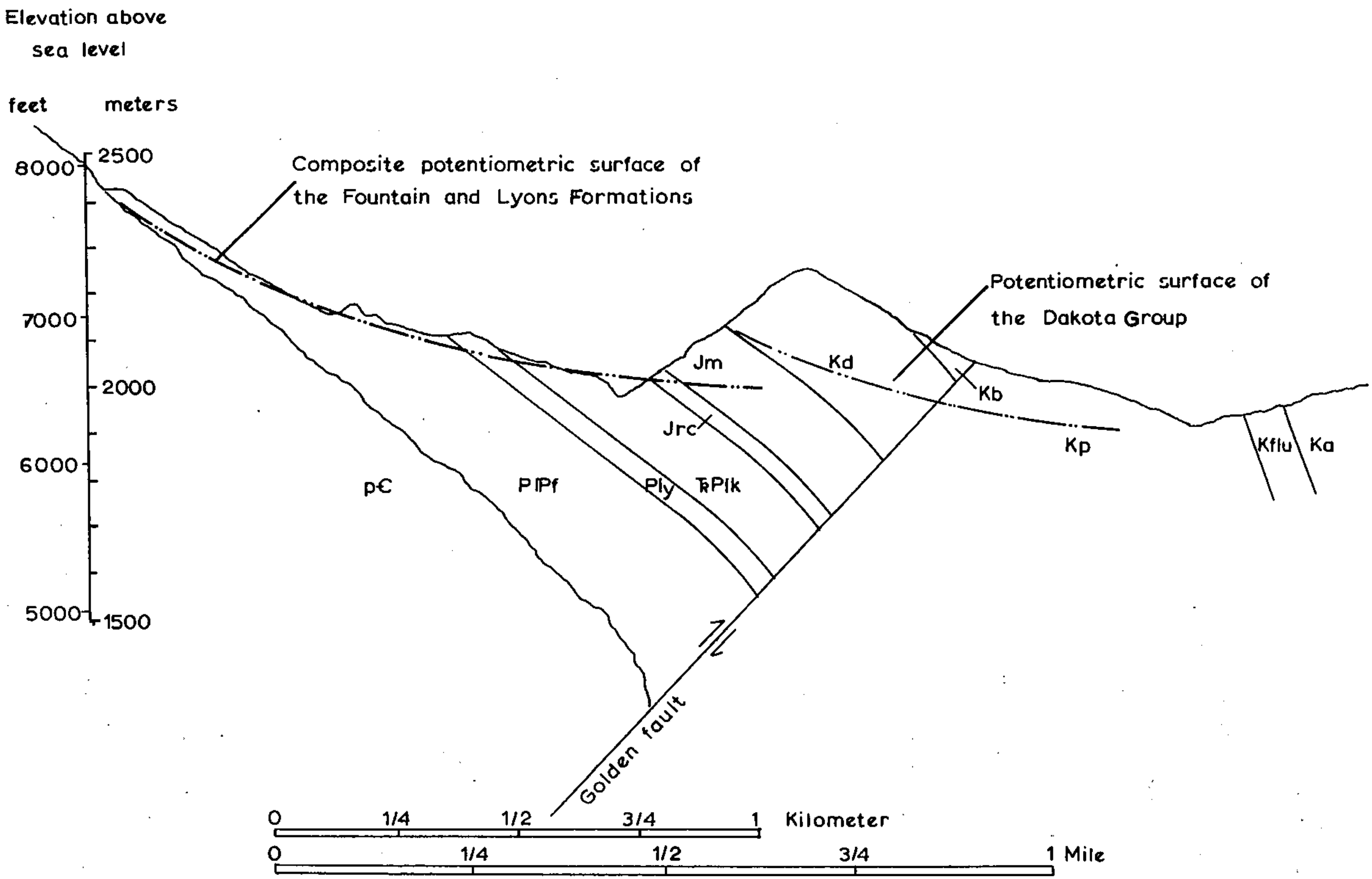

Figure 6. Cross section along the northern part of the foothills near Morrison, Colorado, showing the Precambrian basement through the lower part of the Arapahoe Formation and theoretical potentiometric surfaces of the Fountain and Lyons Formations and the Dakota Group. Geologic symbols: p€, Precambrian; PIPf, Fountain Formation; Ply, Lyons Sandstone; TrPlk, Lykins Formation; Jrc, Ralston Creek Formation; Jm, Morrison Formation; Kd, Dakota Group; Kb, Benton Formation; Kp, Pierre Formation; Kflu, Fox Hills and Laramie Formations undivided; Ka, Arapahoe Formation.

Creek, West Plum Creek and the South Platte River. Recharge to the Dakota from water percolating along the fault plane of the Golden fault is possible.

The water-bearing horizons of the Dakota Group are possibly artificially recharged by the infiltration of water through the porous bottoms of water diversion and storage works which are in contact with the group. Sites where such recharge might occur include the Highline Canal and the Platte Canyon Reservoir, both near Kassler.

The total quantity of recharge to the Dakota Group probably does not greatly exceed the quantity of water withdrawn from wells which tap it. Until evidence to the contrary is developed, it is suggested that recharge to the Dakota ranges between 4,900 and 17,300 cubic meters (4 and 14 acre-feet) per year.

Natural and artificial discharge. The only apparent discharge of ground water from the Dakota Group occurs through well pumpage. The Dakota has not been heavily developed as an aquifer, and less than 20 known domestic wells tap the Dakota. Assuming that the population served by Dakota water ranges between 60 and 100 and a daily per capita water consumption of 190 to 380 liters (50 and 100 gallons), the annual withdrawal of water will be between about 4900 and 8600 cubic meters (4 and 7 acre-feet) per year.

Hydraulic properties of the aquifer. The water-bearing horizons of the Dakota Group can be defined as artesian. The upper confining bed is the Benton Formation (predominantly shale) and the lower confining bed is the Morrison Formation (predominantly mudstone). The non-water bearing horizon separating the two aquifers is composed predominantly of shale.

Logs of existing water wells tapping the Dakota Group indicate that depth to water ranges from 0 to about 30 meters (about 100 feet). Records of water level changes have not been kept but the limited development of the group has probably precluded significant declines. Recent expanded growth of metro-Denver might eventually result in rapid water level declines of a large number of wells are constructed to tap the Dakota Group. The current static head ranges from zero to over 30 meters (fig. 6).

Yields of wells tapping the Dakota Group range from 0.126 to 3.15 liters per second (2 to 50 gallons per minute) with an average of one liter per second (about 15 gallons per minute). Wells producing 15 or more liters per second are most likely to occur about 400 meters (1320 feet) or more east of the outcrop and possibly near faulted areas. Very little aquifer and pump-test data are available for the Dakota Group along the foothills. Most of the aquifer constants on the group are based on studies of the Purgatoire Formation and Dakota Sandstone of southeastern Colorado. Specific capacities of the group range from 0.001 to 3.0 liters per second per meter of drawdown (0.007 and 1.4 gallons per minute per foot of drawdown) with an average of 0.07 liter per second per meter (0.34 gallons per minute per foot). The transmissivity of the Dakota Group as a whole is believed to range between 0.62 and 5 square meters per day (50 and 400 gallons per day per foot width of aquifer with an average of about 2 liters per second per meter (150 gallons per minute per foot). Hydraulic conductivity of the Dakota is estimated to be about 0.12 meters per day (3 gallons per day per square foot). The coefficient of storage and specific yield are estimated to be about 0.001 and 10 percent respectively.

Quantity of water available for withdrawal. The steep eastward dip, limited hydraulic properties, displacement by faulting and economic restraints, restrict the volume of exploitable aquifer. If well drilling operations are economically restricted to depths less than 460 meters (1500 feet), the total saturated volume of material is 1115 X 10^6 cubic meters (about 904,000 acre-feet). With a specific yield of 10 percent and a recovery factor of 50 percent, the quantity of presently recoverable water is about 55.5 X 10^6 cubic meters (45,000 acre-feet).

Laramie-Fox Hills Aquifer

The Laramie-Fox Hills aquifer is the oldest of the major aquifers within the Denver Basin project area. It also covers the largest area of the basin in that its outcrop pattern nearly circumscribes the area investigated. The Laramie-Fox Hills aquifer, referred to as the L-F aquifer, is so named because the water-bearing horizon includes in ascending order, the Milliken Sandstone Member (or massive sandstone member) of the Fox Hills Formation, and the A and B sandstones of the overlying Laramie Formation. Generally, the sandstones are separated by 1.5 to 6 meters (5 to 20 feet) of shale although in some areas shale is a minor constituent and the aquifer consists of a relatively unbroken sequence of sandstones (pl. 3).

The boundaries and shape of the L-F aquifer can be best described with reference to the bedrock geologic map and structure contour map of the top of the L-F aquifer (pls. 1, and 4 and fig. 7). The boundaries of the aquifer are its outcrop areas in the east and southern portions of the basin, the outcrops and faulted portions along the foothills and the northeast-southwest trending fault zone north of Big Dry Creek. A north-south trending line drawn through the nose of the contours roughly parallels the longitudinal axis of the Denver Basin. East of this axis, the L-F aquifer dips gently toward the deep portion of the basin underlying Cherry Creek Reservoir. West of the longitudinal axis, the aquifer is upturned against pre-L-F sediments which abut against Precambrian rocks of the foothills. The aquifer is classed as artesian; the upper and lower confining beds are the Laramie and Pierre Formations respectively.

The thickness of the L-F aquifer ranges from 0 in the outcrop areas to about 120 meters (about 400 feet). The average thickness of the aquifer is about 61 meters (200 feet). Thicknesses exceeding 61 meters occur locally in the Denver-metro area and in the Black Forest region in the south-central part of the basin. They can be attributed to the thickening of the principal sandstones and the possible development of several otherwise insignificant sandstones lying 30 to 61 meters (100 to 200 feet) below the Milliken Sandstone. In areas where the sands below the Milliken are significantly close to the L-F aquifer and are of "sufficient" thickness to form a potential aquifer, they have been included as part of the main aquifer.

Sandstones above the "B" of the Laramie Formation are also unevenly developed. This becomes apparent by examining the northeastern portion of the structure contours of plate 4. The asymetric contours in this area are attributed to such uneven development of sandstones and not, as one might believe, to structural features. Plate 5 shows contours on the base of the lowermost potential water-bearing horizon in the Fox Hills Formation and exemplifies the relatively even structure of the lower horizons.

The quantity of net sandstone in the L-F aquifer ranges from about 30 to 76 meters (100 to 250 feet). Plate 6 shows the distribution of equal thickness of net sand in the study area as interpreted from the examination of about 300 oil and water well logs. Comparison of plate 4 and plate 6 shows thicknesses of sand exceeding 46 meters (150 feet) occur along a relatively narrow band which nearly parallels the longitudinal axis of the Denver Basin. Plate 6, when used in conjunction with other data, can be used as a basis for examining the L-F aquifer in terms of primary or alternative sources of ground water.

Depth to the L-F aquifer ranges from 0 at the outcrop to about 880 meters (2900 feet) in the higher elevations of the Black Forest, 16 to 32 kilometers (10 to 20 miles) south of Franktown. Figure 7 illustrates generalized geologic sections of the post-Pierre bedrock aquifers. Plate 7 is an isobath map of the top of the L-F aquifer and illustrates the generalized depth to the aquifer. Since depth to the aquifer is over 600 meters (2000 feet) in much of the central part of the basin, it is apparent that the interplay between need, economics, and alternative sources of supply might influence its development.

The L-F aquifer is best identified in wells by use of electric logs; as has been brought out in earlier discussion and in plate 3. Figure 8 is a cross section of the post-Pierre portion of the Denver Basin and illustrates with plate 3 the basis for using electric log data in locating the basin's principal aquifers.

Natural and artificial recharge. The Laramie-Fox Hills aquifer is naturally recharged by the infiltration of precipitation in areas of outcrop, subcrop, and probably through fault traces along the foothills and in the structurally complex area northeast of Golden. Infiltration of seepage from live streams probably occurs to a small extent along the foothills and possibly in the southernmost part of the study area. There is a definite possibility that the L-F aquifer is recharged by the percolation of water through the overlying sequence of clay and shale. It is possible that the flow of water through the overlying beds may account for a major portion of the aquifer's recharge. Lines drawn on the approximate potentiometric surface for 1970 indicate that, except locally, the regional movement of water in the aquifer is from south to north (plate 8).

Plate 8 also shows where the L-F aquifer probably accepts direct infiltration of precipitation and seepage from stream flow. Recharge from precipitation and streamflow seepage can occur only where the elevation of the hydrostatic head is below the elevation of the outcrop. Areas which appear to accept such recharge occur along an 80 kilometer (50 mile) length of outcrop in the Limon area and along an approximately 280 kilometer (175 mile) length of outcrop area extending from Township

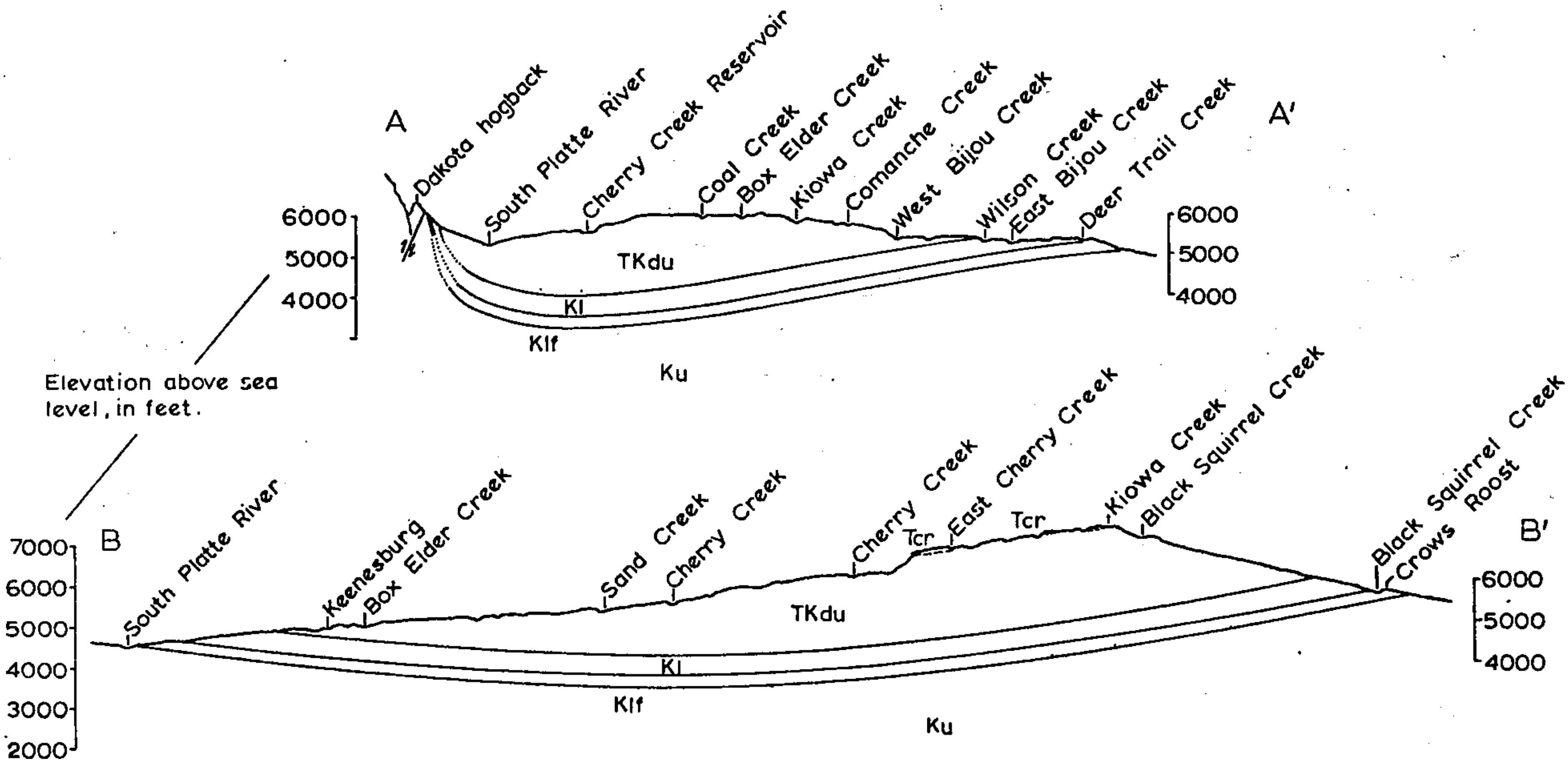

Figure 5. Cross and longitudinal sections of the Denver Basin. Geologic symbols: TKdu, Dawson group undivided; Kl, Laramie formation; Klf, Laramie-Fox Hills aquifer; Ku, Upper Cretaceous rocks undifferentiated. Multiply feet by 0.3048 to find meters.

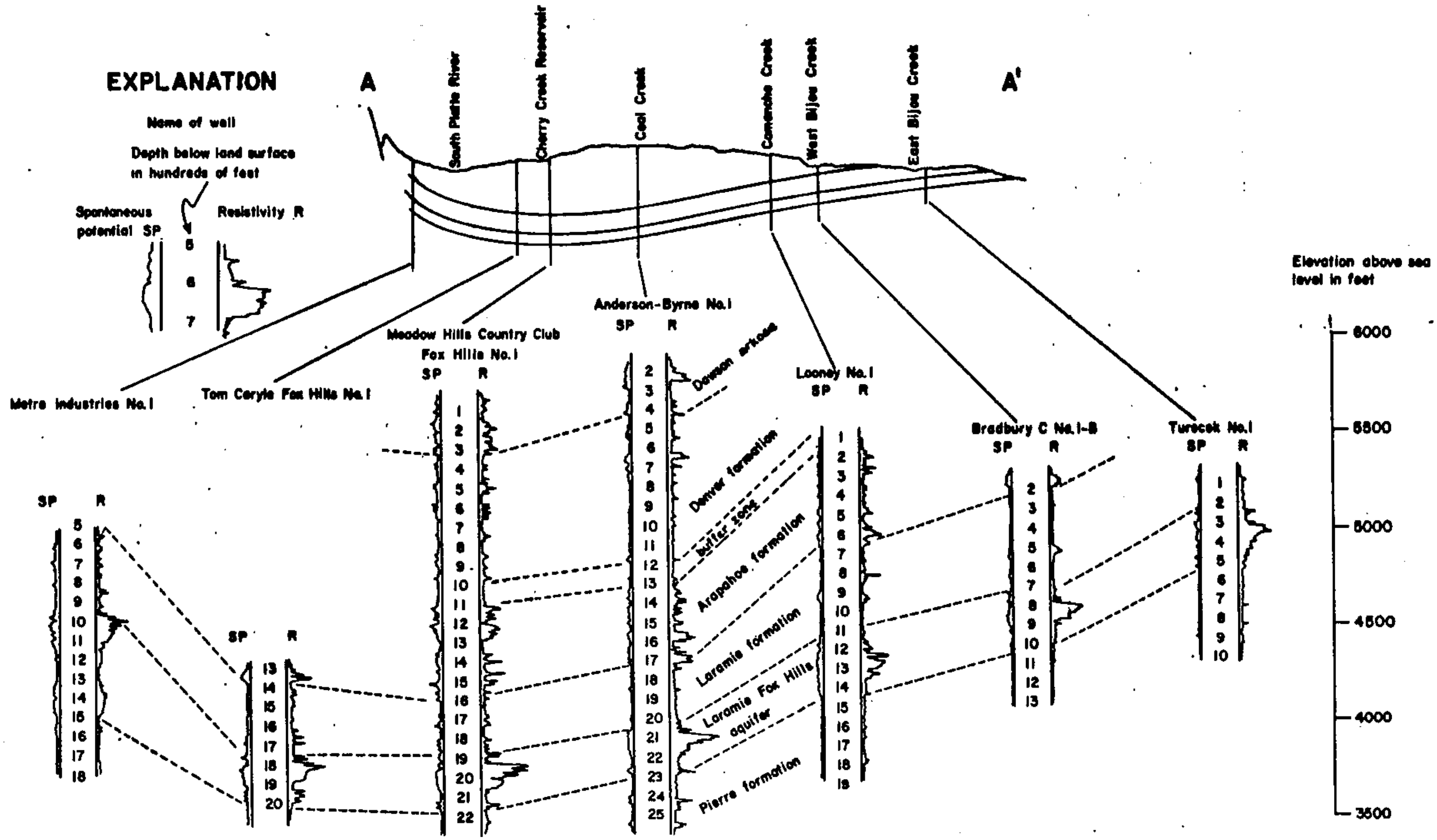

Figure 8. Cross section of the Denver Basin illustrating the use of electric logs for correlation of the principal aquifers. Multiply feet by 0.3048 to find meters.

15 South, Range 60 West clockwise around the periphery of the study area to Township 4 North, Range 62 West.

U. S. Department of Commerce weather data indicates that the regional average annual precipitation on the outcrop areas ranges from about 30 centimeters (12 inches) in the prairie lands to about 35 centimeters (14 inches) along the foothills. Precipitation is more likely to result in recharge to the L-F aquifer during the period May - September when the average for the outcrop area is about 23 centimeters (9 inches). Considering the fact that precipitation occurs generally as thundershowers and that these are commonly of short duration, intense, widely scattered, and that many areas in the prairie lands experience extended rainless periods, it is probable that only a small percentage of the precipitation adds to the aquifer recharge.

The L-F aquifer is also recharged by water which occurs as seepage along fault traces and along live stream cuts. The percentage that such recharge adds to the total recharge to the aquifer is unknown, but is thought to be small compared to that furnished by other sources. Considering the nature of precipitation and possible limited seepage of water along fault traces and stream cuts, the recharge by such sources is tentatively assigned a value of 2.54 millimeters (0.1 inch). Extended over roughly 773 square kilometers (191,000 acres) of outcrop-subcrop area, the annual rate of recharge is about 20 X 10^5 cubic meters (1600 acre-feet).

A major percentage of natural recharge to the L-F aquifer could occur as downward percolation of water through overlying beds of clay and shale. It has been suggested that although the permeabilities of clay and shale are very small, large areas of confining material under a substantial hydrostatic head can transmit appreciable quantities of water (Davis and DeWiest, 1956, pp. 224-229, 348, 349; Muskat, 1946, pp. 258-286; and Todd, 1959, p. 53). The transmission or leakance of water from shales to the L-F aquifer occurs theoretically, during and after the creation of a head differential produced by the pumping of a well. Comparison of plate 8 with plate 4 shows that throughout much of the central part of the study area, the static head along the top of the L-F aquifer ranges from about 152 meters (500 feet) to slightly over 457 meters (1500 feet). The area covered by at least 76 meters (250 feet) of head is about 10,530 square kilometers (2.6 million acres). The maximum quantity of water which could percolate through a confining layer having a hydraulic conductivity of 4.1 X 10^{-3} meters per day (10^{-5} gallons per day per foot^2) under a head differential ranging from 152 to 457 meters (500 to 1500 feet) is approximately 98.68 X 10^5 cubic meters (8,000 acre-feet) per year. The total quantity of natural recharge of water, including the maximum potential recharge as leakance, to the L-F aquifer is estimated to be about 12.34 X 10^6 cubic meters (10,000 acre-feet) per year.

If artificial recharge of water to the L-F aquifer occurs, it probably does so where the latter is cut by or is near earth-bottomed water diversion ditches. Such recharge might occur due to seepage from Ward Ditch or the Warrior Canal east of Morrison, and possibly as seepage from the Platte Canyon Ditch and Highline Canal in the vicinity of Littleton. Recharge from these potential sources is believed to be small compared to that of other sources. Artificial recharge from sewage effluent, over irrigation, and excessive stock watering probably does not occur to a major extent. The sources of such recharge are far removed from their origin and are generally "captured" by the more accessible shallow ground water and surface water systems.

The possibility that the L-F aquifer is artificially recharged by seepage of water from recent stream alluvial deposits has been investigated by Bibby (1969), Kuhn (1968), and Owens (1971). The thesis of Kuhn and Owens' report are based on a linear potentiometric surface, water quality relationships, and ground water and well hydraulics. Kuhn (pp. 23-27) suggests that the potentiometric surface of the L-F aquifer is a plane surface extending from the southern nose of the outcrop northward. Where the planar potentiometric surface lies above the water table at the alluvium-L-F interface, discharge from the L-F aquifer occurs. Where the water table is higher than the potentiometric surface, the alluvial ground water is recharging the L-F aquifer. Kuhn also suggests that the deterioration of water quality of several L-F wells in his thesis ares is due to the encroachment of poor quality water from principally Bijou and Kiowa valley alluvial deposits. Owens (1971, pp. 11-16) approached the problem by the application of ground water and pumping hydraulics. He suggested that the sustained pumping of wells tapping the bedrock formations reverses the natural potentiometric gradient to the extent that ground water in surface alluvial deposits can be induced to migrate through the alluvium-bedrock interface and recharge the bedrock aquifers.

Although sufficient data are lacking to establish recharge rates and because of data mentioned in the natural discharge section to follow, it is possible that artificial recharge due to a reversed potentiometric gradient is presently negligible. However, the time is rapidly approaching when the effects of extensive development of the L-F aquifer might result in measurable degrees of such artificial recharge. Such instances will occur in areas which are presently experiencing a marked growth rate and a change from predominantly agricultural to an industrialized economy. The potential effects of such growth and change are treated in a later section of this report.

Natural and artificial discharge. Ground water from the L-F aquifer is discharged naturally as seepage and possible spring activity in areas where the aquifer's potentiometric surface lies above the elevation of the outcrop of subcrop. Plate 8 shows that such areas possibly exist along an approximately 56 kilometer (35 mile) length of outcrop-subcrop between Limon and the southern part of the outcrop pattern and along a roughly 113 kilometer (70 mile) length of outcrop-subcrop from a point about 19 kilometers (12 miles) east of Byers northward to an area roughly 19 kilometers southeast of Greeley.

The suggestion that the L-F aquifer is naturally discharging water along the outcrop-subcrop southwest of limon is based on evidence that the potentiometric gradient in that part of the basin is locally sloping toward the south and possibly lies above the elevations of the outcrop-subcrop zone. Other phenomena which suggest the possibility of discharge of ground water in this area are localized spring activity and the presence of perennial reaches of streams in the upper reaches of Rush and Horse Creeks and their tributaries which head in the region near

Rush, Colorado. It is possible that the spring activity and perennial reaches of streams are due to the discharge of interflow from surficial deposits. Additional field data will have to be examined before the problem can be solved.

The configuration of potentiometric contours and the presence of other phenomena related to natural discharge indicate that a substantial quantity of water discharges from the L-F aquifer in the northeastern part of the study area. Potentiometric surface contours based on well data furnished to the State Engineer's office within the last five years indicate that the discharge of L-F water possibly occurs along much of the 113 kilometer (70 mile) length of outcrop-subcrop described above and indicated on plate 8. This suggestion is substantiated by the existence of several flowing wells which exist downdip from the outcrop area, the presence of seeps, phreatophyte growth in local outcrop-subcrop zones, and by work accomplished by Bibby (1969). In his thesis (pp. 26-37), Bibby suggests that the L-F aquifer is discharging water throughout all of his thesis area.

