Geology and Occurrence of Ground Water in Otero County and the Southern Part of Crowley County, Colorado

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1799

Prepared in cooperation with the Colorado Water Conservation Board

Geology and Occurrence of Ground Water in Otero County and the Southern Part of Crowley County, Colorado

By WILLIAM G. WEIST, Jr.

With sections on

Hydrology of the Arkansas River Valley in the Project Area

By WILLIAM G. WEIST, Jr., *and* EDWARD D. JENKINS

Hydraulic Properties of the Water-Bearing Materials

By EDWARD D. JENKINS

Quality of the Ground Water

By C. ALBERT HORR

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GEOLOGY AND OCCURRENCE OF GROUND WATER IN OTERO COUNTY AND THE SOUTHERN PART OF CROWLEY COUNTY, COLORADO

By William G. Weist, Jr.

ABSTRACT

Otero County and the southern part of Crowley County include an area of about 1,500 square miles in the Arkansas Valley. Ground water is the principal source of water for domestic use by the residents, most of whom are farmers or ranchers. The climate is semiarid; precipitation averages 11 to 14 inches per year.

Rocks ranging in age from Late Jurassic to Recent crop out in the area and influence the availability of ground water. Five of the rock units are major aquifers: the Wisconsin terrace deposits, the valley-fill deposits, the Nebraskan deposits, the Dakota Sandstone, and the Cheyenne Sandstone Member of the Purgatoire Formation. The Wisconsin terrace deposits are the principal source of ground water for irrigation and municipal supplies, yielding as much as 2,000 gallons per minute; they also supply water for domestic and stock use. The valley-fill deposits supply water to domestic and stock wells and in places yield as much as 400 gallons per minute to a few irrigation wells. The Nebraskan deposits supply water to stock and domestic wells and through springs to two towns and a private water association. The Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation are the sources of artesian water for many stock and domestic wells and for some industrial, municipal, and private water-association wells. They may yield as much as 80 gallons per minute.

Ground water in the unconsolidated materials moves generally eastward over an irregular bedrock surface. The saturated zone is usually less than 40 feet thick. Along the flood plain, water is generally within 10 feet of the land surface. Contour lines on maps are used to indicate the water table, the bedrock surface, and the thickness of saturation along the Arkansas River.

Water in the Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation moves northeastward, as shown by contours on the piezometric surface.

The ground-water reservoirs are recharged by local precipitation, seepage from streams and irrigation canals, spreading of water for irrigation, and inflow. They are discharged by subsurface outflow, evapotranspiration, seepage into streams, and pumping from wells.

Additional supplies of water are attainable from all the aquifers in the project area. The Wisconsin terrace deposits are the best source of large supplies of water; however, they are so heavily developed in most of the area that some wells interfer with each other. Moderate supplies of water for irrigation can

be obtained in places from the valley-fill deposits. The rest of the unconsolidated deposits yield only small amounts of water for stock and domestic purposes. Water in the Dakota Sandstone and the Cheyenne Sandstone Member of the Purgatoire Formation is under artesian pressure and could be developed to a much greater extent.

All the ground water can be classed as sodium calcium sulfate bicarbonate in character. It is generally of fair to good quality for most uses. Water from the unconsolidated formations is rated as hard to very hard, whereas water from the two artesian aquifers is generally rated as soft to moderately hard.

INTRODUCTION

Ground water is a major natural resource in Otero and Crowley Counties. It is the only supply of domestic water for most of the residents. To develop the supply of ground water so that it is fully utilized, the origin and movement of the water and the physical properties of the water-bearing strata must be known and understood.

A study of the ground-water resources of Otero County and the southern part of Crowley County was begun in July 1959 by the U.S. Geological Survey in cooperation with the Colorado Water Conservation Board. The cooperative program is under the general administration of O. Milton Hackett, chief of the Ground Water Branch of the Geological Survey, and Felix L. Sparks, Director of the Colorado Water Conservation Board. This study was made under the direct supervision of E. A. Moulder, district engineer in charge of ground-water investigations in Colorado.

The project area is in southeastern Colorado, including all of Tps. 21–27, S. and Rs. 54–59 W.—about 1,500 square miles (fig. 1). It lies almost completely in the Colorado Piedmont section of the Great Plains physiographic province.

PREVIOUS WORK

The geology and ground-water resources of all or parts of the project area have been described by several geologists, beginning with Gilbert (1896). Darton included the area in his studies of the central Great Plains (1905) and the Arkansas River valley (1906). The western edge of the project area is described in U.S. Geological Survey folios 135 and 186 (Fisher, 1906, and Stose, 1912). In 1924, the Colorado Geological Survey published three reports (Patton, Duce, and Toepelman), in which parts of the area were discussed.

Recent studies of the geology and ground-water resources of nearby areas include Baca County (McLaughlin, 1954), and Prowers County (Voegeli and Hershey, 1962). Fieldwork for studies of Pueblo County and Bent County has been completed.

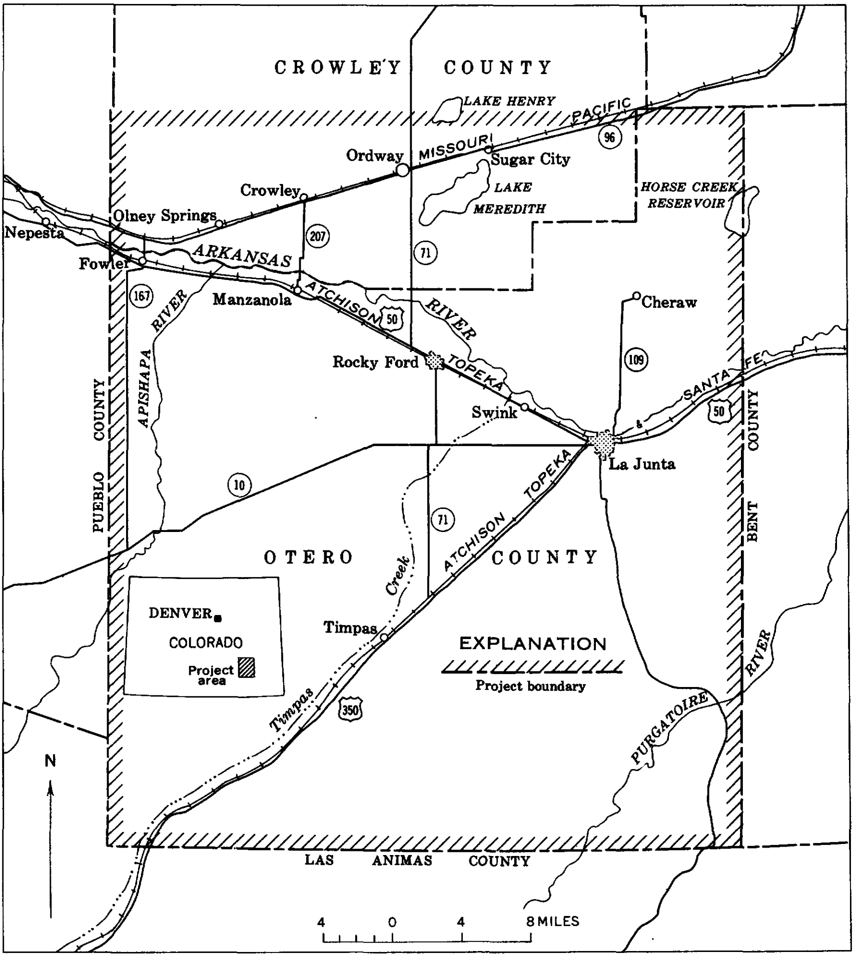


FIGURE 1.—Location of the project area and the important geographical features.

METHODS OF INVESTIGATION

Fieldwork for this report was done during the summers and falls of 1959–61. The writer was assisted by James D. Orner from July 1959 to June 1960. Records of more than 800 wells were collected, including total depth, depth to water, discharge and drawdown of large-capacity wells, and construction data (Weist, 1962). When it was not possible to measure wells in the field, the data were obtained from the well owner or the driller. Test holes were drilled in areas where aquifer information was scant. Tests were made at the sites of 23 wells to determine the water-bearing characteristics of the aquifers. Fifty-six samples of water from the various aquifers were analyzed to determine their mineral content. The geology was mapped on aerial photographs and transferred to the base map by means of a Saltzman projector.

WELL-NUMBERING SYSTEM

Wells described in this report are numbered according to their locations within the U.S. Bureau of Land Management's system of land subdivision (fig. 2). The first letter of a well number indicates the

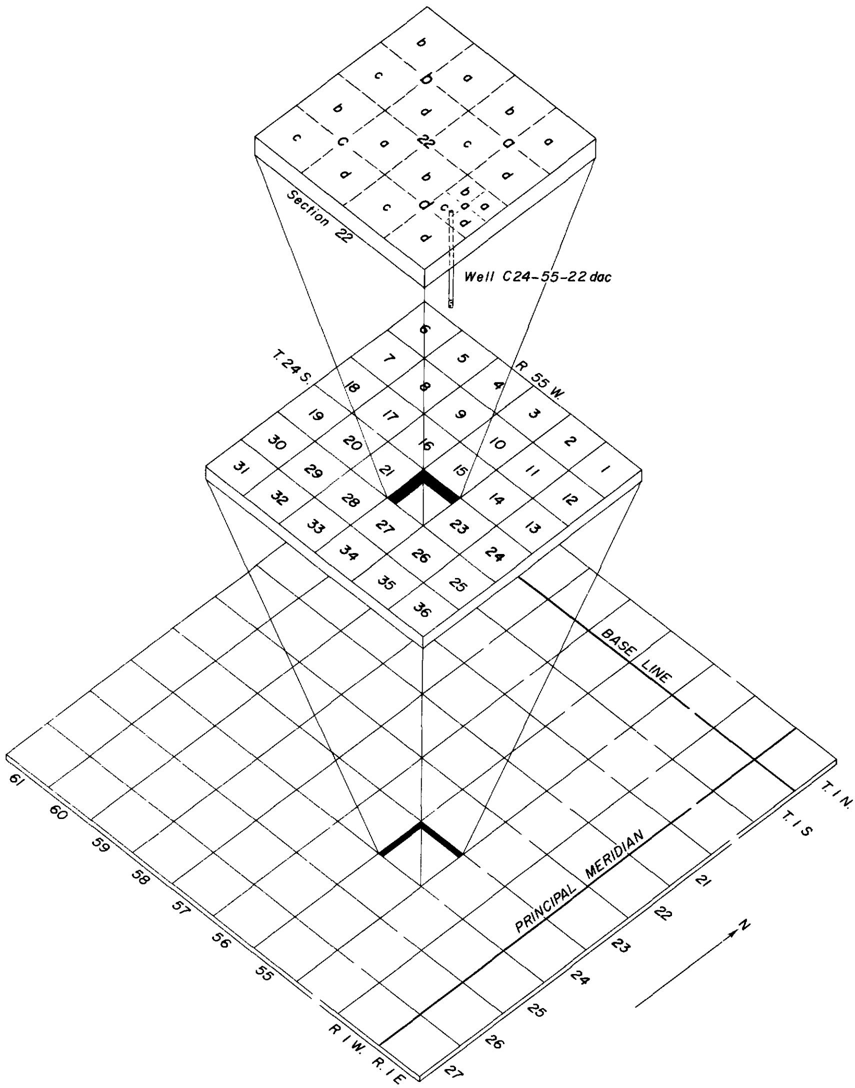


FIGURE 2.—Well-numbering system used in Colorado.