Calculations using hydraulic conductivities ranging from 0.82 to 1.43 meters per day (20-35 gallons per day per square foot) and slope of potentiometric surface of 4 and 5 meters per kilometer (22 and 25 feet per mile) indicate that the total quantity of water naturally discharged from the L-F aquifer ranges from about 68×10^5 to 116×10^5 cubic meters (5500 to 9400 acre-feet).

Water is artificially withdrawn from the L-F aquifer via a large number of domestic, stock, irrigation, commercial, industrial and municipal wells. Plate 8 shows how wells tapping the L-F aquifer are distributed within the basin. Because of the relatively shallow depths, most of the wells are located within or near the outcrop-subcrop areas.

As of winter 1974, there were approximately 600 wells known to tap the L-F aquifer within the bounds of the study area. About 83 percent of the wells are classed as the domestic-stock type. Uses of water from those wells include common household and garden requirements and the watering of livestock. Well discharges average 1 liter per second (15 gallons per minute). There are about 46 municipal wells tapping the L-F aquifer. The number of municipal wells within the Denver Basin was at one time, much higher, but the availability of water from many of the larger water-distribution companies, local pumping, and water quality problems have led to the temporary disuse of many L-F wells. The average discharge of a typical municipal well in the basin is 5 liters per second (about 80 gallons per minute). Records in the State Engineer's well files show that 23 wells tapping the L-F aquifer are classed as commercial and/or industrial. Industrial use implies that the water is used in a manufactured product. The typical commercial and/or industrial well in the basin discharges water at the rate of 4 liters per second (about 60 gallons per minute). Only 16 wells are known to tap the L-F aquifer for commercial irrigation and/or stock purposes. The average discharge of these wells is 6 liters per second (about 90 gallons per minute).

In the past, there was some confusion regarding the definitions of domestic, stock, commercial and municipal, and irrigation wells. The public was only partly aware of the Colorado Ground Water Law and was probably less aware of guidelines utilized by the State Engineer. Consequently, there exists a considerable number of erroneously classified wells in the Denver Basin. For example, a well which produces water for a sizeable trailer court might be on record as a domestic well, and a well which is used for the watering of 5000 cattle in a large feed lot might be classified as a stock well. Unfortunately, such problems are identified and corrected only occasionally. Hence, there is an inherent error in the reported number of wells in each category. Table 2 lists the approximate total annual withdrawal from each type as based on winter 1974 data.

A "safety" factor of 25 percent is included in the withdrawal column to account for the probability that most of the well records report over-estimated yields and that most of the wells do not operate on a 24-hour basis. In addition, most of the rural municipalities and many of the municipal wells within Metropolitan Denver are not metered, hence, no records are available as to annual withdrawals. Table 2 shows that the approximate annual withdrawal of water from wells tapping the L-F aquifer is 203.54×10^5 cubic meters (about 16,500 acre-feet).

Hydraulic properties of the aquifer. Yields of wells which tap the L-F aquifer presently range from one or two liters per second (several gallons per minute) for typical domestic-stock wells to about 13 liters per second (200 gpm) for properly designed municipal or irrigation wells. Thus, 13 liters per second appears to be the maximum sustained yield of wells tapping the aquifer; most "high capacity" wells in the L-F aquifer yield about 6 liters per second (100 gpm). It has been reported that in some areas north and south of Metropolitan Denver, the maximum sustained yields of some wells tapping the L-F aquifer are much less than 6 liters per second. Whether the poor yield is due to locally poor aquifer properties or deterioration of the well is unknown in most cases. In some instances, however, the reduction of yield has been attributed to localized over-development of the aquifer. Specific capacities (ratio between pump discharge and feet of drawdown) and other aquifer properties are given in table 3.

Plate 8 shows the approximate configuration of the potentiometric surface of the L-F aquifer for 1975. The contours clearly indicate those areas where declines occurred because of excessive withdrawals of water. In Metropolitan Denver, there exist local instances of flowing L-F wells in regions which have experienced excessive water-level declines. The fact that some wells in these regions continue to flow is an indication that the aquifer has a low hydraulic conductivity.

Available aquifer and pump-test data for the L-F aquifer indicate a wide range of values of hydraulic conductivity (K). Tests show that the range is from 8.2×10^{-5} to 1.43 meters/day (0.002 to 35 gpd/ft^2). Based on the most reliable of the available data and supported by information in Davis and DeWiest (1966, pp. 348,349) and in Todd (1960, p. 53, and 1970, p. 206), and considering the fact that the L-F aquifer is a good to excellent aquifer throughout most of the Denver Basin, it is suggested that K be assigned to range generally between 0.41 and 1.4 meters/day (10-35 gpd/ft). The transmissivity of the L-F aquifer ranges between 12.4 and 87 square meters/day (1000-7000 gpd/ft).

TABLE 2

List of L-F wells registered in the Colorado Division of Water Resources by four major categories and the estimated combined annual withdrawal of each type as based on 1974 information.

TYPE	NUMBER	TOTAL REGISTERED DISCHARGE		WITHDRAWAL	
		gpm	lps	AF/yr.	Cubic Meters/yr.
Domestic-Stock	517	7700	485	9300	114.73×10^5
Municipal	46*	4300	271	3800	46.87×10^5
Commercial-Industrial	23	1415	89	1700	20.97×10^5
Irrigation-Stock	16	1395	88	1700	20.97×10^5
	602	14,810	933	16,500	203.54×10^5

* Eight municipal wells are presently not in use

TABLE 3

Hydraulic properties of the major bedrock aquifers of the Denver Basin. Properties listed are intended to represent typical aquifer material.

	SPECIFIC CAPACITY		HYDRAULIC CONDUCTIVITY K	
	(gpm/ft)	(lps/m)	(gpd/ft^2)	(m/d)
Dawson Arkose	0.1-3.0	0.02-0.6	20-50	0.82 -2.1
Denver Formation	0.1-3.0	0.02-0.6	10-20	0.41 -0.82
Arapahoe Formation	0.1-3.0	0.02-0.6	20-50	0.82 -2.1
Laramie Formation	0.4	0.08	2-5	0.082-0.21
L-F Aquifer	0.5-1.0	0.1 -0.2	10-35	0.41 -1.43
Dakota Group	0.34	0.07	3	0.12
Lyons-Fountain Formation	0.05	0.01	5-10	0.21 -0.41

	TRANSMISSIVITY T		STORAGE COEFFICIENT	SPECIFIC YIELD
	(gpd/ft)	(m^2/d)	S	%
Dawson Arkose	500-5000	6.2-62	0.002-0.09	15-25
Denver Formation	250-2000	3.1-25	0.002	10-15
Arapahoe Formation	500-5000	6.2-62	0.002-0.09	20-25
Laramie Formation	300	3.7	0.001	10
L-F Aquifer	1000-7000	12.4-87	0.0004	15-20
Dakota Group	100-200	1.2- 2.5	0.001	10
Lyons-Fountain Formation	500-1000	6.2-12.4	0.0001	2-5

Aquifer and pump-test data indicate that the storage coefficient (S) for the L-F ranges between 0.00012 and 0.21. The high values were obtained from laboratory tests performed on core samples taken from outcrops within the Metropolitan Denver area, and in one case from a test performed on a core of sandstone taken from a depth of 556.3 - 556.6 meters (1825-26 feet). The average value of S for artesian conditions is assigned a value of 0.0004. Under water table conditions, the value ranges from 0.07 to 0.21; the average being 0.15. The percentage of drainable storage of the L-F aquifer is estimated to range between 15 and 20 percent.

Quantity of water available for withdrawal. The total volume of saturated L-F aquifer is approximately 5.4×10^{11} cubic meters (437.8 million acre-feet). Applying a specific yield of 15 percent, about 810.5×10^{8} cubic meters (65.7 million acre-feet) could be drained by gravity. The quantity which can be removed by wells is probably considerably smaller. Applying the common "percent available to wells" factor of 50 percent results in 405.2×10^{8} cubic meters (32.9 million acre-feet) of water. The quantity of water in storage represented by the hydrostatic head is about 863.53×10^{6} cubic meters (0.7 million acre-feet). If all of the latter could be withdrawn, the total quantity of presently recoverable water is about 414.5×10^{8} cubic meters (33.6 million acre-feet).

Laramie Formation

Although that part of the Laramie Formation lying above the B sandstone is considered confining strata, there are two relatively prominent sandstone horizons which have been assigned as potential aquifers (pl. 3). Although the two sandstones have not been developed to a great extent within the boundary of this report, they are treated here because of their potential. The sandstone horizons are generally 3 to 6 meters (10 to 20 feet) thick, are separated by 15 to 30 meters (50 to 100 feet) of shale, and occur generally 30 to 60 meters (100 to 200 feet) above the L-F aquifer. Plate 9 is a structure contour map of the top of the Laramie Formation.

Hydraulic properties of the aquifer. Since the upper Laramie sandstones are confined above and below by considerable thickness of clay and shale, and because existing data indicate the water level rises above the bottoms of the upper confining beds, the production zone must be classed as artesian. Yields of typical wells tapping the upper Laramie sands range from 0.2 to over 1 liter per second (3 to over 20 gpm) with specific capacities averaging 0.08 lps/m (0.4 gpm/ft) (table 3). Hydraulic conductivities of the Laramie range from about 0.08 to 0.2 meters per day 2-5 gpd/ft^2). Transmissivity values range from 1.6 to 3.7 square meters per day (130-300 gpd/ft). Based on meager data, the storage coefficient and specific yield are assigned values of 0.001 and 10 percent respectively.

Quantity of water available for withdrawal. Based on a planimetric areal extent of about 12,150 square kilometers (3 million acres), as assigned combined thickness of 12 meters (40 feet) of sand, and a specific yield of 10 percent, the quantity of water recoverable by gravity approximates 148×10^{10} cubic meters (12 million acre-feet). The quantity of water presently recoverable by wells is estimated to be 25 percent or about 37×10^8 cubic meters (about 3 million acre-feet).

Dawson Group

In ascending order, the formations included in the Dawson Group are the Arapahoe Formation, Denver Formation, and the Dawson Arkose. Each of the formations are considered as an aquifer because of the presence of thick sandstone horizons within them. Although individual sandstone layers are commonly separated by shale beds varying in thickness from several centimeters to several meters (several inches to several feet) some horizons are so thick that they can be developed as if they were a single unit. (pl. 3).

The Dawson Group has experienced more groundwater utilization than all of the other bedrock aquifers in the Denver Basin combined. The reasons for the extensive development are economics and water quality. The Dawson Group has proven to be economically desirable to exploit because of the great range of depths which can be utilized as water-bearing horizons. Depending upon the quantity of water desired and location within the basin, the well user can explore water-bearing strata ranging in depth from 30 or 60 meters (100 to 200 feet) to about 760 meters (2500 feet). The latter figure represents the approximate depth to the base of the Arapahoe Formation in the south-central part of the basin. The quality of water tapped from the formations within the Dawson Group is usually more desirable than that from the L-F aquifer primarily because it is 10 to 15 degrees F cooler and does not possess excessive quantities of dissolved gases.

The boundaries and general shape of the Dawson Group are illustrated in plates 1 and 9, and in figure 7. The boundary at the base of the group can be traced by the Laramie-Arapahoe contact in the prairie lands east of the foothills and by the sharply upturned, and in places, downfaulted areas along the foothills.

The basal aquifer of the group is the Arapahoe Formation. The Arapahoe is generally 150 to 180 meters (500-600 feet) thick, composed of predominantly sandstone and conglomerate, and has proven to be a most reliable source of good to excellent quality ground water. At least 90 meters (300 feet) of sandstone is locally present.

Most of the individual sandstone beds of the Arapahoe Formation, particularly those within the upper part, are lenticular in nature and are difficult to trace for great distances. The sandstones of the basal part, however, are so numerous and lithologically unique that they can be easily identified by electric-logging methods and, when well exposed, in the field. The Arapahoe Formation is distinguished from the overlying Denver Formation by overall texture, color, composition, and E-log characteristics. Sands of the Arapahoe Formation are generally much coarser and are lighter colored than those of the overlying Denver, there is a general preponderance of sand over clay, and workable coal seams are rare. The differences in texture and composition are generally revealed in most E-log traces (pl. 3).

Depth to the Arapahoe Formation ranges from zero to about 610 meters (2000 feet) in the deeper parts of the basin. Plate 10 is a structure contour map of the top of the formation.

Overlying the Arapahoe Formation are the claystones, shales, sandstones and conglomerates of the Denver Formation. Unlike the Arapahoe, the Denver Formation does not contain a thick series of closely spaced sandstones which can be easily traced throughout the entire Denver Basin. The sandstones thin considerably in an eastward direction and become interfingered with thick sequences of clays and shales. Toward the south, their development is very irregular; sandstones commonly grade into shale within relatively short distances (Kittleman, pp. 29-37). Beds of lignitic coal are locally developed.

Electric logs and data from various reports, which deal in part with the Denver Formation, indicate that the most likely location of reliable water-bearing strata occur in the lower one-half of the formation. Where best developed, the "aquifer zones" of the Denver are composed of a 30 to 45 meter (100-150 feet) thick series of sandstones interbedded with shale. Spot checks of E-logs indicate that the formation contains roughly 20 to 40 percent sand (pl. 3). Plate 11 is a structure contour map of the top of the formation.

The Dawson Arkose consists of up to 335 meters (1,100 feet) of sandstone, conglomerate and shale. Like the Arapahoe Formation, the Dawson Arkose has proven to be a reliable source of good quality ground water. Although the Dawson contains considerable local thicknesses of clay and shale, the regionally predominant material is coarse, arkosic, and micaceous sandstone. The sandstones are irregularly dispersed throughout the entire formation but appear to be thicker in the lower part and particularly thick near the foothills. Reliable water well drillers' sample logs of the formation are rare, and until recently E-log data was virtually non-existant; hence information regarding the Dawson Arkose is incomplete. Examination of existing data indicates that the principal water bearing horizon occurs in the lower 120 to 150 meters (400 to 500 feet). The upper 150 to 180 meters (500 to 600 feet) does contain water-bearing strata which generally are not as well developed as in the lower half.

Plate 3 illustrates the use of E-logs in identifying the Dawson Arkose. Plate 11, which is a structure-contour map of the top of the Denver Formation, is also a structure-contour map of the base of the Dawson Arkose.

Much work needs to be done before the aquifer characteristics of the Denver Formation and Dawson Arkose can be accurately delineated. The importance of obtaining E-log data for future investigations cannot be overstressed. Indeed, it is the lack of such data that prevents detailed examination of the upper formations of the Dawson Group. Due to emphasis the Colorado State Engineer has recently placed on obtaining E-logs from newly constructed water well bore holes, data regarding the Denver Formation and Dawson Arkose will gradually become more complete.

<u>Natural and artificial recharge</u>. Natural recharge to the members of the Dawson Group is derived primarily from the infiltration of precipitation in areas of outcrop and subcrop, and probably along fault zones which

flank the foothills. Additional natural recharge probably occurs as infiltration of seepage from many of the live streams which head in the Black Forest region. The lower members of the group probably receive a measurable quantity of recharge through overlying clay-shale strata.

Although U. S. Department of Commerce isohyetal maps indicate that annual precipitation on the outcrop and subcrop areas ranges between 38 and 43 centimeters (15 and 17 inches), there exist several factors which could reduce the formation's ability to accept recharge: (1) summer precipitation, although frequently intense is generally of relatively short duration and widely scattered; (2) the area enveloped by the Dawson Group has an average annual evaporation rate of 140 centimeters (55 inches) (U. S. Weather Bureau Class A pans); (3) much of the geologic material is mantled by surficial deposits and vegetative cover; and (4) the Dawson Group has a low overall permeability and its sandstones are markedly lenticular. The net effect of the above conditions is that natural recharge to the group might be rejected in some areas and readily accepted in others. Recharge that does take place probably occurs to a greater degree during the spring from the infiltration of spring snowmelt and rainfall.

Undoubtedly, natural recharge of water to the Dawson Group occurs via seepage through fault traces and along live stream cuts. The percentage that such recharge adds to the formations will remain unknown until more detailed studies have been undertaken. It is probable that the natural recharge from such sources is negligible compared to that furnished by the infiltration of precipitation.

The assigned value of natural recharge to the Dawson Group from precipitation and streamflow seepage is 1.27 centimeters (one-half inch) or 128.29×10^6 cubic meters (104,000 acre-feet) per year. The quantity of potential recharge as percolation through overlying clay-shale strata is highly speculative at this time. Since the potentiometric data are lacking and the area occupied by the Dawson Group is only about 75 percent of the area occupied by the L-F aquifer, the quantity of such recharge or leakance is tentatively assigned a value of 65 percent of similar recharge to the L-F aquifer of 64.15×10^5 cubic meters (5200 acre-feet) per year. Total natural recharge to the Dawson Group is therefore estimated at about 135.69×10^6 cubic meters (110,000 acre-feet) per year.

Water is artificially recharged to the Dawson Group as percolation of waste water from domestic/stock, irrigation, commercial, industrial, and municipal systems. Considerable investigation must be accomplished before the quantity of such recharge can be accurately estimated. Because the aquifer horizons generally lie at a considerable depth below the land surface and that most of the waste water is lost as evapotranspiration or is captured by shallow ground water or surface water systems, it is suggested that such recharge is minimal when compared to natural recharge.

<u>Natural and artificial discharge</u>. As of this writing, there is some evidence that members of the Dawson Group might be discharging water at the surface. Discharge of interflow, overflow from perched water tables, and possibly discharge of water from fault traces account for spring activity which occurs in many parts of the Black Forest region.

Based on limited potentiometric surface data and the probable existence of local discharge of water to underlying aquifers, it is estimated that potential discharge of water by this means is about 64.15×10^5 cubic meters (5200 acre-feet) per year.

As of winter 1974, about 6000 wells were known to tap water-bearing horizons within the Dawson Group. About 90 percent of these wells are classed as domestic-stock. Discharge from typical domestic-stock wells averages 0.82 liters per second (13 gallons per minute). About 130 municipal wells are known to tap the Dawson Group of formations, with their discharge ranging from 3 to 19 liters per second (50 to 300 gallons per minute). Both large and small municipalities are included. Large water agencies are typified by South Adams County Water and Sanitation District and the City of Westminster, small agencies are typified by the City of Strasburg and Federal Heights Water and Sanitation District. About 300 wells tap the Dawson Group for commercial, industrial and commercial irrigation or stock purposes.

As with the L-F aquifer, the same type of confusion exists regarding the public concept of the varying definitions of well uses. Hence, the exact number of wells in each category is not certain. Future investigations will be designed to reveal both the exact numbers and locations of each well and to furnish much needed water-level change information. The data will be used to calculate a more accurate recharge-discharge figure and as an aid in managing and predicting the life of the group as an aquifer.

Table 4 lists the approximate number of Dawson Group wells in each of the four major categories and the estimated annual withdrawal. The figures derived for all wells except municipal are based on operating times of about 70 percent of a 24-hour day.

Hydraulic properties of the aquifers. Most of the water-bearing horizons within the Dawson Group are classed as artesian. The lower confining formation of the group is the Laramie Formation. The confining beds above the Laramie Formation are clay-shale strata within the Arapahoe, Denver and Dawson Formations.

Wells which tap the Dawson Group have been designed to pump from about one liter per second (10 gallons per minute) for typical domestic-stock wells to an average of about 10 liters per second (150 gallons per minute) for typical municipal wells. The extensive development of sand and conglomerate in the Arapahoe Formation and the Dawson Arkose has permitted the construction of wells which yield up to 25 to 30 liters per second (400 to 500 gallons per minute) from properly designed wells.

Since most of the high capacity Dawson Group wells are completed in the Arapahoe Formation, more hydregeologic data are known about them than either the Denver or Dawson Formations. The reason for the numerous high capacity wells in the Arapahoe is at least twofold: (1) most of the municipalities which utilize Arapahoe water are located outside the boundary of the Dawson Arkose, and (2) the concept that the deeper aquifer (Denver vs. Arapahoe) would be a more reliable long-term source of water than the relatively shallow and locally heavily utilized Denver Formation. Existing evidence suggests that although the Denver Formation contains locally extensive development of sand, most of the formation's

Table 4

List of Dawson Group wells registered in the Colorado Division of Water Resources by four major categories and the estimated combined annual withdrawal of each type as based on 1974 information.

Type	Number	Total Registered discharge (gpm)		*AF/yr Withdrawal	
		(gpm)	lps	AF/yr	Cubic Meters/yr
Domestic-stock	5,640	74,100	4668	75,500	931.38×10^5
Municipal	127	10,300	649	11,900	146.80×10^5
Commercial/Indus.	220	15,840	998	25,500	314.57×10^5
Irrig. - Stock	75	9,040	569	10,900	134.46×10^5
Totals	6,062	109,280	6884	123,800	1527.21×10^5

* Additional studies are required to assign values to the average annual withdrawal of water from each formation within the Dawson Group.

sand layers are separated by relatively thick sequences of clay and/or shale. In order to obtain large well yields from such sand-shale sequences, the entire aquifer might have to be tapped; which might be hazardous from a potential water quality degradation concept.

The Dawson shows good potential for supporting high-capacity wells in the south-central part of the basin. An E-log of one oil well test hole indicates the presence of a predominantly sand sequence no less than 183 meters (600 feet) thick (pl. 3). Such sequences of sand should support sustained yields of at least 25 liters per second (400 gallons per minute). The specific capacities of typical Dawson Group wells range from 0.02 to about 0.62 liters per second per foot (0.1 to about 3.0 gpm/ft). High specific capacities can be expected only in wells tapping thick sequences of sand or in wells which are completed in more than one aquifer.

Hydraulic conductivity values obtained from both aquifer and pump tests, and from laboratory tests performed on core samples taken from outcrop areas range from 2.9×10^{5} to 57.4 meters per day (0.0007 to 1400 gallons per day per square foot). The low values were obtained from thoroughly lithified and cemented conglomerates and sandstones of the various members. Fortunately for the well user, only a very small percentage of the Dawson Group sandstones are so tightly cemented. A properly designed and developed well in the lower part of the Dawson Arkose or Arapahoe Formation should normally produce from material with K values in the range of 0.82 and 2 meters per day (20-50 gpd/ft^2). Reliable aquifer and pump test data indicate that the transmissivity of typical wells tapping the Arapahoe and Denver Formations ranges between 1 and 45 square meters per day (80 and 3600 gallons per day per foot). The high values occur in wells tapping thick sequences of sand. Values of transmissivity of the Dawson Arkose are probably within the same range.

Values for the coefficient of storage range from 0.001 to 0.46; the high values being obtained from tests performed on outcrop samples. Storage coefficients obtained from aquifer and pump tests range from 0.0001 to 0.09 with low and high averages of 0.002 and 0.03 respectively. Lenticularity and lithification undoubtedly markedly affect the value of the storage coefficient. The specific yield or quantity of drainable storage of the Dawson and Arapahoe formations averages 20-25 percent.

Because of the lack of data, the aquifer constants for the Denver Formation have not been conclusively delineated. Since sands of the Denver Formation are lenticular, generally fine-grained, and are generally separated by substantial clay-shale sequences throughout most of the basin, the aquifer constants are assigned the following values: hydraulic conductivity 0.41-0.82 meters per day (10-20 gpd/ft^2), storage coefficient 0.002, and specific yield 10-15 percent.

<u>Quantity of water available for withdrawal</u>. Based on an estimated specific yield of 20 percent and recovery factor of 50 percent for the Arapahoe Formation and Dawson Arkose, and a specific yield of 10 percent and a recovery factor of 50 percent for the Denver Formation, the quantity of water that can be removed by pumping from present storage is about 145.57×10^9 cubic meters (118 million acre-feet)(table 5).

Table 5

Estimated total storage in and recoverable amounts of ground water from the Dawson Group.

Formation	Total Storage (AF)	Total Storage (M^3)	Recoverable Storage (AF)	Recoverable Storage (M^3)
Dawson Arkose	34,710,000	42.82×10^9	17,355,000	21.41×10^9
Denver Formation	30,506,000	37.63×10^9	15,253,000	18.82×10^9
Arapahoe Formation	170,550,000	210.84×10^9	85,275,000	105.20×10^9
Rounded totals	236,000,000	291×10^9		145×10^9

The quantity of water in storage represented by the Dawson Groups potentiometric head will remain unknown until data from additional field investigations can be evaluated.

AQUIFER INTERRELATIONSHIPS

Ground waters in the bedrock aquifers are not totally isolated from each other. On the contrary, they not only possess a definite relationship but are also in a state of slow, definite flux. Movement of ground water between aquifers occurs by at least four modes which are listed and discussed in the following order: (1) intermingling of formation waters due to faulty or poorly designed wells; (2) intermingling by water movement along fault traces; (3) intermingling of bedrock and alluvial ground waters at stream channel-bedrock interfaces; and (4) the vertical percolation of ground water through semipermeable confining beds.

Numerous reports of gradual to sudden deterioration of water quality from wells tapping the bedrock formations have occurred during the past and are frequently occurring during the present. Unfortunately, the reports are poorly documented. The data presented here are based on conversation with a number of well users, including municipalities. The evidence reveals that bedrock aquifers producing good quality water can become contaminated if the producing well or other wells in the area are improperly designed or constructed. The contamination, a result of the comingling of poor with good quality water, occurs as a direct result of (1) poor logging control, resulting in an improper casing program; (2) deterioration of casing; (3) failure of or improperly designed seals; and (4) open hole well construction.

A major contributor to the gradual deterioration of water quality in many deep wells was the lack of reliable logging control during the time the wells were drilled. When most of the deep wells in the Denver Basin were drilled, they were logged by a cursory examination of drill cuttings. Since the thickness of strata penetrated is so great and the lithologic sequence is by no means uniform, it is likely that the characters of many of the zones penetrated were incorrectly described. In addition, few attempts were made to test the quality of water of individual aquifers as they were penetrated. The net result is the occurrence of numerous wells with improperly located perforated casing. The chances of occurrence of such sources of contamination are probably quite high in wells designed to tap several water-bearing horizons, especially if water quality tests were mot made before the completion of the well. The problems encountered by examining drill cuttings can be lessened by the application of geophysical logging methods.

A second major source of inter-aquifer contamination undoubtedly is the deterioration of casing material and the failure of or improperly designed seals either at the well head or within the formation. In most cases, deterioration of casing and subsequent failure of seals is caused by age of the well and is difficult to remedy. The placement of an improperly designed seal and casing, however, can be avoided by conscientious examination of drill cuttings when geophysical methods are not used, and by the use of high grade materials.

Open hole wells are the types within which only the uppermost portion of the drill hole is cased. Many of the open hole wells include a hundred or more meters of uncased strata. The possibility for ground water from different strata to mix in such wells is quite high. Although frequently practiced in past, current State Engineer policy is to discourage open hole construction in wells tapping sedimentary formations. Present policy is to require single aquifer completion and to require installation of suitable seals to prevent the comingling of ground water from separate aquifers.