quadrant of the meridian and base-line system in which the well is located. The quadrants are identified by capital letters beginning with A in the northeast quadrant and proceeding counterclockwise. All the wells in this report are in the southwest (C) quadrant of the sixth principal meridian and base-line system. The township in which a well is located is indicated by the first numeral of the well number, the range by the second numeral, and the section by the third numeral. The lowercase letters that follow the section number indicate the position of the well within the section; the first letter indicates the quarter section, the second the quarter-quarter section, and the third the quarter-quarter-quarter section, or 10-acre tract. The letters a, b, c, and d are assigned in a counterclockwise direction, beginning in the northeast quadrant. For example, C24–55–23dac indicates a well in the southwest quarter of the northeast quarter of the southeast quarter sec. 23, T. 24 S., R. 55 W. If two or more wells are located within the same 10-acre tract, they are distinguished by numerals following the lowercase letters, starting with 2 for the second well inventoried in the 10-acre tract.

ACKNOWLEDGMENTS

The cooperation of the residents of the project area who willingly provided data on their wells is gratefully acknowledged. Special thanks are given those who permitted the use of their wells for aquifer tests. Logs of wells, test holes, and seismograph holes were obtained from the following: Folger and Son, M. P. Winp Drilling Co., Marion Hart, Henry L. Bechtold, W. C. Rains, Earl Beegles, Hunt Drilling Co., Harvey Kunau, Kenneth L. Rutt, W. H. Watson, U.S. Forest Service, and Texaco, Inc.

GEOGRAPHY

TOPOGRAPHY AND DRAINAGE

Otero and Crowley Counties lie within the Great Plains physiographic province. Part of southern Otero County is in the Raton section of this province; the rest of the project area is in the Colorado Piedmont section. The area ranges in altitude from 3,975 feet at the point where the Arkansas River enters Bent County, to 5,200 feet north of Delhi, a range of more than 1,200 feet.

Generally speaking, the project area consists of a series of flat to gently rolling surfaces with steep intervening slopes. The southeastern part of Otero County has been deeply cut by the Purgatoire River and its tributaries. The relief along the drainage in the rest of the area is generally much less.

The area is drained by the Arkansas River and its tributaries. Horse Creek is the only tributary north of the Arkansas River, and it flows into Bent County before joining the Arkansas River. South of the river, the Apishapa and Purgatoire Rivers, Timpas Creek, and Crooked Arroyo are the principal tributaries. The Arkansas is a perennial but highly regulated river; the flow of the rest of the streams depends on precipitation and return flow from irrigation. Runoff of most of these streams, as measured by the Surface Water Branch of the Geological Survey, is given in the following table:

Stream runoff

Gaging station	Area drained (sq mi)	Runoff in acre-feet				
		Average for preceding years	Calendar year			
			1945	1950	1955	[1] 1960
Arkansas River near Nepesta	9,345	[2] 516,000	490,400	326,700	360,600	353,900
Apishapa River near Fowler	1,125	[3] 37,700	30,900	25,400	54,290	14,370
Timpas Creek near Rocky Ford	451	[3] 48,200	38,980	(5)	----------	----------
Arkansas River at La Junta	12,228	[2] 211,600	153,800	70,340	160,000	80,360
Horse Creek near Sngar City	1,080	[3] 5,700	2,420	(5)	----------	----------
Arkansas River at Las Animas	14,417	[3] 377,400	152,300	57,580	136,200	64,040
Purgatoire River near Higbee	2,900	[4] 84,400	41,470	44,130	206,000	41.290

1 Records for 1960 are snbject to revision.
2 Average for 1914–44, 31 yr.
3 Average for 1941–44, 4 yr.
4 Average for 1924–44, 21 yr.
5 Measurements discontinued.

CLIMATE

Otero and Crowley Counties are semiarid. The precipitation averages 11 to 14 inches a year; the heaviest rains fall from April to September during the growing season, which averages 160 days (fig. 3).

The area along the Purgatoire River has the most precipitation; the northwestern part of the project area, the least. Mean annual precipitation, in inches, was 14.23 at Higbee weather station (about 17 miles south of La Junta), 1941–52; 12.32 at Rocky Ford, 1931–55; and 11.48 at Ordway, 1931–52.

The temperature may be as high as 107° F during the summer and as low as 30° below zero in the winter. The mean annual temperature at Rocky Ford from 1931–55 was 53.1°. The highest average monthly temperature was 77°, July, and the lowest average monthly temperature was 30.1°, January (fig. 3).

Evaporation from a standard pan 4 feet in diameter has been measured at John Martin Dam in Bent County from April through October since 1940. It ranged from an average of 5.2 inches during October to an average of 12.23 inches during July, or an average of 59.21 inches from April to October.

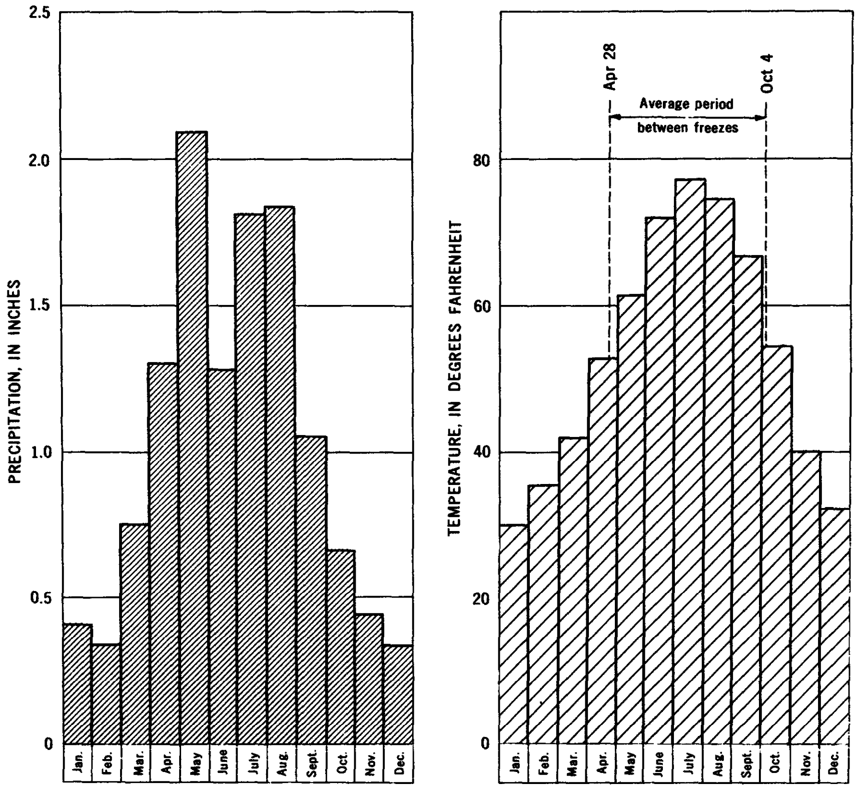


FIGURE 3.—Normal monthly precipitation and temperature at Rocky Ford.

MINERAL RESOURCES

Aside from ground water, the principal mineral resource in Otero and Crowley Counties is sand and gravel, which is quarried extensively for road construction. These deposits are found chiefly on top of mesas and ridges along the Arkansas River.

Locally, some building stone has been quarried from the Dakota Sandstone, the Greenhorn Limestone, and the Fort Hays Limestone Member of the Niobrara Formation.

POPULATION

The population of Otero County, according to the 1960 census, was 24,128, a decline of about 5 percent since 1950. La Junta, the county seat, had a population of 8,026, an increase of about 7 percent. Other towns in the county are Rocky Ford (4,929), Fowler (1,240), Manzanola (562), Swink (348), Cheraw (173), and Timpas.

The population of Crowley County was 3,978 in 1960, a decline of about 25 percent since 1950. Probably 3,500 of the inhabitants reside in the project area. Ordway, the county seat, had a population of 1,254, a decline of about 6 percent. Other towns in the county are Sugar City (409), Crowley (265), and Olney Springs (263).

AGRICULTURE

Otero and Crowley Counties depend heavily on agriculture for their economy and, consequently, are increasingly dependent on the ground-water supplies in the area. The acreage in farmland in Otero and Crowley Counties in 1961 was the greatest it has been since World War II. Most of the land is used for pasture, but the acreage planted to crops has increased considerably since 1944. The following tables show the uses to which the land has been put in the area:

Use of land in Crowley County (513,920 acres)

[Data from U.S. Dept. Agriculture]

	Acreage			
	1944	1949	1954	1959
Land in farms	417,270	420,673	403,692	424,904
Cropland	55,366	97,347	105,163	97,471
Cropland harvested	50,690	58,600	38,963	50,281
Used for pasture	1,229	6,910	13,374	11,961
Not used	3,447	31,837	52,826	35,279
Pasture	351,696	306,539	289,964	321,087
Woodland	24	676	183	----------
Acres irrigated	35,263	41,247	22,712	39,811

Use of land in Otero County (810,880 acres)

[Data from U.S. Dept. Agriculture]

	Acreage			
	1944	1949	1954	1959
Land in farms	708,806	757,953	752,378	[1] 842,944
Cropland	75,519	89,151	85,064	85,293
Cropland harvested	67,693	69,404	60,102	66,109
Used for pasture	2,857	13,508	6,339	10,238
Not used	4,969	6,239	18,623	8,946
Pasture	614,163	647,399	654,616	[1] 739,452
Woodland	7,621	5,119	1,908	1,987
Acres irrigated	71,724	73,612	52,224	66,931

[1] Includes acreage in adjacent counties whose use is regulated from headquarters in Otero County.