As described by Hollister and Weimer (1968) and Scott (1970), the Denver Basin's sedimentary rocks have been cut by numerous faults which extend into the Precambrian basement. Current studies by the U. S. Geological Survey have revealed that faulting might be more widespread than described in earlier publications. Since these faults extend into Tertiary and Quaternary rocks and are relatively active, there is a strong possibility that certain fault traces act as conduits for the passage of ground water pollutants.

The same mechanisms described in the deterioration of water in an open hole well can generally be applied to a well near or on a fault trace. The possibility that fault traces can act as conduits for pollution is suggested by numerous reports of the presence of hydrogen sulfide and methane gases in the water of many Laramie-Fox Hills wells in the northern Denver metro area.

All of the gas and oil wells in the Denver Basin have been shown to contain methane and lack hydrogen sulfide. If a methane bearing strata is connected to an overlying aquifer by means of a fault, it is possible that the gas can migrate upward and permeate the aquifer. The L-F aquifer would generally be the first "receptive" formation encountered in the upward migration of the gas. If only small quantities of methane were present, it is possible that most of it would accumulate in the L-F aquifer, with only undectable quantities passing upward. The hydrogen sulfide which has been reported in many L-F wells is possibly the result of the action of methane on sulfates in the presence of anaerobic bacteria. Hem (1959, p. 223) suggests that anaerobic bacteria can react on many other hydrocarbons and produce hydrogen sulfide. While the methane and hydrogen sulfide can be produced by the action of anaerobic bacteria and organic matter within the L-F aquifer, the fault offers a relatively unobstructed means of intermingling of aquifer waters. The fault traces along the foothills and in the north Denver metro area are the most likely areas for such intermingling to occur. The degree of mixing are functions of the nature of the faults and local ground water hydrodynamics.

The relationship between alluvial aquifers and bedrock aquifers has been presented in previous sections of this report. Of major interest is the effect of time on the interplay of aquifers in the northeastern part of the basin where relatively long segments of the L-F aquifer are cut by the alluvial stream channels of Bijou, Deer Trail, and Muddy Creeks. Hydrogeologic evidence is divided between that which indicates that the L-F either discharges to the alluvium or accepts recharge from the alluvium. Evidence presented by Kuhn (1968) and Owens (1971) suggest that continued development of the L-F aquifer will ultimately result in the formation of aquifer interrelationships of a measurable magnitude.

Interplay between the alluvial aquifers and members of the Dawson Group of formations may occur where sandstone horizons are cut by streams. Movement of water from the alluvium to the bedrock sandstones requires the presence of unsaturated-permeable strata below the water table of the alluvial deposits. Although the aquifers of the Dawson Group contain generally lenticular sandstones, it is possible that many of the thicker aquifer horizons are continuous on a local basis. In localities where such horizons have been extensively developed and are in contact with saturated alluvial deposits, the alluvium probably discharges water to the bedrock in the same manner as in the L-F aquifer - Bijou alluvium interrelationship.

There are at least 5000 more wells penetrating the Dawson Group than the L-F aquifer. Furthermore, the highest density of the Dawson Group wells occurs along the western half of the basin where many stream channels occur. Therefore, it is quite likely to suspect that if a substantial Dawson-alluvium interrelationship exists, it does so in the western half of the basin.

The presence of confining beds in the Denver Basin does not totally isolate the main aquifers. On the contrary, it has already been stated that the confining beds are actually semipermeable and over large areal extent considerable quantities of water can be transmitted through them. Bentall (1963, p. 111) mentioned that the cone of depression created by heavy pumping in an artesian aquifer might encompass billions of square meters and induce the leakance of a considerable quantity of water. It is also suggested that in some situations, well discharge is balanced by leakance through overlying semiconfining beds which can occur from both the overlying and the underlying semiconfining beds. Leakance through the overlying beds will occur if they are in turn overlain by water saturated strata which also might be confined or semiconfined. When water is withdrawn from the main aquifer, a head difference is produced between the top and bottom of the semiconfining bed which induces leakage to the main aquifer. Leakance to the pumped aquifer from underlying and semiconfined beds occurs because of the establishment of spherical flow patterns during pumping. Spherical, three-dimensional flow is a phenomenon which occurs in wells that do not penetrate the entire aquifer.

Leakance is also facilitated by the presence of lenticular sandstones and sandy clays in all of the beds which "confine" the principal aquifers. Lenticular horizons in the Dawson Group are locally so numerous that leakance probably takes place quite readily. Indeed, this is the basis for the suggestion that wells penetrating lenticular horizons may be treated as partially penetrating.

Mathematical development of leaky-aquifer equations is treated in DeWiest (1965, pp. 271-286), Bentall (1963, pp. C48-C55) and Ferris, et al., (1962, pp. 110-118) to name but three references. The methods stress the need of scientifically conducted aquifer tests with one or more observation wells and the passage of enough time to allow for the drawdown in the observation wells to show a derivation from the nonequilibrium (nonleaky) type curve.

The mushrooming interest in the bedrock aquifers of the Denver Basin has created and will continue to create numerous administrative problems. Since the effective administration of the bedrock aquifers requires a source of scientific data upon which to base decisions, well designed aquifer tests should be conducted at every opportunity.

POTENTIOMETRIC SURFACES

The elevation to which water will rise in artesian wells defines the potentiometric surface. Lines drawn between points of equal elevation constitute a potentiometric surface map.

Although the potentiometric surface of the Fountain and Lyons Formations and the Dakota Group were not determined, they can be easily visualized. Each surface dips eastward away from the outcrop area at angles somewhat smaller than the dips of their parent aquifers. Near the bottom of the Fountain-Lyons-Lykins strike valley and 0.8 kilometer (one-half mile) or more east of the Dakota hogback, the potentiometric surfaces locally extend above the land surface (fig. 6, page 32). Several wells were reported to flow in such areas shortly after they were drilled. Since many of the wells penetrating the Fountain, Lyons and Dakota Formations are several years old, it is possible that the potentiometric surfaces have experienced local declines. This possibility will be examined as part of the continuing study program for the Denver Basin.

Plate 8 illustrates the approximate configuration of the potentiometric surface of the Laramie-Fox Hills aquifer for 1975. As stated in the L-F section of this report, the overall or regional movement of water, except for local anomalies, is from south to north. The L-F potentiometric surface evidently is in a state of flux. Evidence indicates that large cones of depression have developed in areas with high well densities in the L-F aquifer. Most of the wells tapping the L-F aquifer are near population centers (Denver, Colorado Springs and Byers-Deer Trail for example) and along the South Platte River Valley downstream from Metropolitan Denver. The cones of depression will increase in size with passing time and continuing withdrawals of water from the L-F aquifer. Extending far beyond their present limits, the cones might eventually be of such magnitude that water production from the L-F aquifer in distant areas will be seriously affected. Water level measurements of several L-F wells in the Denver-Metro area indicate that through the middle 1960's the potentiometric surface of the aquifer has declined locally at rates ranging from 1 to 4 meters (about 3 to 13 feet) per year. During the last six years, rates of decline have changed depending upon the availability of surface water supplies and population-economy trends. Current local rates of decline of the L-F potentiometric surface in the Denver area range from about 0-3 meters (0-10 feet) per year. Water-level measurements of L-F wells in the Brighton area show declines as high as 15 meters (50 feet) per year to less than 3 meters (10 feet) per year. Spring 1974 measurements indicate a trend of local recovery (fig. 9). Since the area is currently experiencing local reorientation from agricultural to industrialized and suburbanized communities, it is suspected that the long-term water level trend will be a decline. The L-F water level decline in the north-central rural areas of the basin ranges from about 1 to 6 meters (3 to 20 feet) per year. The long term trend in the extreme eastern and southeastern part of the basin has not been established. Based on trends in other areas and on data from the town wells of Byers and Deer Trail, the rate of decline is assumed to range between 0.3 and 1.5 meters (1 and 5 feet) per year. Evidence from the Colorado Springs area indicates that water level declines of at least 1 meter per year are common. Slight water-level recovery in some wells during the winter of 1973 might have been a result of reduced ground-water withdrawals - precipitation during

1973 was abnormally high in many regions throughout the state.

The configuration of the potentiometric surfaces of the members of the Dawson Group of formations will be determined during the course of continuing phases of the Denver Basin investigation. In these investigations, the most reliable Arapahoe-Denver-Dawson well log data will be used to construct the maps. An inherent problem in constructing the maps will involve choosing data from wells which have been shown to tap only a specific member of the group. New wells permitted to tap a bedrock formation will be restricted to one major water-bearing horizon.

If a composite potentiometric surface map of the Dawson Group would be constructed, it will possibly very closely resemble the potentiometric surface map of the L-F aquifer (pl. 8). Major differences will involve (1) the general elevation of potentiometric contours with respect to sea level, and (2) the "size" of cones of depression which have probably developed in heavily pumped areas.

Unlike the potentiometric surface of the L-F aquifer, large segments of the composite potentiometric surface of the Dawson Group probably no longer extend above the land surface. Most of the wells which used to flow now must be pumped and there is no available evidence indicating that waters from the Dawson aquifers discharge into the alluvium. Because of its length of use as an aquifer and of its generally widespread development, the composite potentiometric surface of the Dawson Group has experienced very large local declines. In the metropolitan area, water from the Dawson Group has been utilized since 1883 - L-F aquifer was first utilized in the late 1920's. In addition, well records reveal that in the metropolitan area, the cumulative registered discharge rate per township of wells penetrating the Dawson Group range between 130 and 380 liters per second (2,000 and 6,000 gallons per minute) (pl. 11). Emmons (1896, p. 403) and McLaughlin (1955, p. 60, R.M.A.G. Guidebook) submit data from two time periods that show how the rapid development from 1890 to 1954 affected the local artesian head. In 1883, the head was about 61 meters (200 feet) above the land surface and in 1954 the head was locally 137 meters (450 feet) below the land surface - a total decline of about 200 meters (650 feet).

CHEMICAL QUALITY OF THE GROUND WATER

Dissolved mineral matter in ground water is derived from soluble minerals in the atmosphere, soil and rocks through which the water moves. Initially, as rain falls through the atmosphere it contains very small quantities of dissolved minerals but does contain dissolved atmospheric gases. When the rain water penetrates the earth's surface and percolates downward, it dissolves the more soluble minerals. The amount and kind of mineral matter dissolved by the water depends upon the chemical composition and physical nature of the rocks with which the water comes in contact, the temperature, pressure, and duration of contact. In addition, human influence such as oil and water well drilling activities and waste injection to name a few, may greatly affect the type and amount of dissolved mineral matter in ground water.

The general chemical quality of the ground water in the Denver Basin's

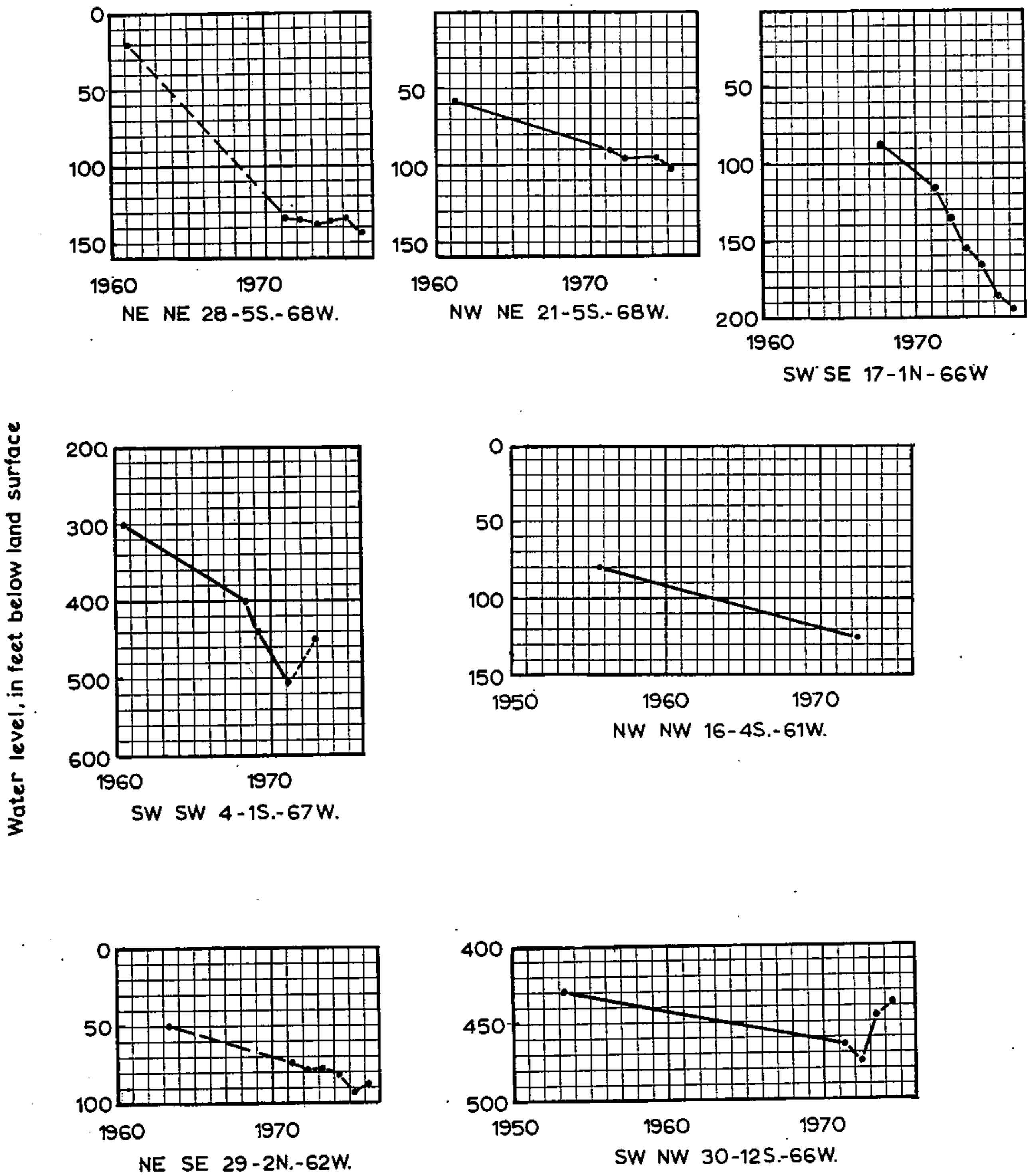

Figure 9. Hydrographs of selected wells tapping the L-F aquifer. Multiply feet by 0.3048 to find meters.

principal bedrock aquifers is shown in table 6. The data was obtained from McConaghy, et al., (1964), Gregg, et al., (1961) and from State Engineer files. Concentrations of the various chemical constituents are given in table 6A and B in parts per million (ppm). Hydrogen-ion concentration is expressed in pH units. pH values lower than 7 indicate acidic solutions whereas pH values higher than 7 indicate basic solutions. The pH of natural water is controlled by chemical reactions and equilibrium among the ions in solution.

CHEMICAL COMPOSITION AND MINERALIZATION

Chemical analyses of ground water from the bedrock formations indicate that the degree of mineralization and chemical composition of the water vary widely. For example, the concentrations of sodium ranged from 6 to 1000 ppm, sulfate from 0 to 1960 ppm, and chloride from 0.5 to 454 ppm; the specific conductance of the waters ranged from 64 to 5040 micromhos per centimeter; and TDS ranged from 108 to 3680 ppm. The relatively great range of chemical constituents within individual formations might be due to differences in chemical composition of the aquifer material, intrusion of water from other aquifers, or chemical contamination from either man-made or natural causes.

Most of the samples were obtained from wells in the Denver metropolitan area. Water quality data from other areas in the basin are represented by tests performed on tap water from several small widely scattered communities.

Analyses of water from the Dawson Arkose indicate that it is among the least mineralized of the water sampled. Assigning a chemical type to Dawson Arkose water is difficult at present due to lack of data; the two tests available indicate calcium bicarbonate. The presence of H_2S in a few Dawson Arkose wells (table 6-B) is possibly due to the reduction of sulfate by hydrogen released through the decomposition of organic matter by anaerobic bacteria. These particular wells are thought to be quite old as they are not listed in present State Engineer's records.

Radiochemical analyses of water from two wells east of Sedalia (table 6-C) indicate the presence of radon 222. This is of particular concern because radon 222 is a "daughter" of radium 226, therefore, the presence of radium 226 is implied, and, both radium 226 and radon 222 are alpha emitters. A well about two miles north indicates the presence of radium, radon, thorium and uranium. Although surface originated contamination is a possible source of the radio-elements, the most likely source is from radioactive minerals within the strata of the Dawson Arkose.

Water from the Denver Formation generally has a low to medium mineral content. Test data indicates that sodium and calcium bicarbonate and sodium sulfate type waters are present. The relation between specific conductance to the concentration of dissolved solids is shown in figure 10. Figure 10 can be used to obtain a rough estimate of the dissolved solids content of water from the Denver Formation in the greater Denver metropolitan area when specific conductance data are available.

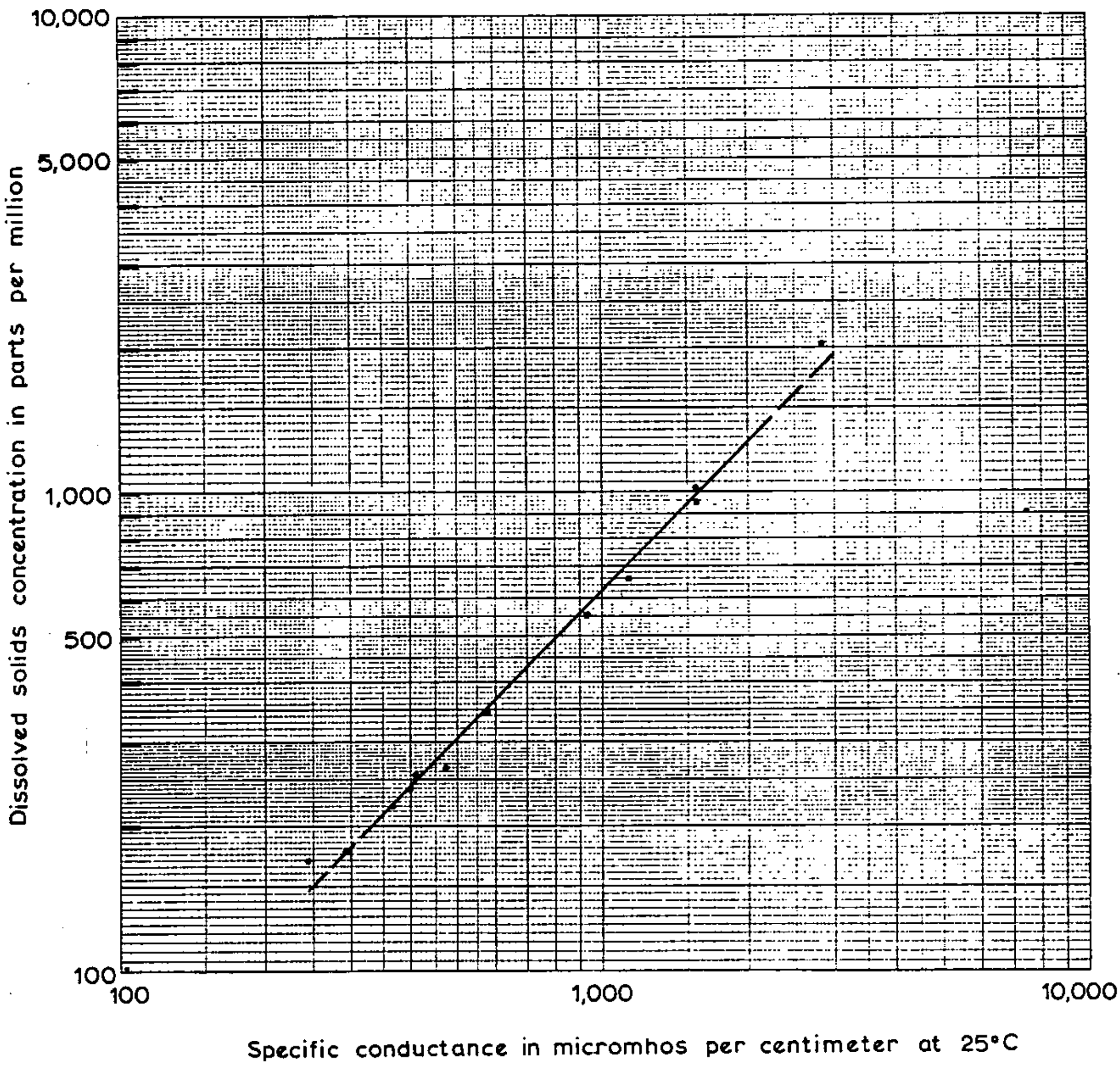

Figure 10. Graph showing relation of specific conductance to dissolved solids for water from the Denver Formation.

The relation of concentrations of principal cations and anions to specific conductance is shown on figures 11 and 12. The calcium and magnesium curves of figure 11 and indefinite as the few data points available are widely distributed. The trend of the relationship between specific conductance and sodium concentration clearly indicates that high conductance is indicative of high sodium content. Comparison of the calcium, magnesium and sodium curves suggests that like sodium, the concentrations of calcium and magnesium increase appreciably when conductance exceeds 1,000 micromhos per cm.

Figure 12 shows that the relation between conductance and bicarbonate concentration is indefinite. The data points on the lower right part of the bicarbonate graph were obtained from wells which are relatively shallow and lie near the indefinite boundary between the Arapahoe and Denver Formations. Until better data is obtained, it is suggested that the curve tentatively follows the dashed line. As of this writing, no definite relationship between bicarbonate concentration and distance from the outcrop area has been established. The sulfate and chloride curves indicate that high conductance relate to high concentrations of each anion. It should be noted that several of the wells containing high sulfate concentration are located relatively near the indefinite Arapahoe-Denver boundary.

Available information indicates that most of the water of the Denver Formation with high conductance and high TDS occurs north of Township 3 South. The reason for this might be the disproportionate number of sample sites in northern Denver metro area. However, it is also possible that the water quality in this area is lower because of either natural geologic phenomena or because of the influx of human contamination from surface sources.

Hydrogen sulfide gas has been reported in several wells which tap the Denver Formation (table 6-B). Its presence is probably due to the decay of organic matter in the presence of bacteria within the immediate vicinity of the well. Radiochemical analyses of water from the Denver Formation indicate local presence of radium, radon, thorium and uranium (table 6-C).

Analyses indicate that water from the Arapahoe Formation also exhibits relatively low mineralization. The total dissolved solids content ranges from about 150 to 1200 ppm with approximately 70 percent of the samples containing about 250 ppm or less total dissolved solids. Figure 13 shows the relation between specific conductance and TDS. The trend of the plots is quite regular, hence the figure can be used to estimate TDS of Arapahoe Formation water when conductance data are available.

The relation between specific conductance and concentration of principal anions and cations within water of the Arapahoe Formation is shown in figures 14 and 15. The relation between concentrations and principal anions and specific conductance is not clearly defined although there appears to be a general trend of increasing anion concentration with increasing conductance. A large part of the scattering of the data points are possibly a result of multi-aquifer completion and/or contamination resulting from deterioration of well casings and seals.

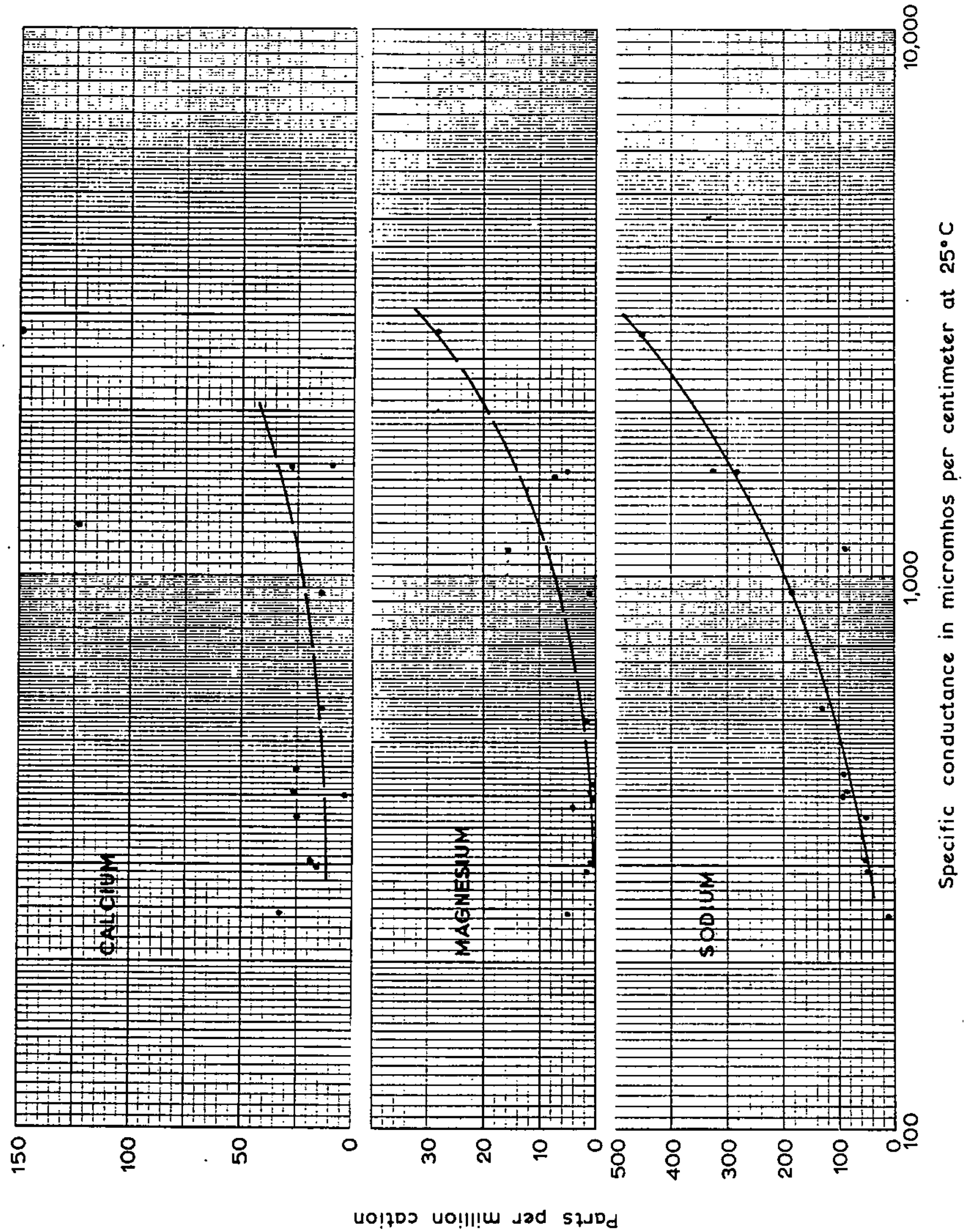

Figure 11. Graph showing relation of specific conductance to principal cations for water from the Denver Formation

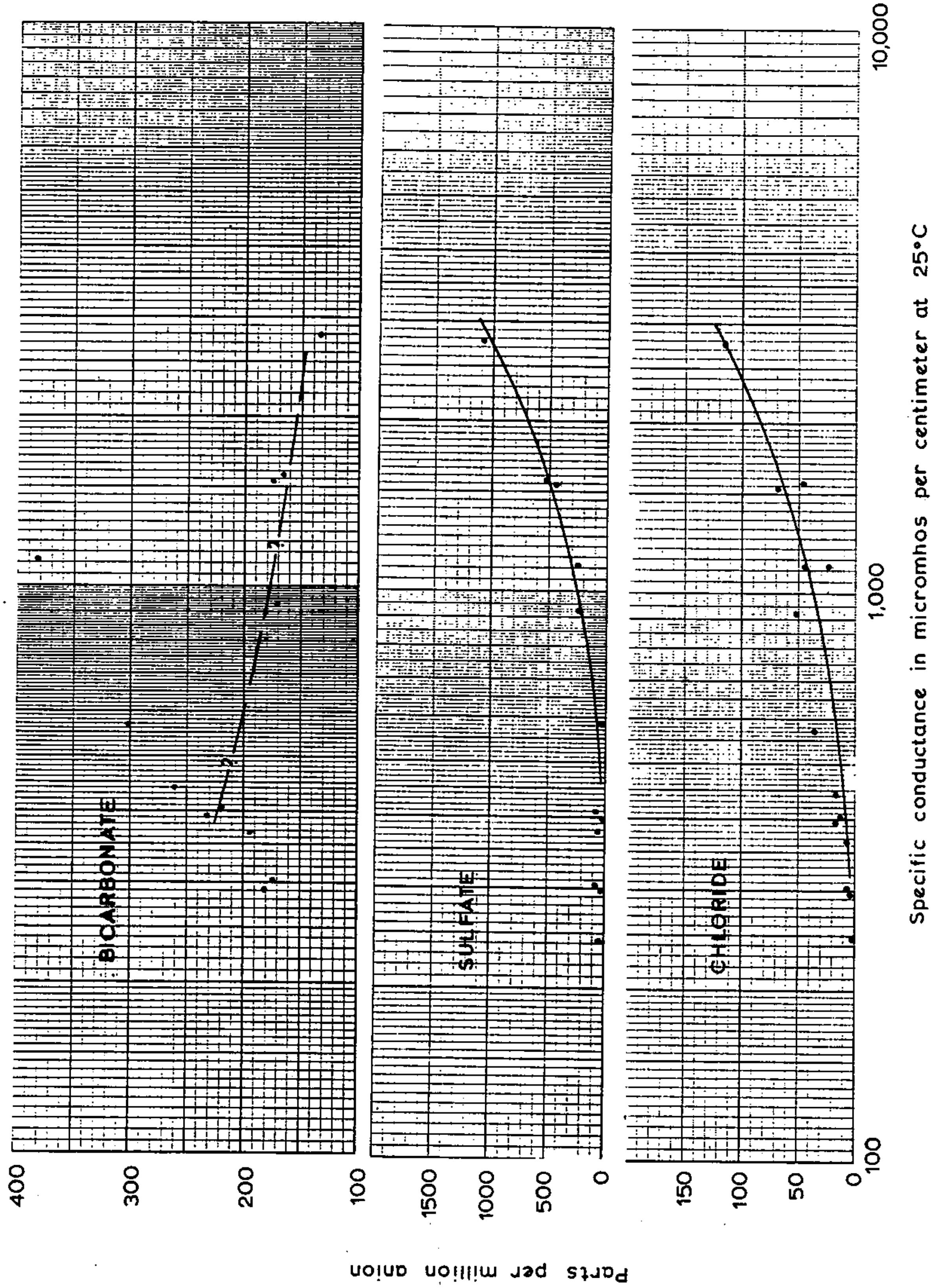

Figure 12. Graph showing relation of specific conductance to principal anions for water from the Denver Formation.

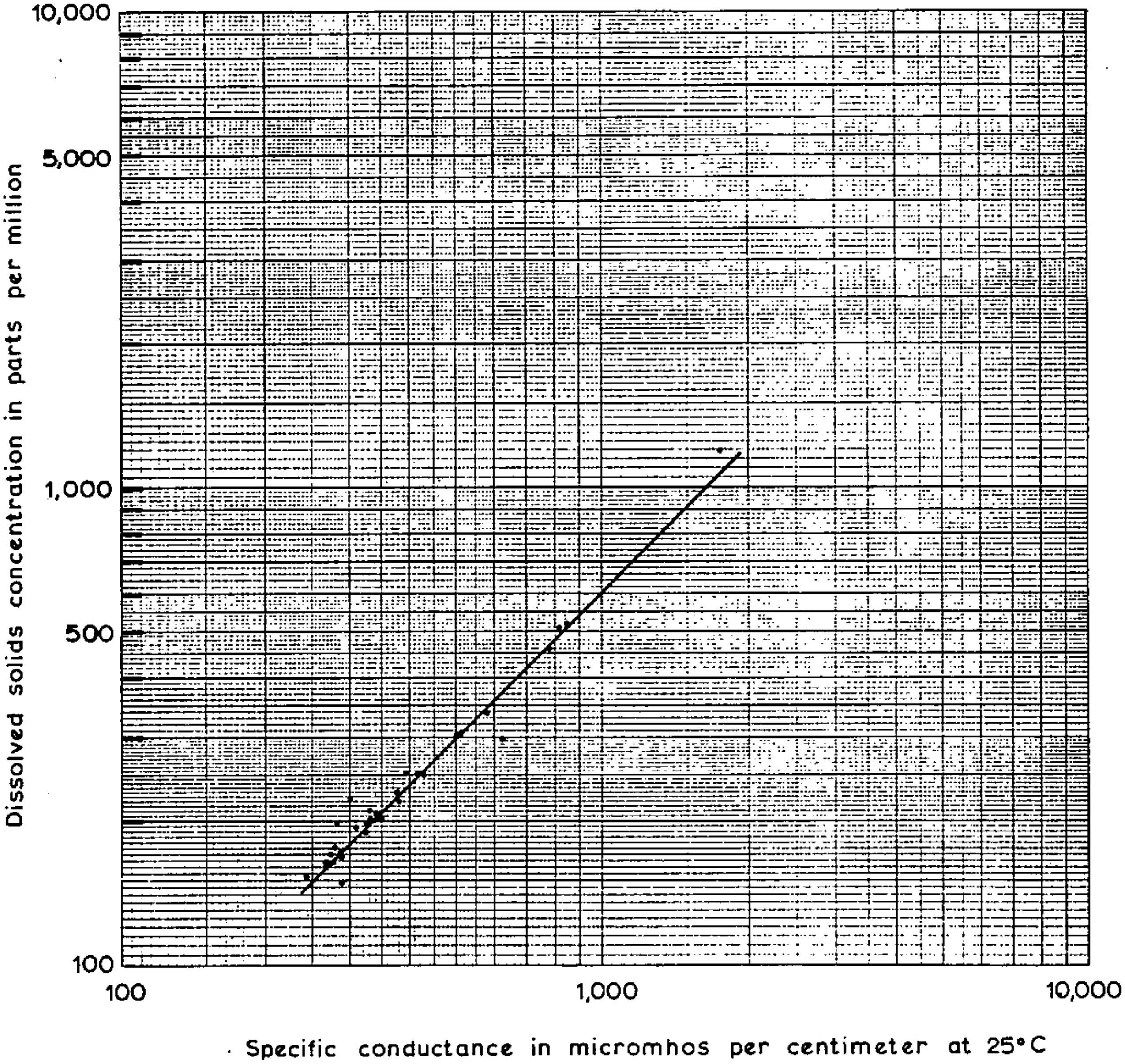

Figure 13. Graph showing relation of specific conductance to dissolved solids for water from the Arapahoe Formation

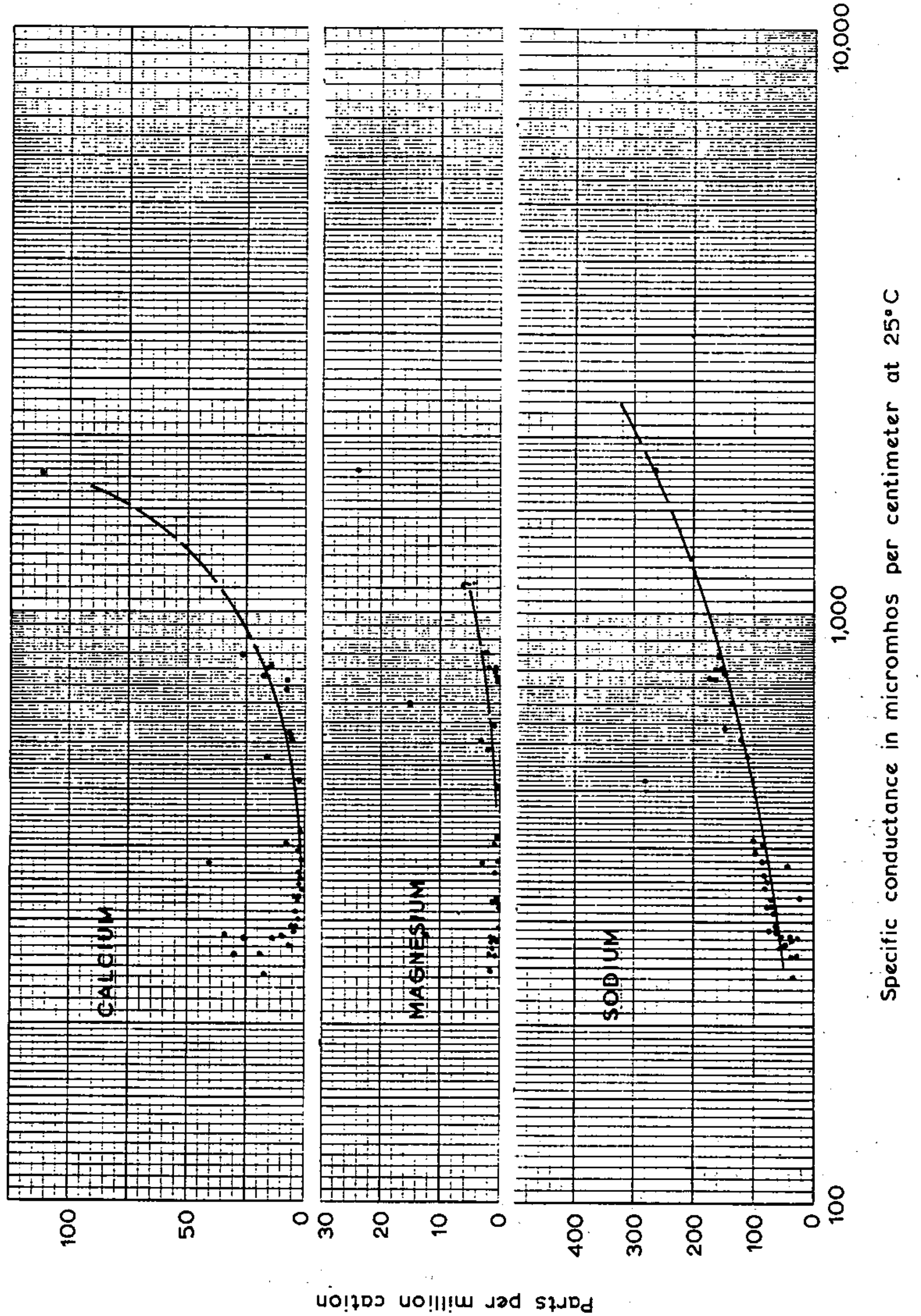

Figure 14. Graph showing relation of specific conductance to principal cations for water from the Arapahoe Formation

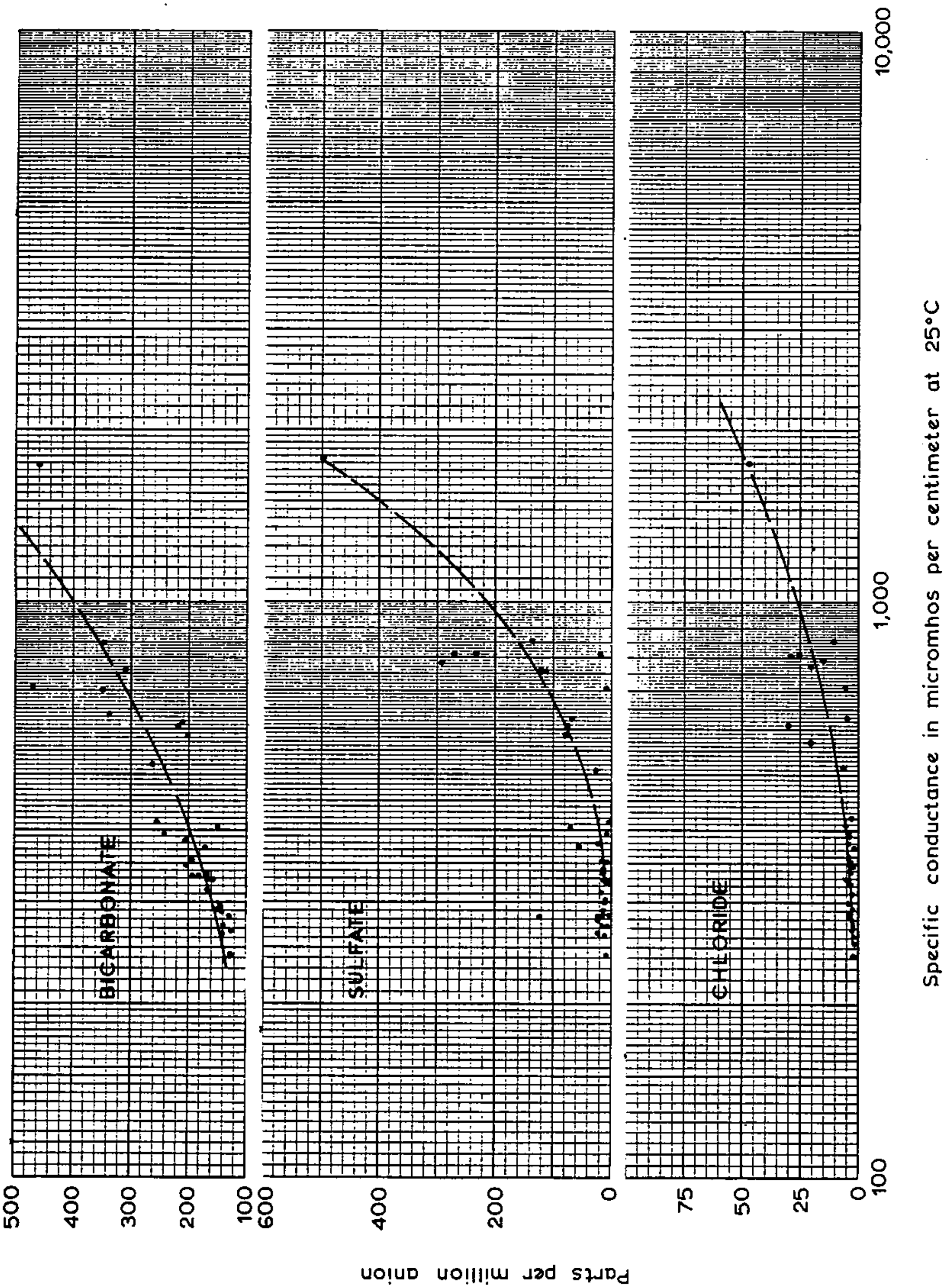

Figure 15. Graph showing relation of specific conductance to principal anions for water from the Arapahoe Formation

Figure 16 shows the vaguely defined relation of bicarbonate concentration to distance from the outcrop or subcrop. The distances plotted are at best approximate but the trend shows how bicarbonate concentration decreases with increasing distance from the outcrop-recharge area. The term outcrop-recharge is used to distinguish recharge which percolates into the formation at the outcrop areas from that which possibly percolates into the formation from overlying strata.

Available test data indicate that water from the Laramie-Fox Hills aquifer is more heavily mineralized than that from the other principal bedrock aquifers. Total dissolved solids content ranges from about 300 ppm to about 3,700 ppm. Approximately 70 percent of the data lie within the range of 450 to 900 ppm TDS. Figure 17 shows the relation of specific conductance to TDS for the L-F aquifer. Because sodium is the principal cation and bicarbonate the principal anion, Laramie-Fox Hills water is classed as the sodium bicarbonate type. The relation of concentration of principal anions and cations to specific conductance is shown in figures 18 and 19.

Other constituents of particular interest include iron, fluoride, and hydrogen sulfide. Figure 20 shows the relation of iron and fluoride to specific conductance and table 6-B lists U. S. Geological Survey data on wells reported to contain hydrogen sulfide at the time of their investigation. Iron content ranges from 0.5 ppm to about 5 ppm. Iron content appears to increase appreciably above a specific conductance of about 1,500 micromhos per cm. Fluoride data points are widely scattered and form only a very general trend. The trend is shown as a cross hatched area. Table 6-C lists the results of U. S. Geological Survey radiochemical analyses of five samples of L-F water.

Available analyses indicate that water from the South Platte Member of the Dakota Group is the least mineralized of all the waters tested. The range of TDS is from about 100 to 200 ppm while bicarbonate varies from about 80 to 150 ppm. Other constituents occur in concentrations predominantly less than 50 ppm. Figure 21 shows the relation of the principal cations and anions to specific conductance and table 6-C lists the wells which were examined for radioactive substances by U. S. Geological Survey personnel.

Although only five analyses are available, the indication is that water from the Lyons and Fountain Formation is of the same general quality as that of the Dakota. With one exception (see table 6-A under Fountain Formation), the concentration of cations and anions is low. Figure 22 shows the relation of concentrations of cations and anions in the Fountain and Lyons aquifers to specific conductance. The highest TDS, calcium, magnesium, sodium, iron, fluoride, bicarbonate, sulfate, and chloride concentrations and conductance occurred in an open-hole well. Although only one aquifer is tapped, the abnormally high concentration of dissolved solids strongly suggests contamination from sources other than the Fountain Formation.

Water quality analyses of several wells which tap the Precambrian basement rocks along the foothills is included in table 6-A.

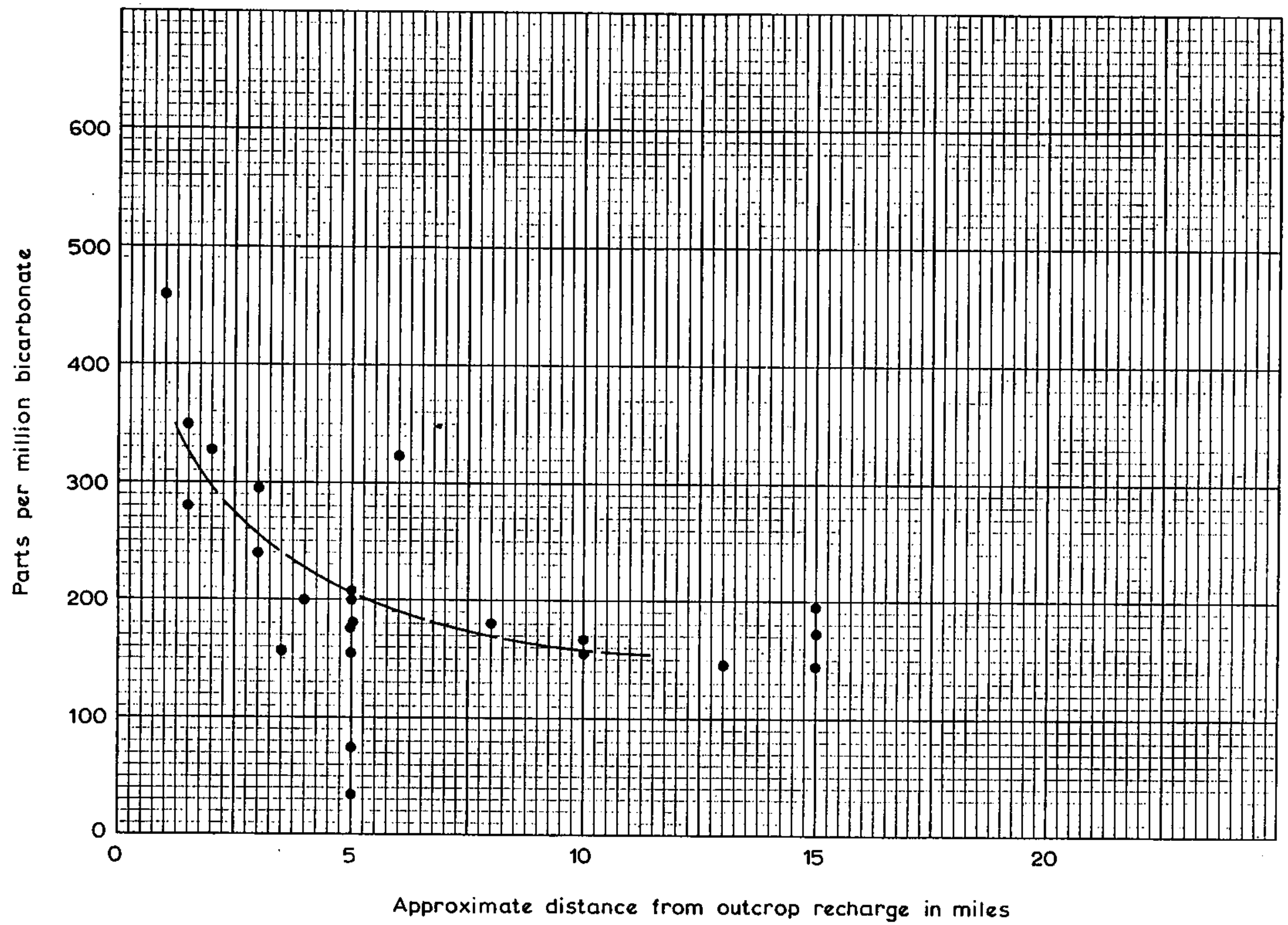

Figure 16. Graph showing relation of distance from outcrop area to bicarbonate for water from the Arapahoe Formation. Multiply miles by 1.609 to find kilometers.

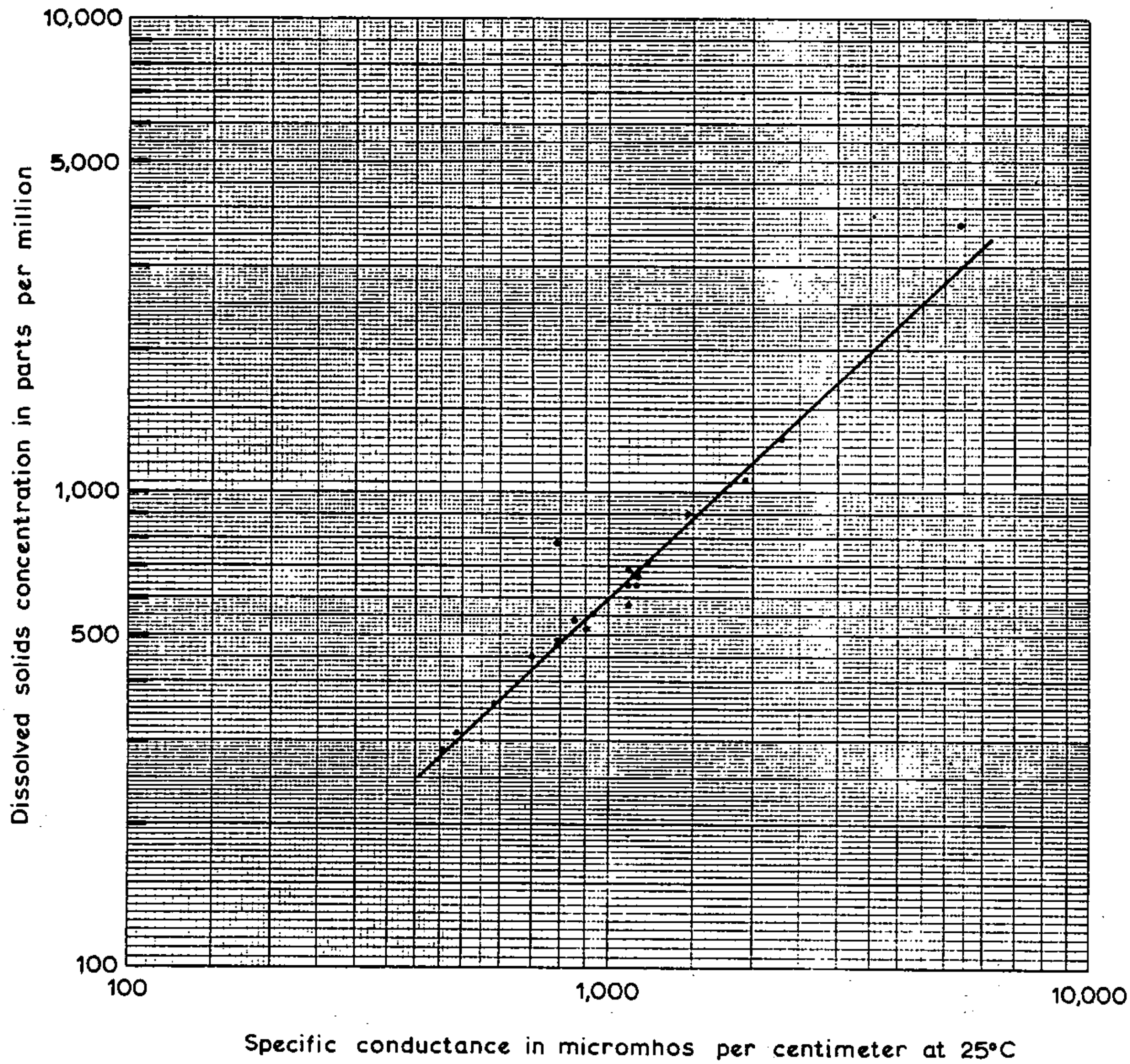

Figure 17. Graph showing relation of specific conductance to dissolved solids for water from the L-F aquifer