The principal crops grown in Otero and Crowley Counties are corn, sorghums, small grains, hay, legumes, sugar beets, and vegetables (potatoes, onions, tomatoes, and melons). The following tables show the acreage planted to various crops since 1944:

Acreage of principal crops in Crowley County

[Data from U.S. Dept. Agriculture]

Crop	1944	1949	1954	1959
Corn	14, 267	11, 621	4, 143	5, 570
Sorghums	8, 464	7, 879	8, 623	15, 146
Small grains	3, 603	15, 762	2, 377	10, 005
Hay	9, 243	13, 039	19, 203	9, 477
Legumes	6, 598	3, 776	3, 746	5, 313
Sugar beets	3, 854	3, 358	1, 853	2, 806
Alfalfa, clover, etc., for seed	----------	1, 800	2, 250	597
Vegetables	3, 962	2, 000	318	704

Acreage of principal crops in Otero County

[Data from U.S. Dept. Agriculture]

Crop	1944	1949	1954	1959
Corn	13, 543	16, 584	12, 037	15, 103
Sorghums	2, 745	1, 132	2, 566	8, 072
Small grains	11, 279	13, 632	6, 220	8, 489
Hay	22, 339	24, 012	28, 755	18, 514
Legumes	1, 974	2, 348	1, 758	2, 192
Sugar beets	5, 188	4, 446	4, 280	6, 364
Alfalfa, clover, etc., for seed	----------	3, 910	2, 723	971
Vegetables	8, 164	5, 985	3, 710	6, 043

TRANSPORTATION

The main line of the Missouri Pacific Railroad Co. runs east from Pueblo through Ordway to Kansas City. The main line of the Atchison, Topeka and Santa Fe Railway Co. splits at La Junta. One line runs southwestward through Timpas to Trinidad. The other continues westward through to Pueblo. A spur line runs from Swink to Cheraw and east to Holly.

The Continental Trailways Bus System serves communities on U.S. Highway 50 and State Highway 96. The Greyhound Bus Lines, Inc., provides bus service from Trinidad along U.S. Highway 350 to La Junta and eastward. The area is not served by commercial air transportation, although there is an airfield at La Junta.

GENERAL GEOLOGY

SUMMARY OF STRATIGRAPHY

All the rocks exposed in Otero and Crowley Counties are sedimentary, with the exception of an igneous dike in southwestern Otero County. The rocks range in age from the Late Jurassic Morrison

Formation to the Recent flood-plain deposits. The areas of outcrop of the various rocks units are shown on plate 1.

A generalized section of the geologic units exposed in the project area is given in table 1. A more detailed discussion of the geologic formations and their water-bearing properties may be found on pages 61–83.

GEOLOGIC STRUCTURE

Otero and Crowley Counties lie near the southern end of the Denver Basin, a large synclinal structure that extends northward into Wyo-

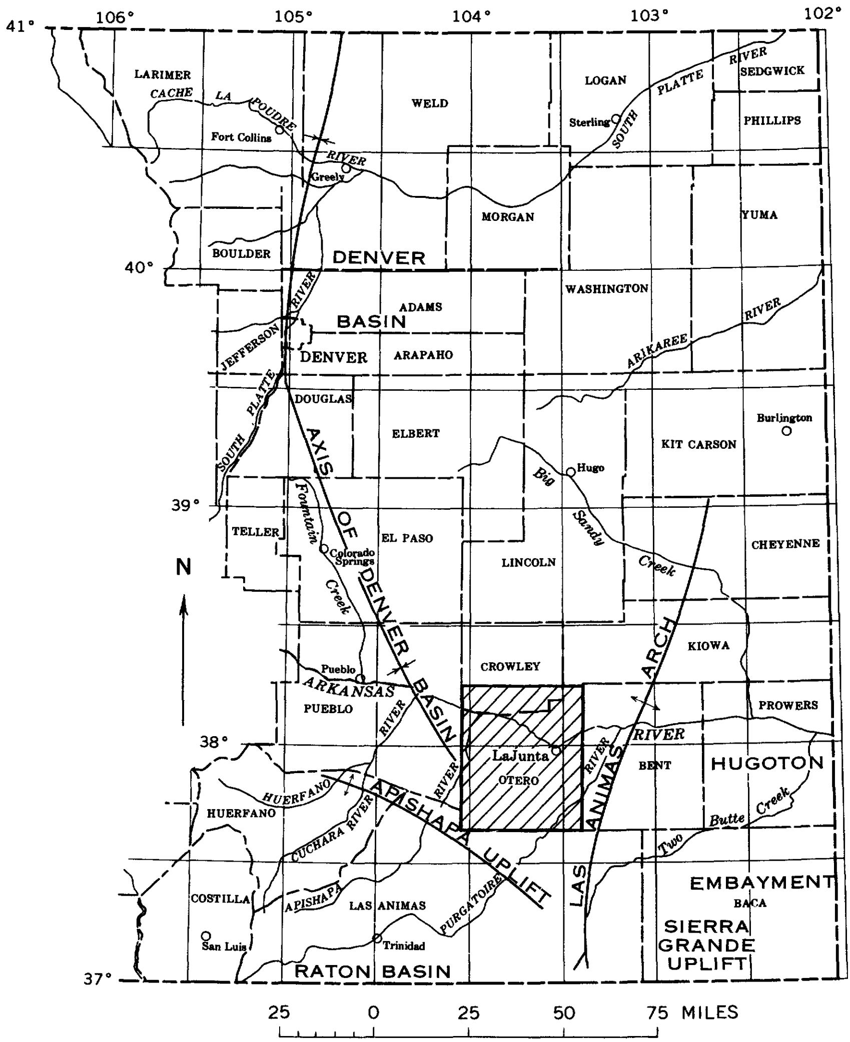
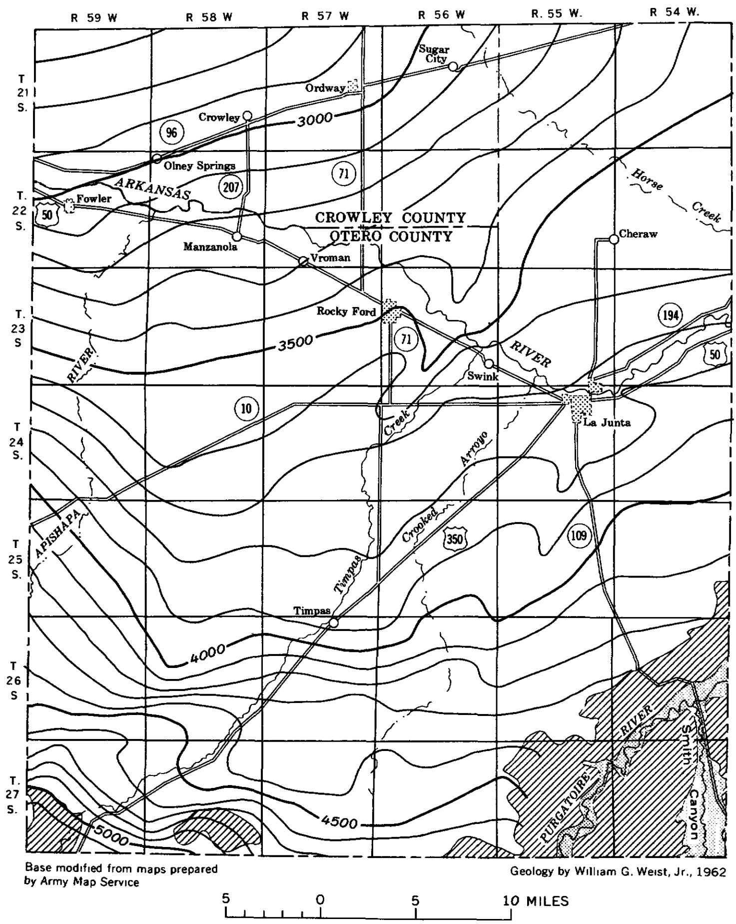