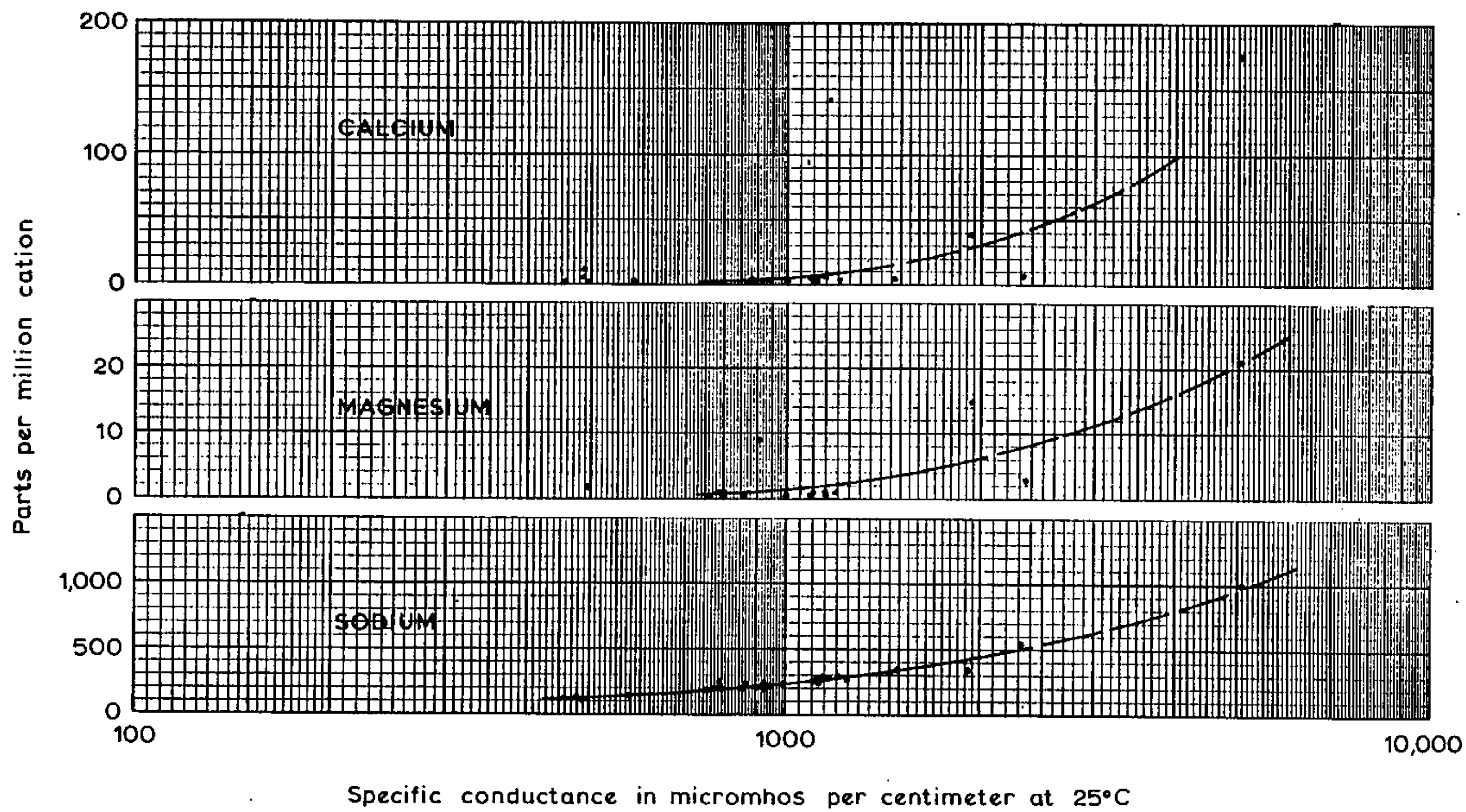

Figure 18. Graph showing relation of specific conductance to principal cations for water from the L-F aquifer

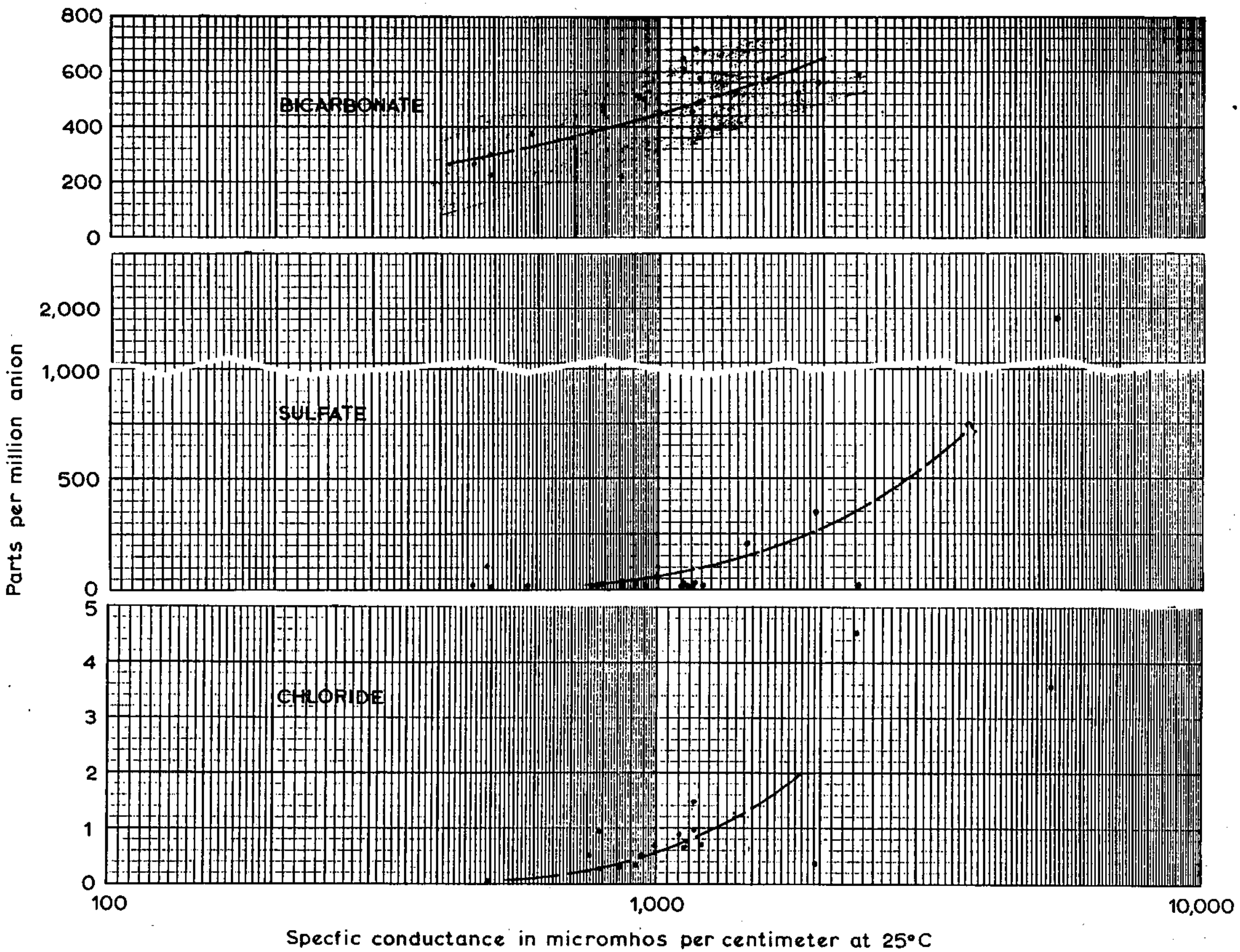

Figure 19. Graph showing relation of specific conductance to principal anions for water from the L-F aquifer

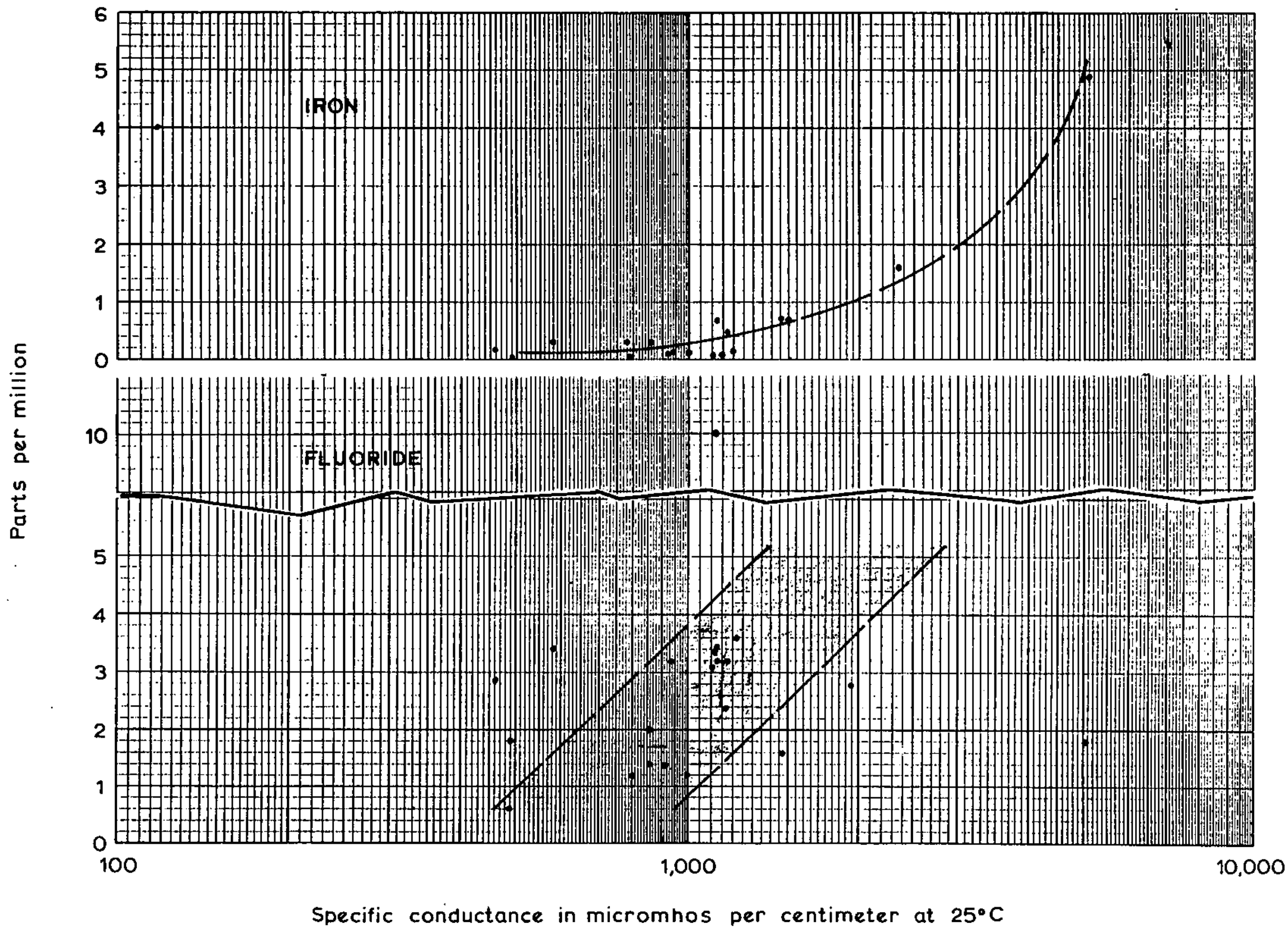

Figure 20. Graph showing relation of specific conductance to iron and fluoride for water from the L-F aquifer

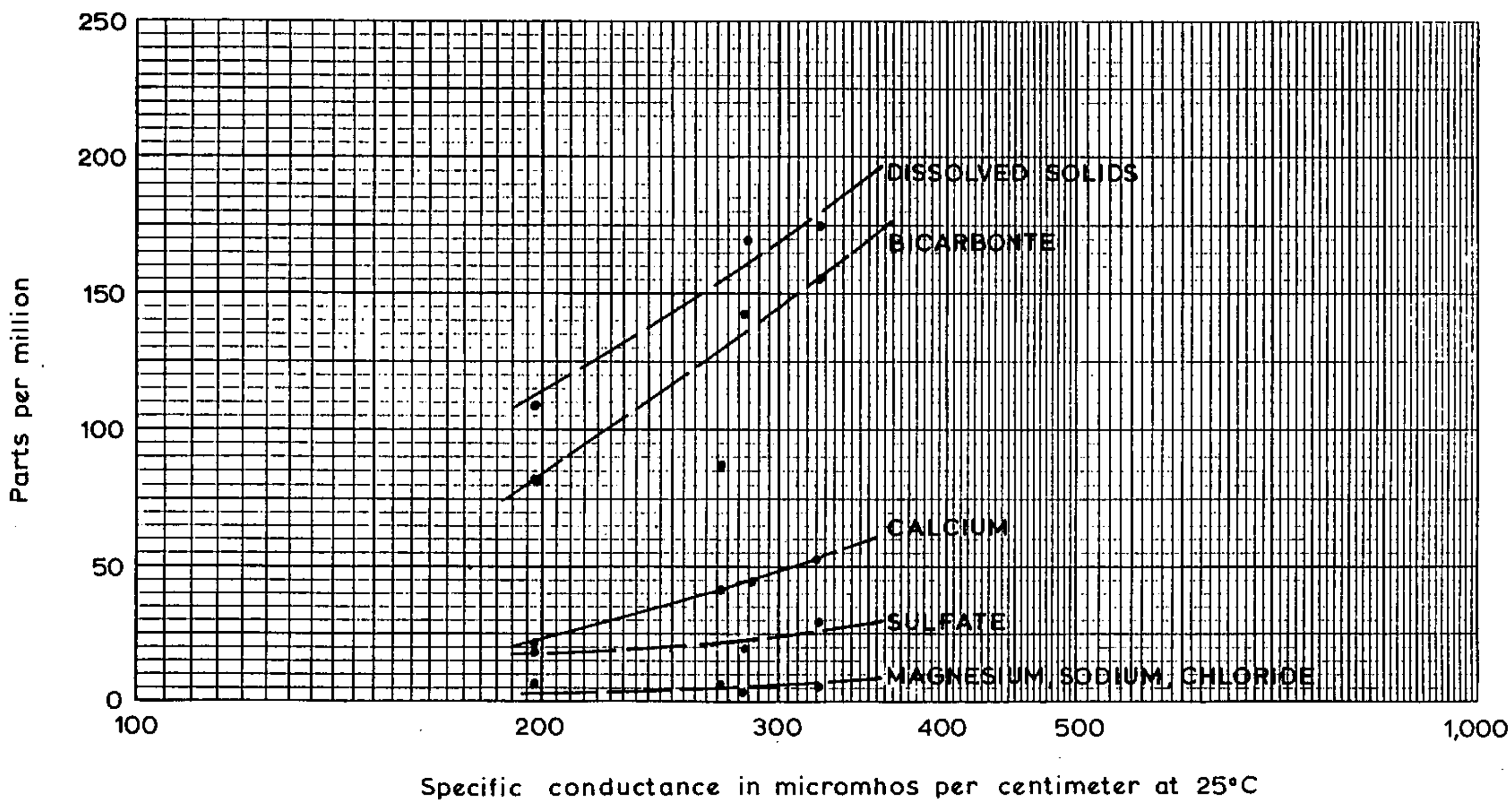

Figure 21. Graph showing relation of specific conductance to principal cations and anions for water from the Dakota Group

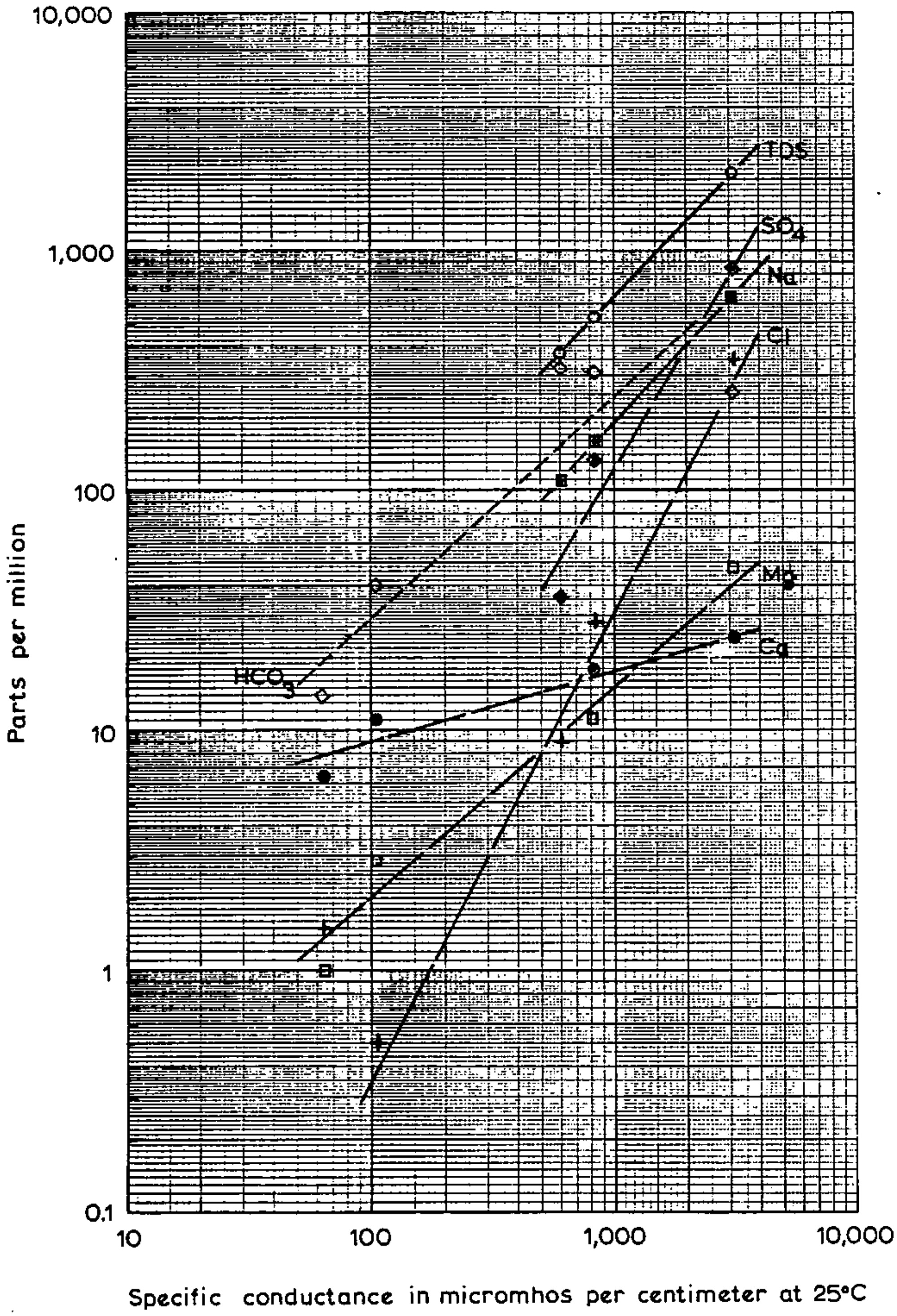

Figure 22. Graph showing relation of specific conductance to principal cations and anions for water from the Fountain and Lyons Formations. Symbols: o, dissolved solids; □, sodium; ◇, bicarbonate; ◈, sulfate; +, chloride.

SUITABILITY AND UTILIZATION OF THE GROUND WATER

It is now recognized that the economic utilization of water for most purposes to a large extent depends upon the chemical composition of the water. The quality required of a ground water supply depends upon its proposed purpose. If the requirements of the raw water are not met, the water can usually be treated to meet the requirements.

Public Supply and Domestic Use

The U. S. Public Health Service (1962) established quality requirements for water used for drinking and culinary purposes. The standards are not compulsory for water that is used locally but they do act as a measure of suitability of water for domestic use. The standards for the major chemical contaminants are:

Constituents	Max. concentration in ppm
Iron (Fe)	0.3
Manganese (Mn)	0.05
Calcium (Ca)	30
Magnesium (Mg)	125
Sulfate (SO_4)	250
Chloride (Cl)	250
Fluoride (F)	1.5
Nitrate (NO_3)	45
Sodium (Na)	10-200
Potassium (K)	1000-2000
Bicarbonate (HCO_3)	150
Copper (Cu)	3
Hydrogen sulfide (H_2S)	0.05
Dissolved solids (TDS)	500-1000

In this paper hardness, expressed as an equivalent, quantity of calcium carbonate in ppm, is generally referred to by the following classification:

Hardness	Class	Suitability
60	Soft	Suitable for most uses
60-120	Moderately hard	Usable except in some industrial applications
121-200	Hard	Softening required by laundries and some other industries
200	Very hard	Softening required for many uses

Among the many physical properties of water which must be investigated is radioactivity. The effects of radiation are viewed as harmful and any unnecessary exposure to radiation should be avoided. Radioactivity in water is especially significant to human health, not only through direct consumption of water, but also through the ingestion of agricultural products and livestock that have accumulated radioactivity

(McKee, J.E. and Wolf, H. W., p. 343).

Ground water may acquire radioactivity by natural sources such as mineral deposits. Man might introduce radioactivity into the ground water system as products from nuclear detonations or from haphazardly disposed waste products from the atomic energy industry, users of radioisotopes and fertilizer leachates. The types of radiation which may be encountered in polluted water are alpha and beta particles, gamma rays and neutrons.

Alpha and beta emitters are particularly hazardous in water and food products because they can become concentrated in specific human tissues such as bones or organs. A few radionuclides of particular importance to the Denver Basin are radium 226 and its daughters, thorium 232, uranium 238, and plutonium 239. For additional information on the health hazards of radionuclides, the reader is referred to McKee and Wolff (1963, pp. 343-354) and Friedlander and Kennedy (1962, pp. 217-219).

All of the waters of the Denver Basin bedrock aquifers have been shown to be pure bacteriologically. Water from deep wells which might at some time indicate bacterial contaminants is probably being polluted from surface sources.

<u>Dawson Group</u>. Analyses of water from the Dawson Arkose indicate that the chemical quality of the water meets most recommended drinking water standards. One test (table 6-A, first well) indicates that a potential well user should examine Dawson Arkose water for excessive iron, manganese and calcium. The detection of radon-222 in water from a well east of Sedalia (table 6-C) is suggestive of the presence of radium 226 and indicates either naturally occurring radioactive material or contamination from a surface source. Most of the water for the town of Castle Rock is obtained from the Dawson Arkose.

Water from the Denver Formation is predominantly soft although the TDS from several wells is on the threshold of being undesirable. Several tests indicate the presence of excessive quantities of calcium, fluoride, hydrogen sulfide, iron, sodium, sulfate and bicarbonate. U. S. Geological Survey tests performed on water from a deep well several miles northeast of Sedalia indicated excessive radium 226 (table 6-C). In general, the water from the Denver Formation is of fair quality for public and domestic use, particularly in those areas where the water-producing strata are in an excess of 150 meters (500 feet) below the ground surface.

Water from the Arapahoe Formation can be classed as predominantly soft, slightly mineralized water. Several Denver suburbs and small rural communities utilize the Arapahoe Formation for public water supplies. Most of the water received little or no treatment other than chlorinization for safety purposes. Filtration, softening and odor control are required in a few supplies. Water quality precautions should be exercised along the northwestern portion of the Denver Basin where fault traces might permit the comingling of poor quality with good quality water.

Laramie-Fox Hills aquifer. The L-F aquifer produces a predominantly soft, slight to moderately mineralized water. It is of fair to good quality for domestic and public use throughout most of the Denver Basin. Locally, the L-F aquifer yields water with high concentrations of fluoride, iron, sodium and bicarbonate. Some users of L-F water have objected to its high temperature, and hydrogen sulfide and methane have been detected in many wells in the northern Denver metro area. It is suggested that local geologic structure has a role in influencing the quality of L-F water in the area. Locally the contaminants have influenced many well users to seek other sources of water. Although the problem appears to be confined to the northwestern part of the basin, it should be noted that many L-F wells are known to yield water of a quality nearly comparable to that of the Arapahoe Formation. Many small communities and numerous private users of L-F water for domestic purposes do not treat the water. A few supplies are chlorinized for safety purposes and a few are treated for odor, taste, coagulation, sedimentation and filtration.

Pre-Laramie-Fox Hills aquifers. Existing analyses of water from the Dakota Group, Fountain and Lyons aquifers indicate the qualities that meet most drinking standards. The waters are predominantly soft with a generally low TDS content. Excessive concentrations of iron, fluoride and other chemical constituents have been reported in faulted areas and residual oil has been reported to occur locally near the base of the Fountain Formation (McConaghy and others, p. 7).

Water from the Precambrian basement complex is predominantly moderately soft with mineralization concentrations that meet all drinking standards.

Industrial and Agricultural Uses

About 19 percent of the water pumped from the Denver Basin's bedrock aquifer is used for industrial purposes. Predominant industrial uses of water in the Denver Basin are air conditioning, baking, boiler feed, brewing, canning, carbonated beverages, cooling, food preparation, ice making and laundering. Since the quality requirements for industrial water supplies have such a wide range, this report presents information of a general nature. Potential industrial water users who must deal in water requirements for certain specialized industries are referred to technical publications specifically designed for that purpose. Table 7 lists the general water quality requirements for the industrial uses mentioned above. Additional data can be found in California State Water Pollution Control Board Publication 3.

In this report, the use of water for agricultural purposes includes water consumed by livestock, the irrigation of lawns and garden crops and in the operation of farm machinery.

Water consumed by livestock has water quality tolerances of the same order as those relating to drinking water for human consumption. Unfortunately, data with respect to specific tolerance are sparse. However, most animals seem to be able to use water considerably poorer in quality than would be satisfactory for humans. Salts specifically toxic to animals are nitrates, fluorides, selenium and molybdenum.

TABLE 7. Suggested water quality tolerances for industrial uses. Chemical constituents expressed in ppm. After Hem, 1959, p. 253

Industry or Use	Turbidity	Color	Temp (°F)	SiO_2	Fe	Mn	Ca	Na	HCO_3	Total Solids	Odor & Taste	Hydrogen sulfide	Hardness as $CaCO_3$	Remarks
Air conditioning					0.5	0.5					Low	1.0		No corrosiveness, slime formation
Baking	10	10			0.2	0.2					Low	0.2		Domestic quality
Boiler feed	1-20	2-80		1-40					0-50	50-3000		0.5	2-80	Al_2O_3 0.01-5; pressure & boiler design critical
Brewing	10		50-60		0.1	0.1		275		500-1000	Low	0.2		Domestic quality, pH 7 or more
Canning	10				0.2	0.2					Low	1.0		Domestic quality
Carbonated beverages	2	10			0.2	0.2				850	Low	0.2	250	Domestic quality
Cooling	50		Cool		0.5	0.5						5.0	50	No corrosiveness, slime formation
Food Preparation	10				0.2	0.2	1000-1500			850	Low	1.0	50-85	Domestic quality
Ice Making	5	5		10	0.2	0.2					Low			Domestic quality
Laundering					0.2	0.2							50	

Turbidity requirements are expressed in standard units, defined in terms of the depth of water to which a candle flame can be clearly distinguished. Low turbidity units indicate clear water, high turbidity units indicate turbid water. Color units, although determined by a different method are more or less comparable to turbidity units. That is, low color units indicate high quality, low color water, and high color units indicate high color water. Iron tolerance applies to both iron alone and the sum of iron and manganese. Blank space indicates standards not developed.

Total dissolved solids standards in use in western Australia and commonly accepted in this country are (Hem, 1959, p. 241):

Animal	Suggested tolerance (ppm)
Poultry	2860
Pigs	4290
Horses	6435
Cattle (dairy)	7150
Cattle (beef)	10,000
Adult Sheep	12,900

Water used for the irrigation of lawns and garden crops should be of such quality that it will not adversely affect the growth of the plants irrigated and the productivity of the land to which it is applied. Although certain mineralogical properties of the water are important in promoting plant growth and soil productivity, several constituents have been shown to be detrimental when they exceed certain maximum concentrations.

These properties are the concentration of the total dissolved solids, the relative proportion of sodium to calcium and magnesium, the concentration of boron or other elements that might be toxic to certain plants, and for some water the concentration of bicarbonate in excess of the concentrations of calcium and magnesium (Smith and others, 1964, p. 100).

Dawson Group. Existing water quality data on the Dawson Arkose indicate the water is probably moderately hard and only slightly mineralized. It meets the standards required for all industrial and agricultural purposes.

Water from the Arapahoe Formtion meets most industrial standards of particular interest in the Denver Basin. Users of Arapahoe water for boiler feed purposes should note that the predominant range of silica (SiO_2) in the water limits boiler pressure to about 21 kilograms per square centimeter (300 psi). Water intended for high pressure boilers will generally require treatment. Other than relatively high concentrations of bicarbonate, water from the Arapahoe Formation should meet all agricultural requirements.

Laramie-Fox Hills aquifer. Except where high temperatures, high concentration of iron, bicarbonate, sulfate, fluoride and hydrogen sulfide occur, water from the L-F aquifer meets most requirements for local industries. Except for moderate concentrations of bicarbonate, L-F water is suitable for most agricultural purposes.

Pre-Laramie-Fox Hills aquifers. The few analyses of water from the Dakota group, Fountain and Lyons aquifers indicate qualities sufficient to meet most industrial and agricultural standards. The chemical constituents which might cause minor, but solvable problems are locally high concentrations of iron, sodium, bicarbonate, sulfate and chloride.

ROCKY MOUNTAIN ARSENAL DISPOSAL WELL

The effects of percolation of industrial wastes through the soil mantle at the Rocky Mountain Arsenal are well documented. The shallow ground water reservoir in a several square mile area down gradient, from unlined holding ponds is seriously contaminated.

The possibility that the deep disposal well at the arsenal could be the origin of localized contamination of certain Denver Basin bedrock aquifers is slight. Wastes injected into the 3671 meter (12,045 feet) well were placed into Precambrian basement rocks. The seals in the well were designed and installed to prevent leakage of contaminants from the injection level into other aquifers. The well is no longer used for injection of wastes.

The possibility that contamination, however slight, might occur in aquifers overlying the injection level is associated with regional structural features. It is known that the region in the northern and northwestern part of the Denver Basin project area is highly faulted. These faults are known to extend into the upper Cretaceous sedimentary rocks. The actual extent of the faults and the nature of individual fault traces, however, is unknown. It has been previously suggested that geologic formations in a structurally disturbed area may be hydraulically connected by faults. Even though the fault traces between the Precambrian and overlying aquifers might be sealed too tightly to permit upward percolation of contaminating solutions, the presence of an extensive volume of toxic material in the basement rocks underlying the northeast Denver-metro area cannot be ignored, particularly by future generations.

HISTORIC DEVELOPMENT OF THE DENVER BASIN BEDROCK AQUIFERS

The following narrative briefly describes the historical development of the bedrock aquifers. Information regarding historical withdrawals of water from the aquifers for municipal purposes was obtained through the cooperation of water supply agency personnel and town managers. Historical data for most of the bedrock water users in the basin are lacking. The data presented in this report are designed to show the trend of increasing water demand that is beginning to occur throughout the entire Denver Basin.

Because they have been developed to a limited extent, the Fountain and Lyons aquifers and Dakota Group have not been treated here. It is suggested that these aquifers should be developed with caution.

HISTORIC DEVELOPMENT OF THE DAWSON GROUP

The first bedrock formations to receive attention as sources of artesian water were the Denver and Arapahoe. The Arapahoe Formation was recognized as a potential source of artesian water in 1883 after a man who was boring for coal near the first St. Lukes Hospital (near the intersection of Speer and Federal Boulevards) struck a large volume of water (Emmons and others, 1896, p. 402, 403). By 1895, over 400 artesian wells were in operation in the greater metropolitan area. Well depths generally ranged from 122 to 244 meters (100 to 800 feet). By the turn of the century, many of the artesian wells stopped flowing and pumps had to be installed. During the early 1900's, the use of artesian water in the Denver metropolitan area experienced a decline as more surface water supplies became available.

A few bedrock wells drilled on farms and ranches in the country did not experience a substantial decrease in water level during this period. These wells had low discharges and were widely scattered. Since water from the alluvium of small stream systems furnished most of the water requirements, only those farms and ranches which might have been in part or totally isolated from shallow ground water systems had wells extending to the bedrock aquifers.

During the 1940's and 1950's, the Dawson Arkose and the Denver and Arapahoe Formations received extensive development as a source of water for a large number of industries, commercial businesses, and individual domestic supplies in suburban areas, as well as for several municipal water supplies. During this period, communities such as Arvada, Castle Rock, Monument, Strasburg and Westminster became dependent upon members of the Dawson Group for either part or all of their water supplies.

Suburbanization in the Denver metro area continued into the 1970's. Throughout the entire period, the demand for more water has increased proportionately. The recently instituted Blue River (Denver) and Homestake (Aurora) projects have provided substantial quantities of excellent quality, low cost water to the metro area. The result has been localized reductions in the withdrawals of Dawson Group water by several municipalities, businesses of various types, and domestic users. Figure 23 shows graphically the development of the quantity of water withdrawn from shallow wells by the City of Aurora during the period 1956-1971. The marked reduction of ground water withdrawals after 1966 is due to the availability of water from the Homestake Project which diverts water from the Sawatch Range northwest of Leadville, Colorado. Although Aurora's Dawson Group wells are not represented in the graph (the wells are not metered) their production was reduced proportionately.

In other areas throughout the Denver Basin, surface water supplies are either lacking or limited and the withdrawal of water from the Dawson Group of aquifers has increased at a rate proportional to growth of the area. Typical water distribution agencies in this category include the South Adams County Water and Sanitation District and the Town of Castle Rock. Figure 24 illustrates how the demand for water from these agencies has increased with time. The need for Dawson Group water by individual well users in some suburban areas and most rural areas has been steadily increasing since World War II. The areas which are growing at relatively fast rates include the northern metropolitan Denver area and a 20 mile wide strip lying along the east flank of the foothills and extending from Littleton on the north to Colorado Springs on the south. Other areas which are beginning to show signs of growth include those lands in proximity to Interstate Highways 70 and 80 east and along certain portions of U. S. Highway 24 east of Colorado Springs. Development along these highways is showing a trend of reorientation from primarily agricultural to

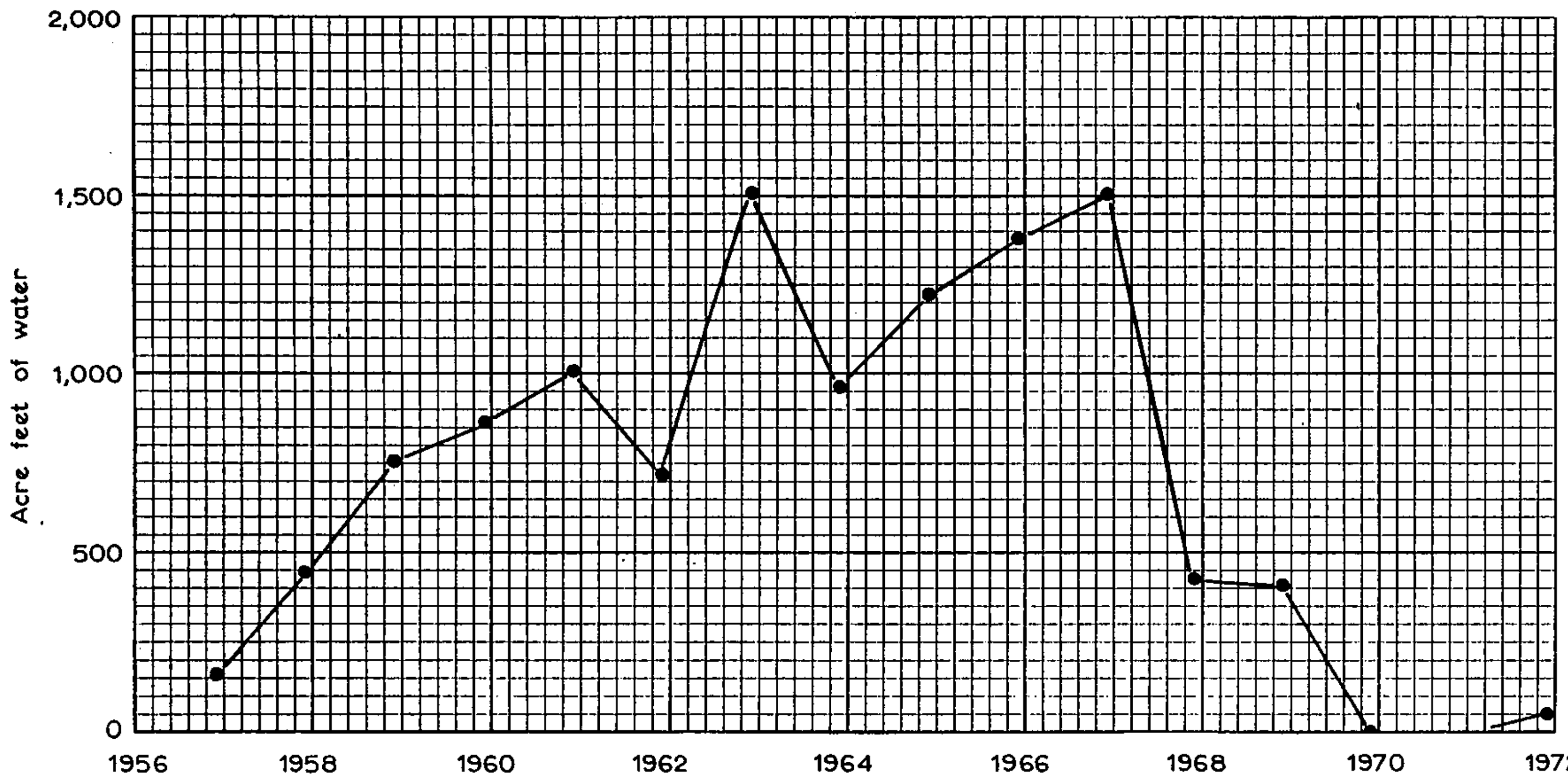

Figure 23. Graph showing quantity of water pumped by the City of Aurora's water wells. The rapid decline during 1967-1970 is due to the influx of surface water made available by the city's Homestake water diversion project. Multiply acre feet by 1233.62 to find cubic meters.

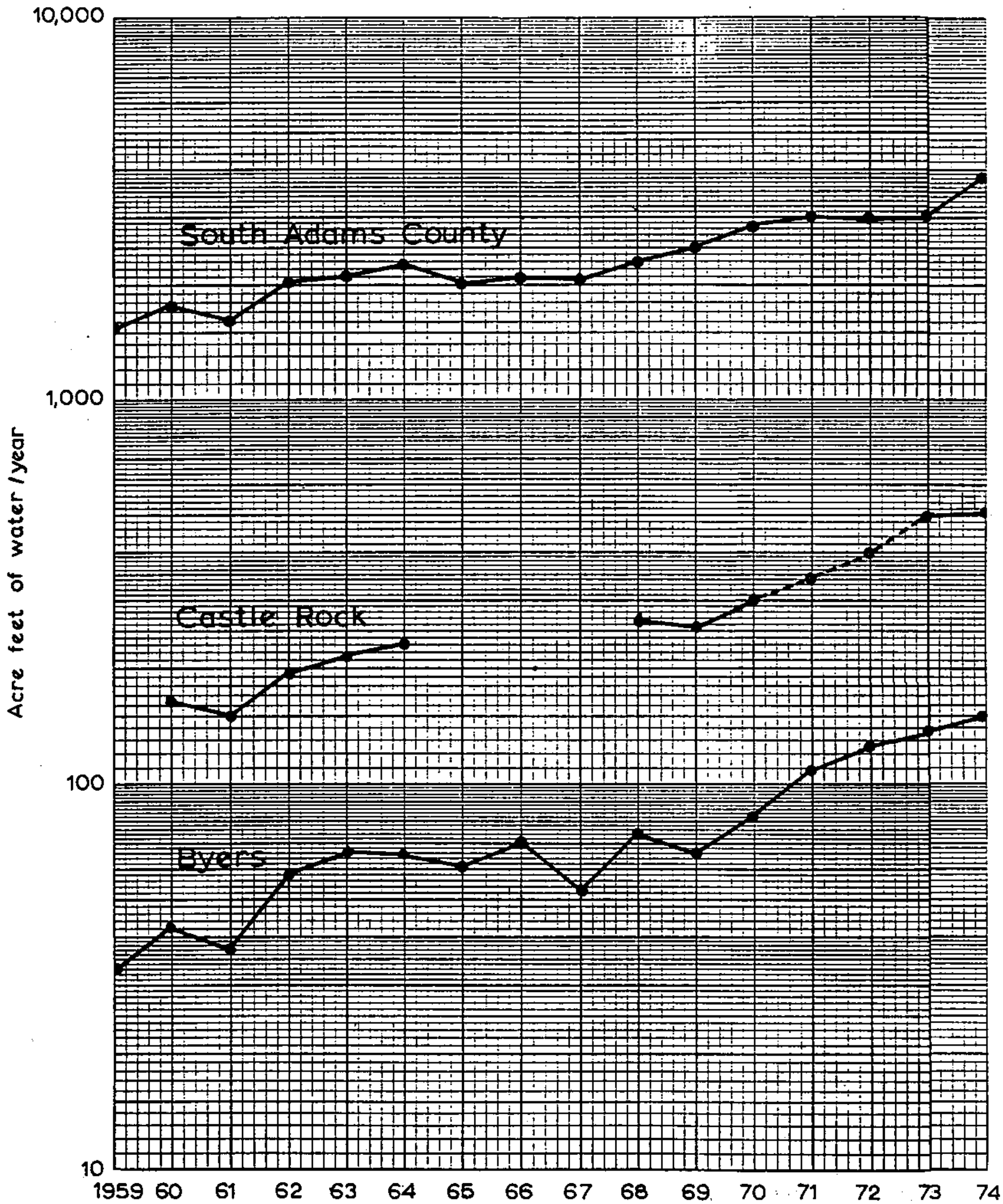

Figure 24. Graph showing rate of increase of ground water withdrawals by typical water supply agencies within the Denver Basin. Multiply acre-feet by 1233.62 to find cubic meters.

industrialized and suburbanized communities. Plate 12 shows the density of total registered discharge from wells tapping the Dawson Group aquifers.

HISTORIC DEVELOPMENT OF THE L-F AQUIFER

The L-F aquifer did not receive extensive use until the 1920's and 1930's. Before that time, a few widely scattered domestic-stock wells existed near the outcrop areas in the eastern and southern part of the basin. In the 1940's and 50's, the desire to obtain artesian water for private purposes, and, in some cases, demand for water where surface supplies were not available increased. Consequently, there occurred a relatively rapid increase in the exploitation of deep aquifers. The L-F aquifer is desirable because many of the wells drilled into it at that time flowed and the water was predominantly very soft and only moderately mineralized. During the late 1940's and through the mid-1960's numerous L-F wells were drilled in the Denver area for suburban communities and water districts, and several industrial and commercial water users who could absorb the cost required to drill beyond the Arapahoe Formation.

Within the past 5 to 10 years, local withdrawals of water from the L-F aquifer have declined because of the increased availability of surface supplies and because of local water quality problems. However, some areas north of Denver do not have ready access to surface water supplies and the Arapahoe Formation becomes less effective as an aquifer as the outcrop areas are approached from the south. Of particular interest in this category is a wide strip of land flanking the South Platte River Valley and extending from about Township 2 South through Township 4 North. Since the late 1950's this area, which is tentatively called "the South Platte River corridor," has undergone localized suburbanization and reorientation from formerly agricultural to industrialized and commercialized economies. The change has resulted in the construction of a large number of wells in the L-F aquifer. The current rate of L-F well construction in this area is about 10 wells per year. Plate 8 illustrates the relatively dense development of L-F wells along the South Platte River corridor northeast of Denver, and figure 25 is a graph showing the rate of L-F well construction within the corridor from the early 50's through 1973.

Because the areas in the eastern and southern portions of the Denver Basin are agriculturally oriented, the rate of utilization of the L-F aquifer has not been particularly rapid. Most of the development in these areas has occurred in the vicinity of Keenesburg and in the region surrounding the small communities of Byers, Calhan and Deer Trail where water pumped from the L-F aquifer is used for both domestic/stock and municipal purposes. In the region east and northeast of Colorado Springs, the L-F aquifer has been tapped by a few domestic water users and by a few small quasi-municipal water districts. Most of the utilization of the L-F aquifer has occurred since the late 1940's. Although the rate of use of water has not increased appreciably in rural areas, most of the town managers reported their areas of jurisdiction have experienced slight population increases and proportional increases in

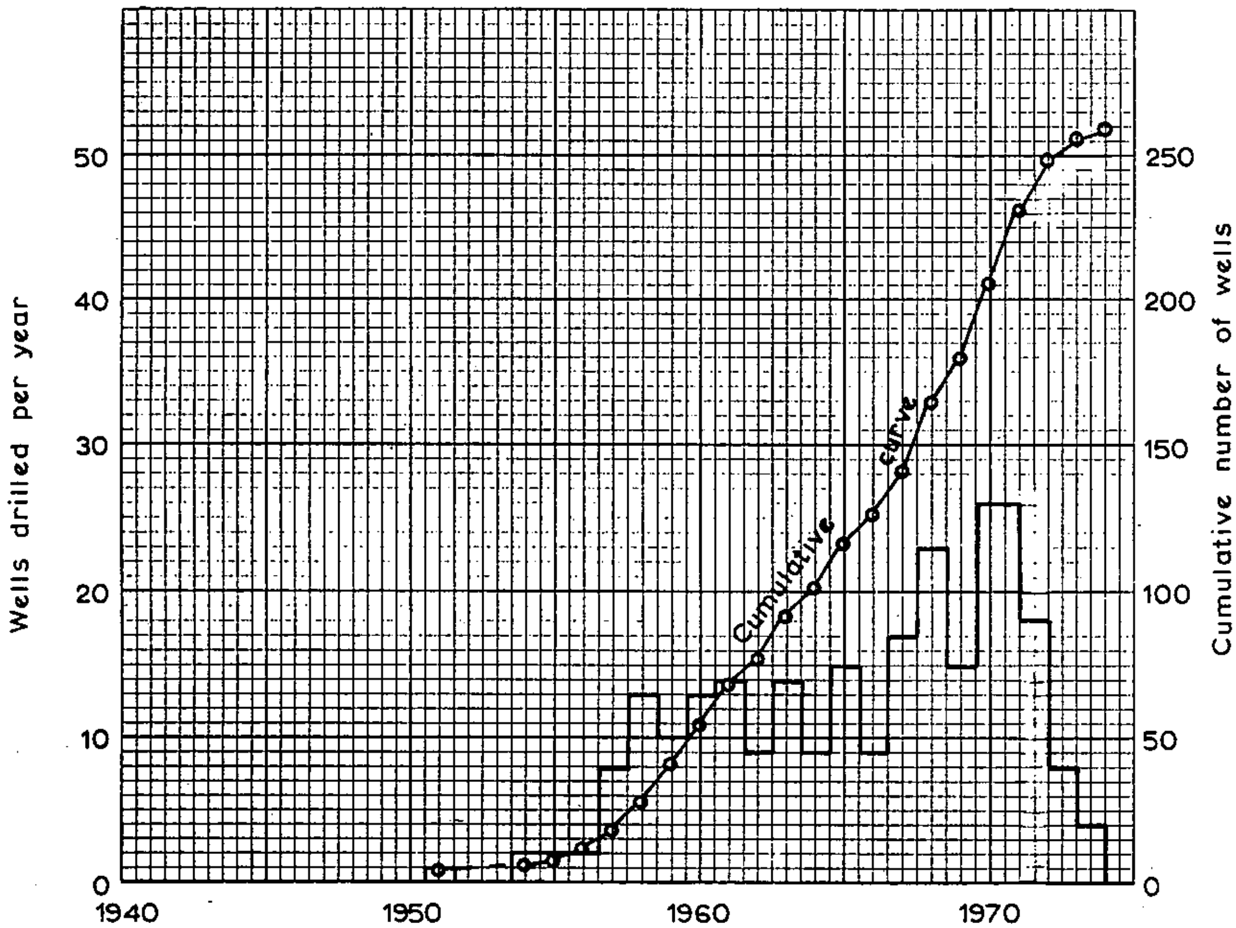

Figure 25. Graph showing rate of development of L-F wells along the South Platte River Corridor

the demand for L-F water. Typical of these small communities is Byers, Colorado, where a local water supply agency has reported a three million gallon-per-year increase in L-F water use during the period 1966-1971. Figure 24 illustrates the trend of water supplied to users from 1959 through 1971.

Exploration of the L-F aquifer has periodically occurred east of the foothills between Denver and Colorado Springs. Whether or not the aquifer will be heavily developed in the immediate future remains to be seen for the following three reasons: (1) In areas available for development in the immediate future, the L-F aquifer lies at depths commonly exceeding 460 meters (1,500 feet) below land surface; (2) The shallower Dawson Group aquifers are proving to be a reliable source of good quality water; and (3) Several investigators have reported that the potentiometric surface of the L-F aquifer is locally about 305 meters (1,000 feet) below the land surface and that the aquifer might be unreliable as a long-term source of water for certain uses.

EFFECTS OF LARGE WITHDRAWALS OF WATER FROM THE AQUIFERS AND POSSIBILITIES OF ADDITIONAL DEVELOPMENT

Continuous data on the historical effects of the withdrawals of large quantities of water from the Denver Basin bedrock aquifers are scarce. Emmons and others (1896, p. 402) briefly described the effects of early development of the Denver and Arapahoe Formations and McLaughlin (R.M.A.G. Guidebook, May 1955, pps. 62-67) described water level fluctuations of the Arapahoe and Fox Hills aquifers. A few deep wells were periodically checked by the U. S. Geological Survey in the late 50's and early 60's, but most have either been abandoned or are temporarily capped. As a continuing phase of the Denver Basin study, the Colorado Division of Water Resources in cooperation with the U. S. Geological Survey hope to establish a permanent well measuring network for the Dawson Group and the L-F aquifers.

The information available is of sufficient quantity and quality to permit the identification of areas that have experienced marked water level changes since the aquifers have been tapped. As mentioned earlier, these areas include the Denver metro area, the South Platte River valley downstream from Denver (South Platte River corridor), and the region near Byers and Deer Trail.

Since current local rates of water level decline range from 0 to 15 meters (0 to 50 feet) per year, it is obvious that certain parts of the Denver Basin artesian system have become over-developed. In the areas which have experienced excessive annual water level declines, local and state planning directors should discourage the construction of new developments which must rely totally on bedrock water resources. Existing developments which rely either totally or partially on bedrock water should be aware of the possibility that at some future date the bedrock formations might become ineffective as aquifers.

All existing and potential users of ground water in the Denver Basin should be aware of the effects of extended withdrawals of water from the bedrock formations. These effects are significant from both physical and legal viewpoints. Obvious physical effects include those which have already been mentioned - - water level decline over an area. By examining documented physical reactions of the bedrock aquifers to withdrawals of water, or by applying hydrogeologic constants to areas which are yet to be developed, the existing and potential user of bedrock water is able to formulate sound water supply plans for the future. From the legal viewpoint, water administrators should be aware of the effects which have occurred in the past, are occurring at present, and in the case of undeveloped areas, may possibly occur in the future.

Figures 26 and 27 are head loss curves for the L-F, Arapahoe, and Dawson aquifers intended to serve as tentative aids in estimating the effects of water withdrawals in areas for which no time drawdown information has been recorded in the past. The curves were constructed by application of the Theis non-equilibrium formula. Pertinent aquifer constants were assigned values which are believed to be typical of the aquifers as a whole (table 3, p. 43). The hydrogeologic properties of the aquifers vary widely between different localities. Therefore, the drawdown curves should be applied with caution. Particularly when radii of investigations exceed one kilometer (0.62 miles). Comparison of the figures illustrates how drawdown in observation wells is influenced by aquifer constants. They particularly illustrate the need for a sufficient quantity of geologic information on the area of interest. Existing wells located within the area of influence compound the problem as each well will contribute to the head loss to a certain degree.

Denver Metro Area. As mentioned above, the withdrawal of large quantities of water from the bedrock aquifers in greater Metropolitan Denver has resulted in large declines of potentiometric surface. Both the L-F aquifer and the Dawson Group of aquifers have experienced declines in head ranging from about 30 to 183 meters (100 to 600 feet) during the period of record. The greatest declines have occurred in the northern and southern parts of metropolitan Denver where more frequent occasions to develop the artesian aquifers exist (pls. 8 and 12).

Although heads have declined over a wide area in the metro area, the aquifers have not lost their capacity to deliver relatively large quantities of water to wells. Indeed, the well field of the City of Arvada has experienced head declines of generally less than 30 meters (100 feet) since the 1950's. Most of the wells tap the Arapahoe Formation and show no indications of faltering. The fact that the local pumping water level of the Arapahoe formation has remained nearly static, even after extensive withdrawals of water, shows that the aquifer can support additional, but cautiously planned, development. Existing data indicates that the formation can locally withstand an additional head loss of about 45 to 60 meters (150 to 200 feet) in the north Denver metro area. Such declines will place pumping level near the uppermost part of the producing zone of the Arapahoe and near the level at which pumping under water table conditions will begin.