Figure 4.—Major tectonic elements in eastern Colorado.

ming. The project area is bounded on the east and southeast by the Las Animas arch and on the south and southwest by the Apishapa uplift. These regional anticlines start at the Sierra Grande uplift near the New Mexico State line (fig. 4).

These major structural features combine to give a general northward or northwestward dip to the consolidated beds throughout most of Otero and Crowley Counties. In the southwestern part of Otero



EXPLANATION

Approximate areas of outcrop of the Dakota Sandstone and the Purgatoire Formation

Approximate areas where the Dakota Sandstone and the Purgatoire Formation have been eroded away

3500

Structure contours
Drawn on the top of the Dakota Sandstone. Contour interval 100 feet Datum is mean sea level

FIGURE 5.—Structure contours in Otero County and part of Crowley County.

TABLE 1.—*Generalized section of the geologic formations*

[Work done since publication of the basic-data report (Weist, 1962) has led to changes in the terminology of the Pleistocene and Recent deposits. The term "valley-fill deposits" is now used for all undifferentiated alluvial deposits; "flood-plain deposits" replaces the term "alluvium" and is restricted. In the well tables and table of analyses under geologic source, Qal should now read Qtw]

System	Series	Formation		Member	Thickness (feet)	Physical character	Water supply
Quaternary	Recent	Dune sand			0– 45±	Very fine to very coarse poorly sorted sand.	Not known to yield water to wells.
		Valley-fill deposits	Food-plain deposits		0– 15±	Clay, silt, and sand.	Do.
	Recent and Pleistocene	Upland deposits			0– 80±	Clay and fine sand containing some gravel in places.	Generally yield small quantities of water to stock and domestic wells.
	Pleistocene	Valley-fill deposits	Wisconsin terrace deposits	Qtw_1	0– 60±	Clay, sand, gravel, cobbles, and boulders; in places, contain a hard cemented zone ½ to 5 ft thick.	Yield small to large quantities of water to wells and springs.
				Qtw_2	0– 85±		
			Illinoian terrace deposits		0– 50±	Clay, sand, gravel, and cobbles; generally contains a crossbedded cemented zone.	Yield small quantities of water to wells and springs.
		Kansan deposits			0– 30±	Clay, sand, gravel, and cobbles; contain considerable caliche.	Yield small quantities of water to springs.
		Nebraskan deposits			0–100±	Clay, sand, gravel, and some cobbles; contain considerable caliche. Generally has has a hard cemented crossbedded zone near bottom.	Yield small to moderate quantities of water to stock and domestic wells, springs and seeps.
Tertiary	Miocene(?) or Oligocene(?)	Intrusive rocks			15±	Porphyry dikes.	Yield no water to wells.
		Pierre Shale			500±	Bluish-gray to black marine shale and sandy shale containing thin limestone lenses. Selenite occurs in lower part and ironstone concretions that weather rusty brown in upper part. A few teepee buttes occur north of Olney Springs.	Not known to yield water to wells.
				Smoky Hill Marl	400–700	Soft yellowish-orange marl and dark-tan to bluish-gray shale; thin beds of limestone and bentonite.	Yields small quantities of water to wells.

Cretaceous	Upper Cretaceous	Niobrara Formation	Fort Hays Limestone	45–70	Hard blocky white to light-gray limestone beds ½ to 3 ft thick alternating with thin beds of gray shale.	Do.
		Carlile Shale	Codell Sandstone	3–12	Hard brown sandy petroliferous limestone.	Do.
			Blue Hill Shale	75±	Bluish-gray to black fissile marine shale; contains large calcareous concretions in upper part.	Not known to yield water to wells.
			Fairport Chalky Shale	75±	Tan to blue-black chalky calcareous shale; contains thin beds of limestone in lower part.	Do.
		Greenhorn Limestone	Bridge Creek Limestone	30–85	Interbedded black calcareous shale and light-gray fossiliferous limestone.	Yields small quantities of water to wells.
			Hartland Shale	10–30	Dark-gray shale; contains thin beds of bentonite.	Not known to yield water to wells.
			Lincoln Limestone	25–50	Gray thin-bedded petroliferous limestone and calcareous shale.	Yields small quantities of water to wells.
		Graneros Shale		90–200	Dark-gray to black fissile gypsiferous shale; contains zone of calcareous concretions about 40 ft below top. Alternating beds of shale and sandstone at base.	Not known to yield water to wells.
	Lower Cretaceous	Dakota Sandstone		75–140	White to brown fine-grained thin-bedded to massive sandstone; contains beds of gray to black shale.	Yields adequate quantities of water for domestic and stock wells in most of the area. In places, yields sufficient water for industrial and municipal supplies.
		Purgatoire Formation	Kiowa Shale	50–130	Yellowish-brown to black calcareous shale. In places unit is a brown fine-grained sandstone.	Not known to yield water to wells.
			Cheyenne Sandstone.	70–110	White to buff fine- to coarse-grained massive sandstone. In places, unit consists mostly of varicolored shale.	Yields adequate quantities of water for domestic and stock wells. In places, yields sufficient water for industrial and municipal supplies.
Jurassic	Upper Jurassic	Morrison Formation		125–175	Red, green, gray, and brown shale; contains thin beds of sandstone and limestone.	Sandstone may yield small quantities of water to stock and domestic wells.

County the effects of the Apishapa uplift are more pronounced, and the beds generally dip northeastward. Figure 5 shows the structure in the area by contour lines at the top of the Dakota Sandstone.

Dips are generally between 1° and 3° but locally may be as much as 36° (Patton, 1923, p. 25). Dips greater than 3° are more common south of the Arkansas River. Locally, there are abrupt changes in both the amount and direction of dip.

Small faults in the area are numerous; most of them are in the Codell Sandstone Member of the Carlile Shale and the Fort Hays Limestone Member of the Niobrara Formation. These faults are usually nearly vertical and have a displacement of less than 40 feet. Few of the faults can be traced for as much as a mile before they lose their identity in less competent beds.

Duce (1924, p. 84) defined two local structural features in southern Otero County. The first is the Ayer flexure, a small monoclinal fold just east of Ayer siding, which he described as an unclosed dome with the south end open. It has no topographic expression and appears as an inlier of Greenhorn Limestone on the geologic map (pl. 1). The other feature is the "Black Hills dome" southeast of Bloom siding. It is a small dome imposed on a monocline. Most of the dome is south of Otero County.

GEOLOGIC HISTORY

Otero and Crowley Counties are underlain by a thick sequence of sedimentary rocks, which record the geologic and geographic history of the area. Accurate interpretation of this record is difficult because most of the rocks are deeply buried. Most of the conditions under which the rocks were deposited were the same throughout eastern Colorado and adjacent areas; however, an examination of well cuttings and of the rocks where they crop out has revealed much of this record.

PALEOZOIC ERA

At the start of the Paleozoic Era most of Colorado was a broad rolling plain. A gentle downwarping of this plain allowed the sea to gradually cover the area during part of the Cambrian and Ordovician Periods and to deposit sand and limy mud before the sea withdrew. No rocks of Silurian and Devonian age have been found in the region, and probably none were deposited. During the early part of Carboniferous time, the area was invaded again, and more sand and limy mud was deposited. As the sea withdrew near the end of this period, the mountains were upwarped, and streams flowing into the shallow water deposited first coarse arkose, then fine beach sand, and finally silt and clay. By the end of the Paleozoic Era the sea had withdrawn from the region, and deposits, including some gypsum and salt, were mostly nonmarine.

MESOZOIC ERA

The early part of the Mesozoic Era was a time of erosion and deposition of continental deposits in this region. The Triassic red beds and the Jurassic Entrada and Morrison Formations were deposited under these conditions. The Cretaceous Period saw the last marine invasion of the North American interior. During this invasion the following formations were deposited: Dakota Sandstone, Graneros Shale, Greenhorn Limestone, Carlile Shale, Pierre Shale, and the Purgatoire and Niobrara Formations. The Fox Hills and Laramie Formations do not occur in this area and probably were not deposited.

The Laramide Orogeny started near the end of the Mesozoic Era and continued into the Cenozoic Era. This orogeny was the last major episode of uplift in Colorado.

CENOZOIC ERA

The early part of the Cenozoic Era was largely a time of erosion in Otero and Crowley Counties. The only unit of Tertiary age in the area is a dike in southwestern Otero County, which is probably related to the igneous activity in the Mesa de Maya region.

During Pleistocene times, streams flowing across the area deposited sand and gravel along their flood plains. The thick deposits of sand and gravel north and west of Olney Springs were laid down during the Nebraskan Glaciation, probably by streams flowing from high areas near what is now the Black Forest. Because these streams meandered over a wide area, they deposited extensive sand and gravel deposits. The present drainage pattern began to form during the Kansan Glaciation, and deposition during Kansan, Illinoian, and Wisconsin time was limited largely to the present valleys.