Although the Arapahoe Formation can probably withstand additional development in the greater Denver metro area, it cannot be over-emphasized that when such development occurs (there is no indication that it will not), it should proceed with much caution and foresight on the part

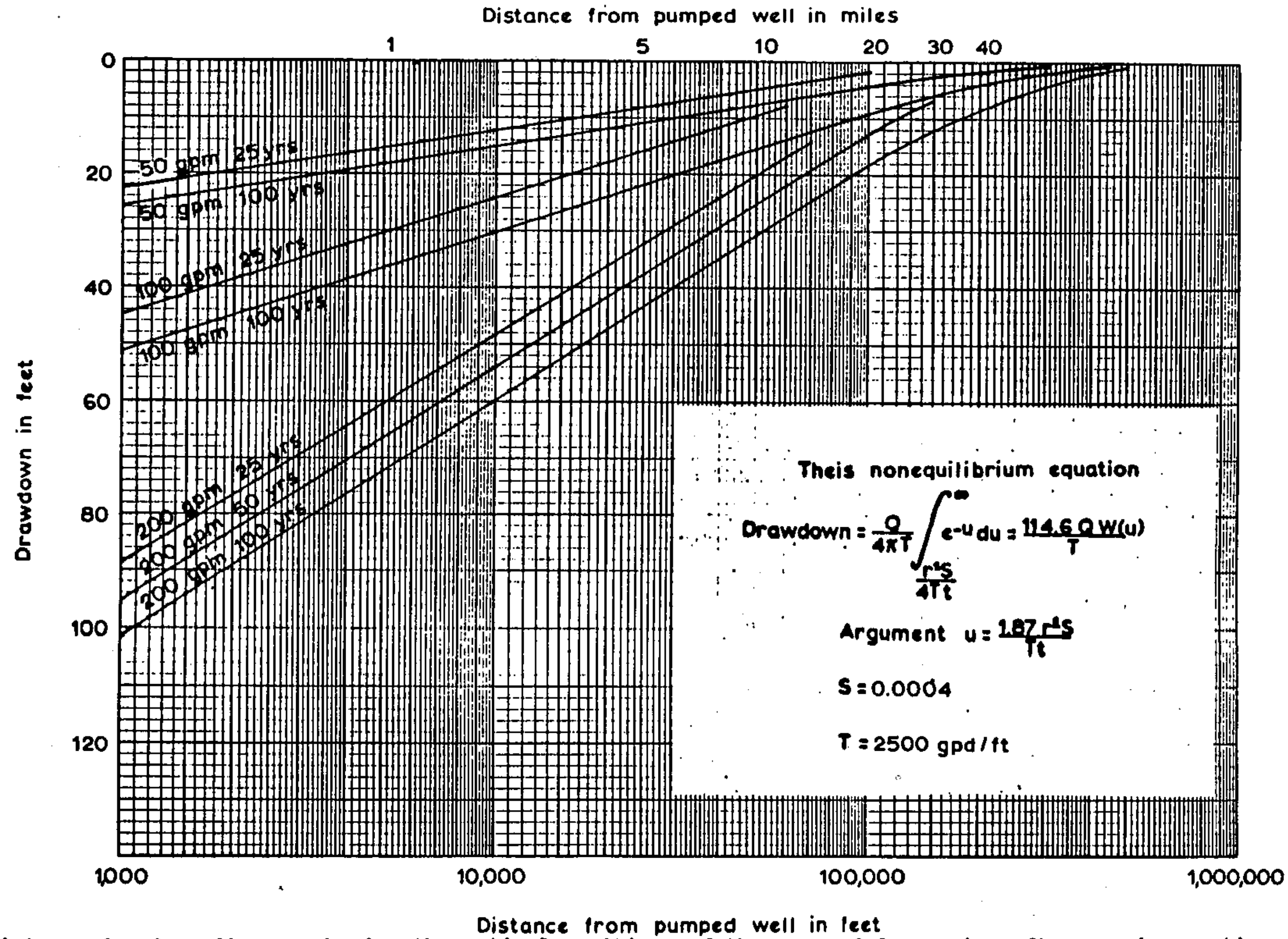

Figure 26. Distance-drawdown diagram showing theoretical positions of the cone of depression after pumping continously for 25, 50, and 100 years, respectively, at constant rates of 50, 100, and 200 gallons per minute from the L-F aquifer Multiply gallons per minute by 0.063 to find liters per second, feet by 0.0348 to find meters, miles by 1.609 to find kilometers, and gallons per day per foot (T) by 0.0124 to find square meters per day.

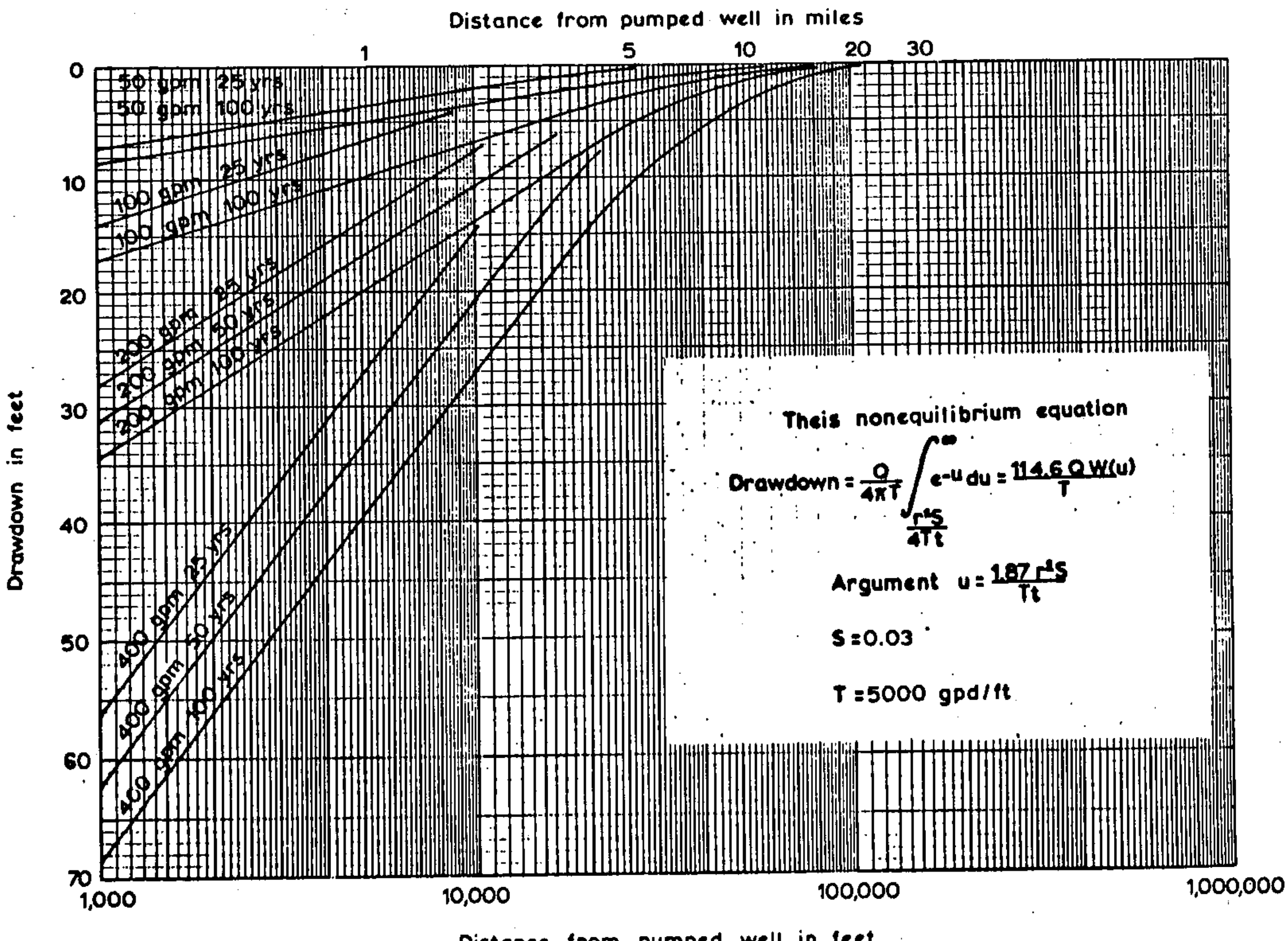

Figure 27 A. Distance-drawdown diagram showing theoretical positions of the cone of depression after pumping continously for 25, 50, and 100 years, respectfully, at constant rates of 50, 100, 200, and 400 gallons per minute from the Arapahoe Formation and Dawson Arkose. Multiply gallons per minute by 0.063 to find liters per second, feet by 0.3048 to find meters, miles by 1.609 to find kilometers, and gallons per day per foot (T) by 0.0124 to find square meters per day.

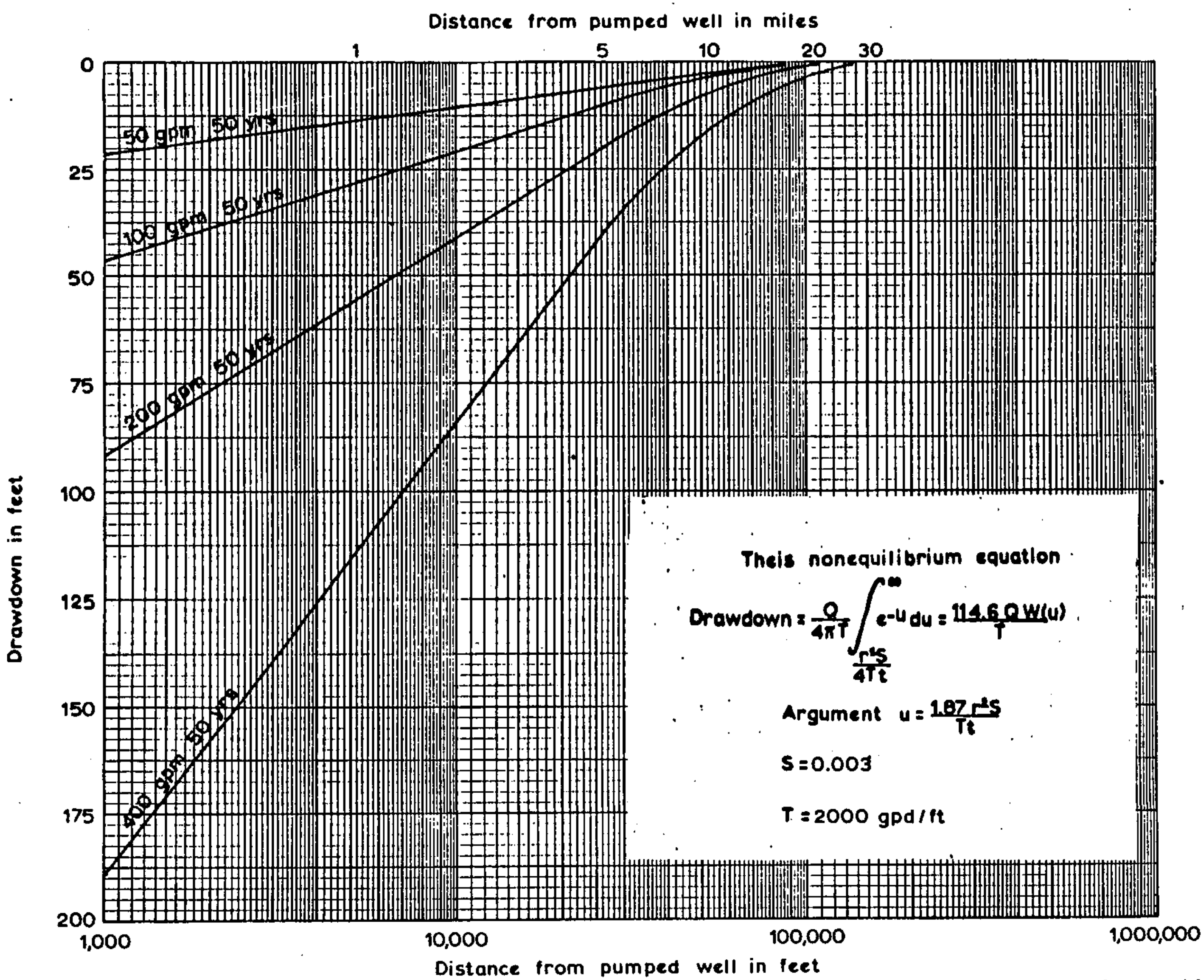

Figure 27 B. Distance-drawdown diagrams showing theoretical positions of the cone of depression after pumping continously for 50 years at constant rates of 50, 100, 200, and 400 gallons per minute from the Arapahoe Formation and Dawson Arkose. Multiply gallons per minute by 0.063 to find liters per second, feet by 0.3048 to find meters, miles by 1.609 to find kilometers, and gallons per day per foot (T) by 0.0124 to find square meters per day.

of planners and administrators. The reasons for this caution are suggested by Emmons (1896, p. 403) because of the relatively rapid decline of head over a seven year period, the fact that the Arapahoe Formation is presently heavily developed in local areas, and by metro Denver's proximity to the outcrop area.

The drawdown curves of figures 26 and 27 can be utilized to obtain an insight on the effects of pumping at various discharges over various lengths of time. The curves can also be used to estimate the effects caused by the pumping from a well field where the drawdown at any point is the sum of the drawdowns caused by each well individually, or
$D_s = D_1 + D_2 + D_3 + D_4 \ldots$ etc.

A large number of the small capacity domestic wells in the metro Denver area are obtaining water from the Denver Formation. Depths of the Denver Formation wells range from about 45 - 152 meters (150 to 500 feet) depending upon the locations of well sites with respect to stream valleys and whether or not sufficient quantities of water required for particular requirements can be found at shallower depths. Current water well drilling activities south and east of downtown Denver indicate that the water levels encountered in various horizons do not differ greatly from those reported during drilling activities 10 or more years ago. This indicates that the Denver Formation might also locally withstand additional development. However, the same precautions should be practiced for the additional development of the Denver Formation that were recommended for the development of the Arapahoe Formation.

The effects of the withdrawal of large quantities of water from the L-F aquifer in the Denver metro area is shown on plate 8, and they have been treated in the section describing potentiometric surfaces. Although local production from the L-F has been reduced, the local artesian head has continued to slowly decline in the metro area. Continuous local decline of head is probably due to the residual effect of an extensive cone of depression, which was developed in the metro area during the aquifer's early stages of development. Although the L-F's artesian head is declining at rates ranging from about 1 to 4 meters (3 to 13 feet) per year in the metro area, it is still 305-380 meters (1,000 to 1,250 feet) above the top of the aquifer. It is possible that the artesian head will continue to decline and in some cases pumping plans might require alteration to cope with greater lift. However, it is economically insound to restrict the development of the aquifer when sufficient quantities of water are available for additional development in other areas where limited loss of head has occurred.

Development of the aquifers in the metro area should proceed with caution and with the realization that all previous data indicate the water is being "mined" and will be available for pumping for a fixed time. Potential developers should be aware of the relationship of a pumped well, the drawdown around it, and plan accordingly. Excessive declines of head in such areas will therefore demand the use of pumping facilities which might lie far beyond the economic capabilities of the private well owner. Depth to the top of the L-F aquifer in most of the metro area lies between 305 and 460 meters (1,000 and 1,500 feet), and its thickness ranges between 46 and 76 meters (150 and 250 feet). Therefore, the depths required to pump the aquifer under these conditions will range between about 396 and 549 meters (1,300 and 1,800 feet). This condition will tax common pumping equipment and impose heavy economic burdens on the well user.

South Platte River Corridor. The effect of extensive utilization of the L-F aquifer in the South Platte River corridor is shown in plate 8. The increased number of L-F wells in this area has resulted in water level declines ranging from 3 to 15 meters (10 to 50 feet) per year. Several L-F wells west of Brighton are reported to be presently pumping under water table conditions. Existing evidence suggests that the aquifer is locally overdeveloped and continuous population growth in the corridor will probably result in increases in the rate of head decline. If the present trend continues, most of the L-F wells in the corridor will be pumping under water table conditions within 25 years.

Although the artesian head in the corridor has declined rapidly in recent years, the L-F aquifer can possibly support additional local development. The aquifer thickens toward the northwest, where it is close to a probable recharge area, and lies at only moderate depths below the land surface. The additional development would impose hardships on existing L-F water users by increasing the costs involved as pumping lift increases. It is obvious that any additional development should be carefully planned and closely observed.

The Eastern Prairie Lands. The prairie lands and the area east of Interstate Highway 25 between Denver and Colorado Springs are predominantly agricultural and the bedrock aquifers have not experienced the intensified development that has occurred near the population centers. Thus, most of the bedrock wells in the prairie lands are used for agricultural purposes, and small farm-ranch communities such as Keenesburg, Byers and Deer Trail. During recent years, these areas have experienced slight population growth as an increasing number of people move away from the rapidly expanding population centers. With the prairie lands becoming more attractive as sites for population growth, a more thorough understanding of past bedrock well development and the predicted response of the aquifers to extended withdrawals of water is needed.

The region surrounding the small communities of Byers and Deer Trail contains a higher density of L-F aquifer wells than do other agricultural areas east of Denver. At least two factors account for this density: (1) the area is near the eastern outcrop of the L-F aquifer within easy reach of common well drilling equipment, and (2) the area is served by an efficient highway system.

The withdrawal of water from the L-F aquifer by the domestic and stock wells and by the communities of Byers and Deer Trail has formed a cone of depression which practically encompasses the two communities and appears to extend to the outcrop area along the eastern border of the basin (pl. 8). The current rate of head loss in the area is about two feet per year. Southwest of Interstate Highway 70, approximately 90 to 180 meters (300 to 600 feet) of head remains above the top of the L-F aquifer.

With the completion of Interstate 70, the Strasburg-Byers area became within easy commuting distance from Denver. The result has been a trend toward developing the area commercially or simply as new living space. Because extended development of the L-F aquifer will result in additional head losses, the question arises as to the extent of the head loss and its relationship between the L-F outcrop where it is overlain by water saturated alluvial deposits. The North Kiowa-Bijou Ground Water Management District has expressed its concern over the possibility that extensive withdrawals from the L-F aquifer will reverse the currently north sloping potentiometric surface. The theoretical result, which is supported by many investigators, is that along certain reaches of the Bijou Creek system, recharge will occur from the alluvium to the L-F aquifer.

The concern of the North Kiowa-Bijou Ground Water Management District can be appreciated by examing the L-F drawdown curves of figure 26 (p. 87). The 13 liter per second (200 gpm) curves show that a well or well field producing 13 lps could possibly create substantial drawdowns in observation wells 64 kilometers (40 miles) distant. The small slopes of the aquifer and the potentiometric surface and the slowly moving ground water should have only a minimal effect on the shape of the curves.

In the vicinity of I-70 west of Strasburg, it is possible to drill to the L-F aquifer and the Arapahoe and Denver Formations. However, for each anticipated well, whether it be for an individual user or a housing or business development, the effects of drawdown and the existence of preexisting wells should be considered.

Existing data indicate that between Denver and Strasburg, the potentiometric surface of the L-F aquifer is from about 183 to 396 meters (600-1,300 feet) above the top of the aquifer. Therefore, considerable development of the aquifer is possible depending upon local aquifer properties, legal complications and the ability of well users to make adjustments for possibly limited well production and increasing drawdowns.

Water level trends in the Arapahoe and Denver aquifers in the prairie lands have not been established. Assuming the water producing capabilities of the Arapahoe Formation are more or less uniform throughout the central portions of the basin, it is believed that it can support considerable additional development. If such development does occur, the potentiometric surfaces will probably decline locally in the same manner as experienced in the Denver area in the 1800's.

Falcon-Peyton-Calhan Area. The area along U. S. Highway 24 between Colorado Springs and Calhan has experienced considerable population growth in the past decade. The once agriculturally oriented area is attracting both the individual in search of a large rural homesite and large scale land developers. Both the Dawson Group of aquifers and the L-F aquifer are being utilized as water supply for this development.

Development of the L-F aquifer in this area has been restricted in the past to the peripheral areas of the basin where it is utilized principally for individual domestic and/or stock purposes, and at Calhan where the aquifer furnishes about 75 percent of the town's water supply. The L-F aquifer in the Falcon-Peyton-Calhan area can withstand additional planned utilization. The sandstone isolith map of the L-F aquifer indicates that 46 to slightly over 60 meters (150-200 feet) of sandstone is present throughout most of the area (pl. 6). Available data indicates that from about 152 to 305 meters (500 to 1,000 feet) of artesian head remain on the aquifer. The depth to the top of the L-F is approximately 457 meters (1,500 feet) in most of the area and at least an additional 60 meters (200 feet) is required to penetrate through it. When pumping levels extend to the top of the aquifer, the cost of pumping equipment and power supplies will undoubtedly place a considerable economic strain on the water users. Until that time, existing and future water users should expect declining heads with increased development of the aquifer.

Most of the wells in the Falcon-Peyton-Calhan area are less than 152 meters (500 feet) deep and tap just the upper part of the Dawson Group. The wells have small capacities and do not appear to tap one particular stratigraphic horizon. Measured depth to water is just as variable now as they were several years ago, hence, no general trend for a particular horizon has been established.

The area is generally underlain by more than 305 meters (1,000 feet) of material belonging to the Dawson Group and probably contains from 25 to 50 percent sand and gravel. The aquifers can probably tolerate considerable development so long as the capacities of wells are limited. Existing logs indicate that most of the sands in the upper 305 meters are lenticular. Thus, the potential water user must use caution so as to prevent overdevelopment of small lenses. Recharge to the lenticular sandstones in this area is probably quite limited and the exhaustion of all of the recoverable water from some lenses could mark the end of their usefulness as aquifers.

Potential large scale water users of the Arapahoe Formation should use every means at their disposal to test the aquifer before committing themselves financially. Scattered E-log information in the area indicates that the Arapahoe is frequently less than 122 meters (400 feet) thick and the sands are not as well developed as in other areas to the north and northwest.

The Black Forest and Other Areas. In this report, the Black Forest is defined as about 2,072 square kilometers (800 square miles) in the southwest and central part of the Denver Basin which supports dense growths of pine trees. The northern, eastern and southern boundaries correspond to surface elevations of 1828, 1920 and 2134 meters (about 6000, 6300, and 7000 feet) respectively. The designated western boundary is I-25 between Denver and Colorado Springs. Small communities which serve the area are Castle Rock, Franktown, Elizabeth, Kiowa, and Elbert.

In the past, the area was predominantly agricultural. Current interest involves homesite development. The efficient highway system and proximity to both metro Denver and Colorado Springs have resulted in very high rates of population growth. Since most of the development is occurring on interstream divides, water wells of sufficient depth to tap the bedrock formations must be constructed. Exemplifying the growth of the Black Forest region is the Town of Castle Rock, which has experienced steady growth since the early 1960's. This growth is reflected in the annual increase in the total quantity of water supplied by the town water department (fig. 24, p. 83). The town presently has two wells tapping the Dawson Group.

Practically all of the wells which have been drilled have been constructed on an individual basis by users desiring only limited quantities of water from small capacity wells. Due to the lenticularity and wide stratigraphic distribution of water producing horizons in the Dawson aquifers, wells are drilled to depths verying from about 30 meters (100 feet) to generally less than 305 meters (1,000 feet). It is common for this range to occur within an area less than 1.6 square kilometer (1 square mile). Over 80 percent of the wells which tap the bedrock aquifers in the Black Forest are less than 305 meters deep: most are obtaining water from the Dawson Arkose. Only a few penetrate to the Arapahoe Formation.

Until quite recently, data collection in the Black Forest has been practically non-existant, therefore, no definite long-term trends of the water levels are known. Scant evidence obtained from the driller's logs in the area indicate that no significant change has occurred in the upper 152 meters (500 feet) of the Dawson Group. Comparison of driller's completion reports made in the 1950's and early 60's with recent completion reports indicates that some areas, which are obtaining water from the 152 to 274 meters (500 to 900 feet) levels, and a few wells with a depth of 457 meters (1,500 feet) or more, possibly have experienced water level declines of 2.5 meters (eight feet) per year. This comparison shows that a large number of closely grouped small capacity wells tapping the same aquifer will cause substantial water-level declines.

Most of the new land owners in the Black Forest will probably drill individual wells with depth generally less than 152 meters (500 feet). A few, however, particularly corporations contemplating large housing, commercial and industrial developments, will undoubtedly construct wells designed to tap the basal portion of the Dawson Arkose or the Arapahoe Formation. Electric logs of these formations indicate aquifer thicknesses commonly approaching 152 meters (500 feet) with a net sand value averaging 76 meters (250 feet). Aquifer tests performed on similar thicknesses of the Arapahoe Formation in the southeast Denver metro area indicate that 13 to 26 liters per second (200 to 400 gpm) can be withdrawn without causing substantial drawdowns in the pumped well. The Arapahoe can be expected to produce such quantities of water in most of the Black Forest region except in the southern part where sand horizons are not as well developed as those to the north. The basal part of the Dawson Arkose aquifer is very desirable in the Black Forest because its sands are locally quite thick and permeable and the water pumped from it has a high chemical quality.

The Dawson Arkose and Arapahoe Formation will undoubtedly prove to be major sources of water. However, water users and administrators should be totally aware of the dangers of over-development and plan accordingly; well spacing and ground water withdrawals should be closely scrutinized, particularly in the peripheral areas where ground water storage is limited and where the aquifers are cut by stream systems and to a certain degree, are tributary to those systems.

The Denver Formation has proven to be a reliable aquifer for domestic and limited commercial purposes in other parts of the Denver Basin and the same should be expected in the Black Forest region. Particular attention should be made to well spacing because Denver sandstones are notoriously lenticular, and to potential water quality problems in sections known to contain coal.

Although the L-F aquifer exists in the Black Forest region, little is known of its local hydrogeologic properties. Throughout much of the region, the L-F lies below a depth of 610 meters (2000 feet) and is generally not penetrated; southeast of Castle Rock it lies at a depth approaching 914 meters (3,000 feet). Thus, it is questionable that it will experience large scale development by average water users. Water users who can economically exploit water wells of such depths will find the general thickness of net sand impressive (pl. 6), but should anticipate potential water quality and drawdown problems.

Another area which is currently experiencing rapid growth of population which relies heavily upon ground water from the bedrock formations is bordered by the foothills escarpment, I-25, metropolitan Denver and Colorado Springs. This area is both physiographically attractive and is within easy commuting distance of Denver and Colorado Springs. Previously, most development occurred near the main highway system. Currently, development is taking place in the once isolated hogback areas several miles west of the main highways and in the rolling table lands between the hogbacks and Black Forest. Most of the wells in the area are of the domestic and stock type. Typical municipal use of bedrock water resources are represented by the small community of Louviers, and the Woodmoor Water and Sanitation District at Monument, Colorado. The U. S. Air Force Academy utilizes the Denver-Arapahoe and L-F aquifers as sources of water for the dilution of sewage effluent and irrigation purposes. Several industrial and quasi-municipal wells also tap the bedrock aquifers in this area.

Plates 8 and 12 show the density of wells in the L-F aquifer and the relative discharge density of wells in the Dawson Group of aquifers and indicate that through mid-1973, the area was not heavily developed. This probably was due to the once relatively poor accessibility of the area and readily available land closer to the main highway system. This area or "strip" could probably tolerate considerable additional development, provided that both water administrators and water users are aware of the strict limitations placed upon the aquifers by nature. As discussed in earlier sections of this report, the basin's sedimentary rocks either outcrop as hogbacks or are cut by the fault system. Therefore, ground water storage in the bedrock aquifers diminishes in a westward direction.

Although data are lacking, a distinct possibility exists that faulting is not limited to rocks in proximity to the Rampart Range and Golden fault systems. Eastward extensions of the faults, whether they are related to the Laramide Revolution or subsequent structural adjustments, would result in isolating segments of the bedrock aquifers. Such physical phenomena might not affect the needs of wisely spaced domestic-stock wells. However, a water user whose requirements would greatly exceed the demand of an individual household unit or small commercial-industrial installation, should examine all available hydrogeologic data on the prospect area, and if the need arises and funds permit, invest in a test drilling program.

Existing data indicates that depth to the L-F aquifer in the strip ranges from zero at the outcrop to about 732 meters (2,400 feet) west of Castle Rock (pl. 7). Such depth, combined with reports that the aquifer's potentiometric surface is locally over 305 meters (1,000 feet) below the land surface, will probably limit most present and immediate future development to the Arapahoe, Denver, and Dawson Formations.

Land Subsidence. Subsidence of land adjacent to areas which have experienced substantial declines of artesian pressure from the withdrawal of ground water is well documented. Most investigators agree that the common cause of land subsidence is the withdrawal of water, gas, or petroleum from confined zones in consolidated or partially consolidated sedimentary deposits. This removal of fluids results in a reduction of the artesian pressure and an increase in overburden load on the formation. When the overburden load is increased, more of the stress is transferred to the matrix within the deposits. This change in stress results in changes in the particle, pore, and bulk volume of the rock. Compaction and accompanying land subsidence is of interest because of their affect on aquifer properties and man-made structures on the land surface.

The major hydrogeological effect caused by aquifer compaction is the reduction of the aquifer's capacity to store and yield water. In summarizing his investigation of part of the San Joaquin Valley in California, Poland (1961, pp. B-53, B-54) reported that the storage derived during compaction of clayey interbeds and confining beds may be equal to or greater than that derived from the coarse fraction of the aquifer. He also states that the water yield from the clayey beds is large only during the first decline of artesian pressure. If pressures are allowed to recover, and then were drawn down again through the same interval, the additional compression of the clayey beds would be only a small fraction of that in the first phase. It is reasonable to conclude that compression of the clayey beds within the aquifer materially reduces the aquifer's capacity to store and yield ground water.

The possibility that certain parts of the Denver Basin will be affected by subsidence should not be ignored. The potential certainly exists, particularly in light of the lowering of artesian heads of several hundred feet, and the northwestern part of the basin being a site of tectonic activity. Postulated and known causes of subsidence which might apply to the Denver Basin are: (1) water reservoir compaction due to ground water withdrawals; (2) possible lack of local structural stability.

The artesian head in the northern part of metropolitan Denver has already experienced a decline exceeding 60 meters (200 feet). Any effect of lowering the potentiometric surface 60 or more meters is unknown at this time. However, it is possible that closely monitored land level stations and tectonic studies can be utilized to reveal the existence of any land subsidence. Numerous faults cut the bedrock formations and the area has experienced over 2000 earthquakes since early 1962. The well known Derby earthquakes have been related to the injection of fluid wastes at the Rocky Mountain Arsenal disposal well. It is possible that the earthquake activity has masked shallow events which might have occurred due to the lowering of artesian head. It should be noted that prior to 1962 no seismic instruments in the area were capable of registering events having an activity of less than III on the modified Mercalli activity scale (about 2 to 3 on the Richter scale). Therefore, if ground water withdrawals from artesian aquifers did produce low intensity events, they were not recorded.

Seismic events related to lowering the artesian head will be somewhat difficult to detect. The tectonic stresses in the basement rocks of the basin have resulted in periodic seismic activity regardless of the degree of dewatering. Investigators examining the possibility of land subsidence induced by lowering of artesian head must develop a closely coordinated program of both seismic studies and precise land-level surveys.

The dangers of subsidence in the Denver Basin are possibly lessened somewhat because the sedimentary materials from which artesian water is withdrawn are to a certain degree preconsolidated. Hence, the basin possesses a certain degree of structural stability. It is therefore possible that the basin's artesian aquifers can withstand a substantial lowering of artesian head without experiencing substantial compaction and subsequent subsidence. Or, if compaction and subsidence does occur, it should be of such small magnitude that it will be extremely difficult to detect.

Evidence suggests that compaction and subsidence in the Denver Basin are not occurring rapidly if at all. If the nature of the artesian aquifers is such that stresses created by extensive dewatering can be relieved only after years of build-up, the Derby earthquakes could have acted as triggering mechanisms for release of the stresses. Any relief of these stresses in the past were probably of such low intensity that they were not recognized as products of sub-surface activity.

If extensive pumping from the Denver Basin artesian aquifers will produce detectable seismic activity or subsidence in the future, such events should occur in the areas of heaviest artesian aquifer development. Certain parts of metropolitan Denver, for example, are experiencing marked population expansions. The water supplies of many of these areas are to be either partially or totally dependent on local artesian aquifers. Since thick sections of Laramie-Fox Hills aquifer and Arapahoe Formation are to be exploited, a definite potential for aquifer compaction exists. Because of the presence of large buildings and a complex network of conduits, the degree of the compaction is important.

It is evident that in the Denver Basin some means should be employed to monitor the reaction of artesian aquifers to extensive dewatering. Data obtained from select monitoring programs could be used to predict sites of potential subsidence and aid in the prediction of aquifer life. Methods used to monitor subsidence in California, which can readily be applied to the Denver Basin, include (1) old and new well log comparisons; (2) use of buried dead-man anchors (Lofgren, 1961);

(3) wire-line depth measuring of casing joints; (4) radioactive tagging of marker beds; and (5) the monitoring of a network of precise land level stations.

At present, it is unknown if local dewatering in Denver Basin artesian aquifers will result in extensive subsidence. Some compaction will certainly occur, but the extent and nature of the subsidence is somewhat problematical. Analytical methods are available to predict the severity and timing of such events, but their application requires sophisticated data which is obtained only with difficulty. Since certain parts of the Denver Basin are probably going to experience artesian head declines of at least 150 meters (500 feet) in the next 10 or 20 years, it is important that the extent of possible subsidence is known. The fact that once the fine fractions of the artesian aquifers have been compressed and dewatered, they cannot be recharged by either natural or artificial means, cannot be over-emphasized.

FUTURE BASIN DEVELOPMENT AND MANAGEMENT OF BEDROCK AQUIFERS

The principal objective of this report is to aid in the formulation of legal and technical plans which, if put into effect, would use the Denver Basin's bedrock-water with maximum productivity and life, with minimum waste and cost. The bedrock aquifers contain a vast quantity of water in storage but in order to accommodate the numerous federal, state, county and individual interests, it will be necessary to coordinate all development of the resource.

Significant head losses wherever the aquifers have been developed are clear indications that the "safe yields" are easily exceeded. The significant widespread and prolonged head losses indicates that the quantity of water recharged to the aquifers is greatly exceeded by the quantity of water withdrawn by pumpage. It has also been shown that low permeabilities and irregular development of sandstones prevent large-scale artificial recharge practices. These two facts seriously limit resource management alternatives. Overshadowing the premise that alternatives are severely limited is the fact that the resource has little value if it is not put to beneficial use.

Because the water of the bedrock aquifers is being mined, the priority doctrine is not a suitable approach to its management. Application of the doctrine to the basin's bedrock aquifers would necessitate the immediate halt to construction of all new high capacity wells, and the imposition of pumping limitations on most existing high capacity wells. Such action, which in effect can be classed as a "type" of moratorium, would certainly extend the life of the resource, but might severely injure local economies and would probably tax the water delivery capabilities of other systems.

It is safe to assume that waste water reclamation and re-use, and restrictive measures will play a vital role in augmenting the water needs of the future. To what extent these measures will affect over-all water demands is beyond the scope of this report. It is becoming increasingly clear, however, that provisions must be made to integrate the use of the ground waters in the Denver Basin with other available supplies to meet the growing water demands of the area. Indeed, what is needed is a thorough analyses of the water resource availability and use along the entire Front Range so that all water users can be included in a comprehensive water plan for the future. Until such a plan is available, however, there is a growing demand to utilize water from the bedrock aquifers and this resource must be developed in an orderly manner.

Another prospect that could extend the life of the aquifers is to make available a plentiful supply of low cost imported water. Neither the political climate for transmountain diversions nor the availability of such water can be predicted or guaranteed.

Certain protective measures must be employed to achieve timely and effective use of the ground waters in the bedrock aquifers to maintain a minimal influence of one well upon another. The effect of pumpage from an artesian aquifer anywhere in the basin will ultimately be transmitted throughout the entire aquifer. To minimize head loss, it is recommended that spacing and construction criteria, based on aquifer characteristics, be established, and that use permits clearly provide no guarantee of the current pumping head.

SUMMARY OF PROBLEMS AND CONCLUSIONS

Major problems which will confront administrators and users of water from the Denver Basin's bedrock aquifers include those associated with declining water levels and deterioration of water quality.

Areas in which current water level declines are rapid enough to cause concern are the South Platte River corridor, the Strasburg-Byers-Deer Trail area, and parts of metropolitan Denver. Although the rate of water level decline in certain parts of the Denver area has been buffered by transmountain diversions, other parts are growing at a phenomenal rate. In such areas, there is an increase in the desire to use the bedrock aquifers for large quantities of water. This is particularly true in the Black Forest and other areas where new and future developments must rely totally on bedrock water supplies. It is suggested that development in such areas proceed with caution as too rapid growth might result in water level declines which greatly exceed the economic capabilities of current pumping equipment.

Water quality problems of the Denver Basin's bedrock aquifers are confined predominantly to the Laramie Formation and L-F aquifer. Water from these units is locally known to contain troublesome amounts of hydrogen sulfide, methane, iron, fluoride and, frequently, sodium. Although local geologic phenomena might be the cause of many of the contaminants, the possibility of contamination resulting from human activities should not be ruled out.

Many water quality problems encountered in utilizing the bedrock aquifers can probably be eliminated by avoiding multi-aquifer completions, particularly in the case of mixing L-F water with Dawson Group water. When more than one aquifer is penetrated during drilling operations, water-bearing horizons found or suspected to contain poor quality water should be effectively isolated. Use of any of the sedimentary rocks of the Denver Basin as receptacles for disposal products must be avoided.

Successful future management of the bedrock aquifers of the Denver Basin will require the collection and utilization of a considerable amount of additional data, particularly in those areas where data is either scarce or totally lacking. The importance of additional electric logs, geologic sample logs, and aquifer test data cannot be over-emphasized. Water quality tests are inexpensive and should be made at every opportunity. Of major importance is the need for an extensive network of observation wells in which water-level fluctuations can be monitored. Completion of an observation network of this type is anticipated during the fiscal year 1975-1976. Accurate measurements of the quantities of water withdrawn from the aquifer are needed to predict the useful lives and the response to additional development.

The bedrock aquifers of the Denver Basin contain vast quantities of ground water suitable in most localities for all beneficial purposes. If managed with caution, the basin can supply the water needs of several generations.

APPENDIX A

WELL NUMBERING SYSTEM

Wells described in Table 6 are numbered according to their location within the Federal system of public land subdivision (fig. 28). The number shows the location of the well by quadrant, township, range, section, and position within the section. The capital letter at the beginning of the location number indicates the quadrant of the meridian and base line-system in which the well is located. All wells in the Denver Basin project area lie in the northwest (B) or southwest (C) quadrant of the sixth principal meridian and 40th parallel baseline system. The first segment of the well number indicates the township, the second the range, and the third the section. Lower case letters following the section number locate the well within the section. The first letter denotes the quarter section, the second the quarter-quarter section and so on. When more than one well is located within the smallest subdivision indicated, consecutive numbers beginning with 2 are added to the identifying number in the order in which the wells were inventoried.

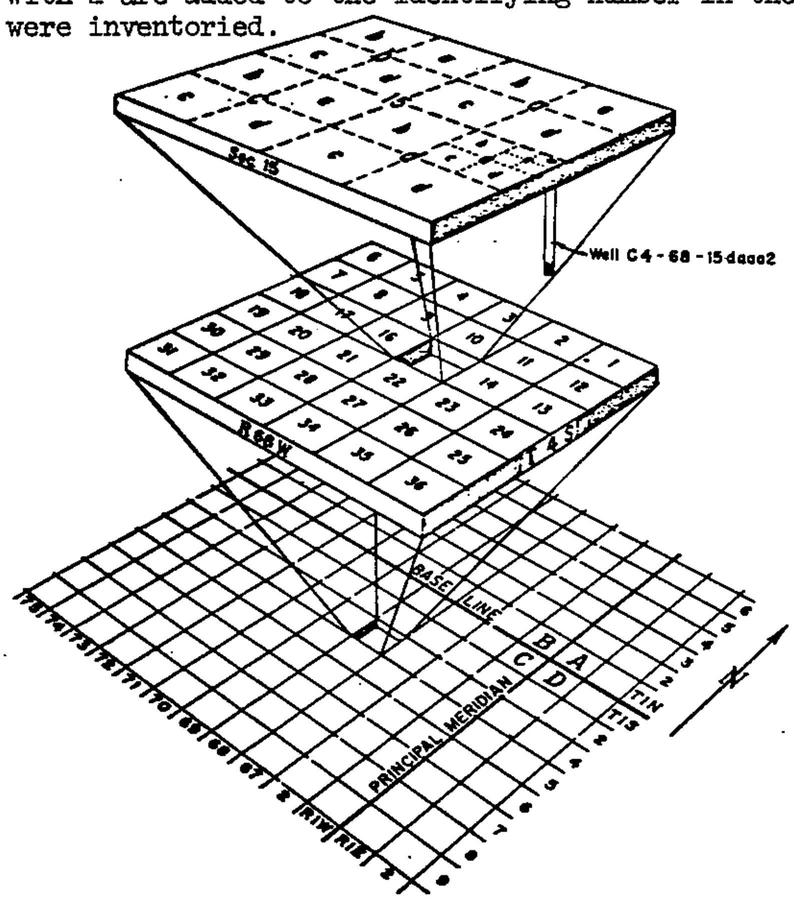

Figure 28. Method of numbering wells in Colorado. From McConaghy, James A. and others, 1964, Hydrogeologic data of the Denver Basin, Colorado: Colorado Water Conservation Board Basic Data Report No. 15; prepared by U.S. Geological Survey, p. 3.

APPENDIX B

GLOSSARY AND CONVERSION FACTORS

Technical terms which have special hydrogeologic significance and those whose definitions have undergone slight modification within the last few years are defined below. This is followed by a list of conversion factors.

Aquifer - A geological formation, group of formations, or part of a formation containing sufficient saturated permeable material that can yield a sufficient quantity of water that may be extracted and applied to beneficial use.

Drawdown - Drawdown in a well is the extent of lowering of the water level when pumping is in progress or when water is discharging from a flowing well.

Hydraulic Conductivity - The capacity of an aquifer to transmit water. A porous medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross-section of unit area, measured at right angles to the direction of flow, under a unit hydraulic gradient. It is expressed as meters per day. The abandoned term is coefficient of permeability, gallons per day per square foot.

Hydraulic Gradient - The change in static or hydraulic head at a certain point within an aquifer with respect to the hydraulic head at a different point within the same aquifer. Generally expressed as $^{dh}/dl$ or static or hydraulic head difference (h) divided by the distance (l) between the points of interest.

Potentiometric Surface - The potentiometric surface is an imaginary surface connecting points to which water would rise in tightly cased wells from a given point in an aquifer. It represents the artesian pressure or hydraulic head throughout all or part of an artesian or confined aquifer.

Specific Capacity - Specific capacity of a well is the ratio between its discharge and drawdown. In the past, it has been expressed as gallons per minute per foot of drawdown. It now is expressed as liters per second per meter of drawdown.

Specific Yield - The specific yield of an aquifer is the ratio of the volume of water which, after being saturated, it will yield by gravity to its own volume. The specific yield of most unconfined aquifers ranges from about 0.1 to 0.3 and averages about 0.2. The coefficient is dimensionless.

Storage Coefficient - Storage coefficient is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. The storage coefficient of most confined aquifers ranges from about 0.005 to 0.00005, indicating that large pressure changes over extensive areas are required to produce substantial water yields. The coefficient is dimensionless.

Transmissivity (T) - Aquifer transmissivity is the rate at which water is transmitted through a unit width of the aquifer, extending through the full saturated thickness and under a unit hydraulic gradient (1.00 or 100 percent). It has been expressed as gallons per day per foot. Current terminology is square meters per day.

Water Table - The upper surface of the zone of saturation in an unconfined aquifer is called the water table. It is also defined as that imaginary surface within an unconfined aquifer at which the pressure is atmospheric.

The following factors may be used to convert English units to the metric or International System of units (SI).

MULTIPLY ENGLISH UNITS	BY	TO OBTAIN SI UNITS
inches	25.4	millimeters (mm)
inches	0.0254	meters (m)
feet	0.3048	meters (m)
miles	1.609	kilometers (km)
acres	4047	square meters (m^2)
square miles	2.590	square kilometers (km^2)
gallons	3.785	liters (l)
gallons	0.003785	cubic meters (m^3)
cubic feet	0.0283	cubic meters (m^3)
acre feet	1233	cubic meters (m^3)
cubic feet per second	28.32	liters per second (l/s)
	0.02832	cubic meters per second (m^3/s)
gallons per minute	0.06309	liters per second (l/s)

SELECTED REFERENCES

Ballew, W. H., 1957, The geology of the Jarre Canyon area, Douglas County, Colorado: Unpublished M. S. thesis, Dept. of Geol., Colorado School of Mines, Golden, Colorado.

Bentall, Ray, 1963, Shortcuts and problems in aquifer tests: U. S. Geol. Survey Water Supply Paper 1545-C.

Bibby, Robert, 1969, Flow between the confined aquifer of the Fox Hills sandstone and the alluvial aquifer in the North Kiowa-Bijou District, Colorado: Unpublished M. S. thesis, Dept. of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Bjorklund, L. J., and Brown, R. F., 1957, Geology and ground water resources of the lower South Platte River Valley between Hardin, Colorado and Paxton, Nebraska: U. S. Geol. Survey Water Supply Paper 1378.

Burbank, W. S. and others, 1935, Geologic map of Colorado: U. S. Geol. Survey in cooperation with Colorado State Geol. Survey Board and Colorado Metal Mining Fund.

Chase, G. H., and McConaghy, J. A., Generalized surficial geologic map of the Denver area, Colorado: U. S. Geol. Survey open file map.

Colorado Department of Health, 1971, Colorado drinking water supplies.

Crain, H. M. (Editor), 1948, Guide for the geology of central Colorado: School of Mines Quarterly, v. 43, no. 2.

Dane, C. H., and Pierce, W. G., 1936, Dawson and Laramie formations in the southeastern part of the Denver Basin, Colorado: A.A.P.G. Bull., v. 20, no. 10, p. 1308-1328.

Dane, C. H., Pierce, W. G., and Reeside, J. B., Jr., 1937, The stratigraphy of the upper Cretaceous rocks north of the Arkansas River in eastern Colorado: U. S. Geol. Survey Prof. Paper 186-K.

Davis, Stanley N. and DeWiest, Rojer, J. M., 1966, Hydrogeology: John Wiley and Sons, N.Y.

DeWiest, Rojer, J. M., 1965, Geohydrology: John Wiley and Sons, N.Y.

Duke, H. R., and Longenbauth, R. A., 1966, Evaluation of the water resources in Kiowa and Bijou Creek basins, Colorado: Report prepared for the Colorado Water Conservation Board.

Elkin, Alex D., 1958, Geology of southeastern Elbert County, Colorado: Unpublished report prepared by U. S. Soil Conservation Service.

Emmons, S. F., and others, 1896, Geology of the Denver Basin in Colorado: U. S. Geol Survey Mon. 27.

Erker, H. W., and Romero, J. C., 1967, Ground water resources of the upper Black Squirrel Creek basin, El Paso County, Colorado: Report prepared for the Colorado Ground Water Commission.

Ferris, D. B., and others, 1962, Theory of aquifer tests: U. S. Geol. Survey Water Supply Paper 1536-E.

Finlay, G. I., 1916, Description of the Colorado Springs quadrangle, Colorado: U. S. Geol. Survey Atlas, Folio 203.

Gabriel, V. G., 1933, The Castle Rock conglomerate and associated placergold deposits, Douglas County, Colorado: Unpublished Ph.D. dissertation, Geology Dept. Colorado School of Mines, Golden, Colorado.

Greeg, D. O., and others, 1961, Public water supplies of Colorado: Colorado State University Agricultural Experiment Station, Genrl. series 757.

Hem, John D., 1959, Study and interpretation of the chemical characteristics of natural water: U. S. Geol. Survey Water Supply Paper 1473.

Henderson, J., 1920, Cretaceous formations of northeastern Colorado plains: Colorado Geol. Survey Bull. 19, p. 22, 23.

Inter County Regional Planning Commission, 1965, 1969, Metropolitan water study: Reports prepared for the Denver Regional Council of Governments, Denver, Colorado.

Jenkins, Edward D., 1964, Ground water in the Fountain and Jimmy Camp Valleys, El Paso County, Colorado: U. S. Geol. Survey Water Supply Paper 1583.

Johnson, D. H., 1961, Geology of the Devil's Head quadrangle, Douglas County, Colorado: Unpublished M. S. thesis, Geology Dept., Colorado School of Mines, Golden, Colorado.

Johnson, J. Harlan, 1934, Introduction to the geology of the Golden area, Colorado: Colorado School of Mines Quarterly, v. 29, no. 4.

Kittleman, Laurence R., 1956, Post-Laramie sediments of the Denver- Colorado Springs region, east-central Colorado: Unpublished M. S. thesis, Geology Dept., University of Colorado, Boulder, Colorado.

Kuhn, Alan, 1969, Hydrogeology of the Fox Hills aquifer, North Kiowa-Bijou District, Colorado: Unpublished M. S. thesis, Geology Dept., Colorado State University, Fort Collins, Colorado.

LeRoy, L. W., 1946, Stratigraphy of the Golden-Morrison area, Colorado: Colorado School of Mines Quarterly, v. 41, no. 2.

Lofgren, Ben E., 1961, Measurement of compaction of aquifer systems in areas of land subsidence: U. S. Geol. Survey Prof. Paper 424-B, pp. B49 - B52.

MacLachlan, J. C., 1961, Cambrian, Ordovician, and Devonian systems, eastern Colorado subsurface: Rocky Mountain Assoc. Geologists symposium on Lower and Middle Paleozoic rocks in Colorado.

Malek-Aslani, M. K., 1950, Geology of southern Perry Park, Douglas County Colorado: Unpublished M. S. thesis, Geol. Dept., Colorado School of Mines, Golden, Colorado.

Mayuga, M. N., and Allen, D. R., 1966, Long Beach subsidence: Engineering Geology in southern California, a special publication of Los Angeles Section of the Association of Engr. Geologists, Glendale, California.

McConaghy, J. A., and others, 1964, Hydrogeologic data of the Denver Basin, Colorado: Colorado Water Conservation Board Basic Data Report 15, Prepared by U. S. Geol. Survey.

McCoy, Alex W., III, 1953, Tectonic history of the Denver Basin, Colorado: A. A. P. G. Bull., v. 37, no. 8, p. 1873-1875.

McGovern, H. E., and Jenkins, E. D., 1966, Ground water in Black Squirrel Creek valley, El Paso County, Colorado: U. S. Geol. Survey Hydrologic Atlas, H. A. 236.

McKee, J. E. and Wolf, H. W., 1963, Water Quality criteria: California Water Quality Control Board Publication 3-A.

McLaughlin, Thad G., 1946, Geology and ground water resources of parts of Lincoln, Elbert, and El Paso Counties, Colorado: Colorado Water Conservation Board Ground Water Series Bull. 1. Prepared by U. S. Geol. Survey.

Moody, John D., 1947, Upper Montana group, Golden area, Jefferson County, Colorado: A. A. P. G. Bull., v. 31, no. 8, p. 1454-1471.

Mundoff, James C., 1964, Fluvial sediment in Kiowa Creek basin, Colorado: U. S. Geol. Survey Water Supply Paper 1798-A.

Muskat, M., 1946, The flow of homogeneous fluids through porous media: J. W. Edwards, Inc., Ann Arbor, Michigan.

Owens, Willard G., 1967, Ground water resources of the Lost Creek drainage basin, Weld, Adams, and Arapahoe Counties, Colorado: Report prepared for Colorado Ground Water Commission by Nelson, Haley, Patterson, and Quirk, Inc., Greeley, Colorado.

Owens, Willard G., 1971, Hydrogeologic study of bedrock aquifers in the North Kiowa-Bijou Ground Water Management District, Colorado: Report prepared for Board of Directors of North Kiowa-Bijou District by Willard Owens and Assoc., Denver, Colorado.

Owens, W. G., and Hamilton, J. L., 1971, Ground water resources of the Big Sandy Creek drainage area in southeast Colorado: Report prepared for Colorado Division of Water Resources by Willard Owens and Assoc., Denver, Colorado.

Pearl, Richard H., 1971, Pliocene drainage in east-central Colorado and northwestern Kansas: G. S. A. Bull., v. 42, p. 25-30.

Poland, J. F., 1961, The coefficient of storage in a region of major subsidence caused by compaction of an aquifer system: U. S. Geol. Survey Prof. Paper 424-B, pp. B-52-B-54.

Reichert, Stanley O., 1954, Geology of the Golden-Green Mountain area, Jefferson County, Colorado: Colorado School of Mines Quarterly, v. 49, no. 1.

- - 1956, Post-Laramie stratigraphic correlations in the Denver Basin, Colorado: G. S. A. Bull. v. 67, p. 107-112.

Richardson, G. B., 1915, Description of the Castle Rock quadrangle, Colorado: U. S. Geol. Survey Atlas, Folio 198.

Romero, John C., 1965, Geologic control of ground water in the Kiowa-Wolf-Comanche Creek area in central Adams County, Colorado: Unpublished M. S. thesis Geol. Dept., Colorado State University, Fort Collins, Colorado.

Scott, Glenn R., 1961, Preliminary geologic map of the Indian Hills quadrangle, Jefferson County, Colorado: U. S. Geol. Survey Miscellaneous Geol. Invest. Map I-333.

- - 1962, Geology of the Littleton quadrangle in Jefferson, Douglas, and Arapahoe Counties, Colorado: U. S. Geol. Survey Bull. 1121-L.

- - 1963, Bedrock geology of the Kassler quadrangle, Colorado: U. S. Geol. Survey Prof. Paper 421-B.

- - 1970, Quaternary faulting and potential earthquakes in east-central Colorado: U. S. Geol Survey Prof. Paper 700-C, p. 11-18.

Smith, J. H., 1964, Geology of the sedimentary rocks of the Morrison quadrangle, Colorado: U. S. Geol. Survey Miscellaneous Geol. Invest. Map I-428.

Smith, Rex O., and others, 1964, Ground water resources of the South Platte River basin in western Adams and south-western Weld Counties, Colorado: U. S. Geol. Survey Water Supply Paper 1658.

Soister, Paul E., 1968, Geologic map of the Corral Bluffs quadrangle, El Paso County, Colorado: U. S. Geol. Survey Geol. Quad Map GQ-725.

Stewart, W. Alan, 1955, Structure of the foothills area west of Denver, Colorado, R. M. A. G. Guidebook, p. 25-30.

Todd, David, 1960, Groundwater hydrology: John Wiley & Sons, N.Y.

Todd, David, and others, 1970, The water encyclopedia: Water Information Center, Water Research Building, Manhasset Isle, Port Washington, N. Y.

U. S. Public Health Service, 1962, Drinking water standards: U. S. Public Health Service Pub. 956.

Van Horn, Richard, 1957, Bedrock Geology of the Golden quadrangle, Colorado: U. S. Geol. Survey Quad Map GQ-103.

Varnes, D. J., and Scott, G. R., 1967, General and engineering geology of the U. S. Air Force Academy site, Colorado: U. S. Geol. Survey Prof. Paper 551.

Waage, Karl M., 1959, Dakota stratigraphy along the Colorado Front Range: R. M. A. G. symposium on the Cretaceous rocks of Colorado and adjacent areas, p. 115-123.

Welsh, Fred, Jr., 1969, Geology of the Castle Rock area, Douglas County, Colorado: Unpublished M. S. thesis, Geol. Dept., Colorado School of Mines, Golden, Colorado.

Wilson, Woodrow, 1965, pumping tests in Colorado: U. S. Geol. Survey, Colorado Water Conservation Board Ground Water Circular 11. Prepared by U. S. Geol. Survey.