The period since the end of the Pleistocene has largely been one of erosion, during which much of the material deposited during the Pleistocene was removed. Some Recent deposition is indicated, however, by the silt and clay along the present flood plains. During late Pleistocene and Recent times, sand dunes formed in several places. Most of these dunes have been stabilized by vegetation, but a few areas are covered by loose sand.

THE HYDROLOGIC SETTING

Surface water and ground water are the two general sources of water for residents of Otero and Crowley Counties. The Arkansas River is the principal source of surface water, supplying water for at

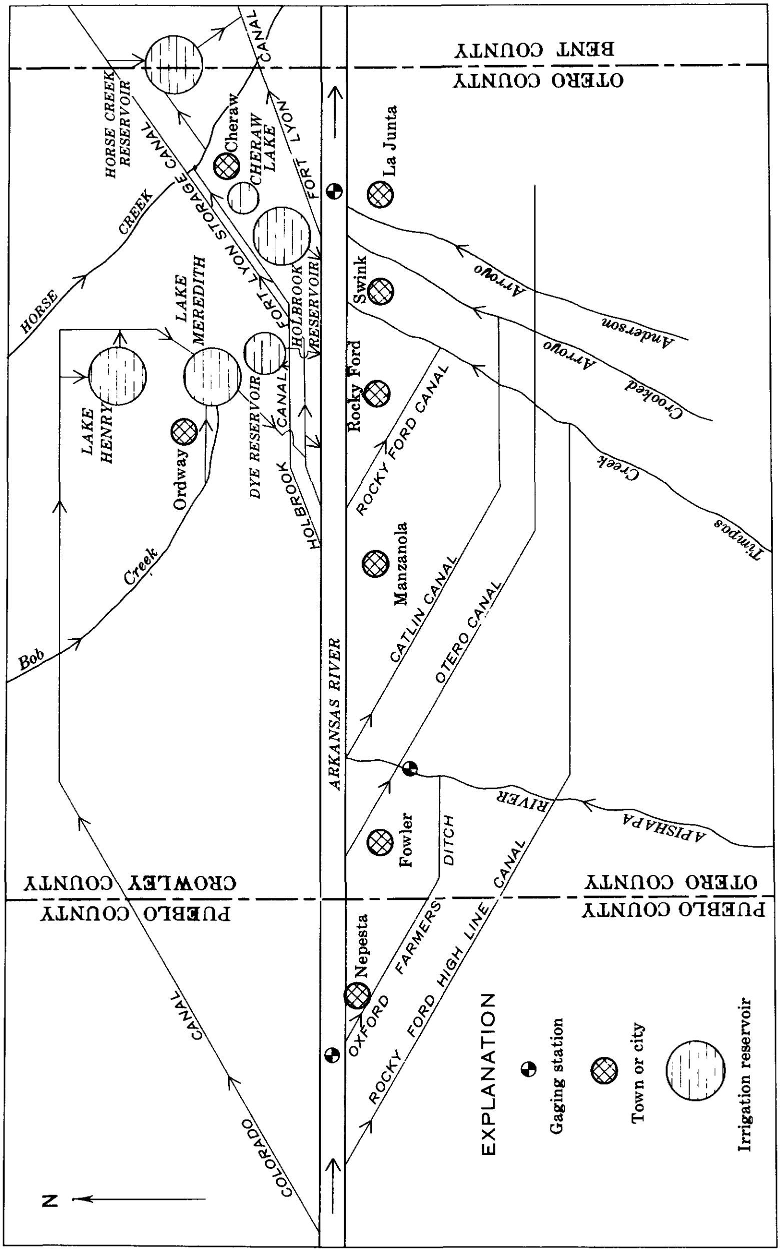


FIGURE 6.—Canals and reservoirs in the project area.

least nine canals in the area, and most of the lakes are fed by several of these canals. This system of canals and lakes is shown on figure 6.

Some surface water also enters the project area in the Apishapa and Purgatoire Rivers, Timpas, Horse, and Bob Creeks, and their tributaries. Most of these streams, however, carry water only after storms, and much of it either evaporates or seeps into the ground. The area receives an average of about 12 inches of precipitation annually. Some of this precipitation helps to fill the lakes and reservoirs, but between 9 and 10 inches is evaporated and transpired.

Fourteen rock units in the project area are known to yield water to wells and springs. These rock units, or aquifers, get their water directly from precipitation (about 2 in. per year for the shallow aquifers), from irrigation water (about 25 percent of the irrigation water reaches the water table), and from subsurface underflow.

A state of equilibrium exists between the surface water and the ground water. A heavy increase in pumping from the shallow aquifers along the streams results eventually in a decrease in underflow to the streams. A period of below-normal streamflow results in less recharge to the aquifers and a decline in the water table.

HYDROLOGY OF THE ARKANSAS RIVER VALLEY IN THE PROJECT AREA

By William G. Weist, Jr., and Edward D. Jenkins

The hydrology of the Arkansas River valley in the project area is summarized in table 2. Records of streamflow were obtained from the U.S. Geological Survey. Records of canal diversion (table 3) were obtained from the Colorado State Engineer's Office, U.S. Bureau of Reclamation, and officials of canal companies. Because of unavoidable errors in discharge measurements and incomplete data, conclusions based on the water budget should not be considered as final quantitative answers. Rather they should be regarded as indicators of order of magnitude.

The average annual recharge to the irrigated lands along the river valley from precipitation was assumed to be 0.2 foot per year. This amount of recharge is greater than for areas of dryland farming because the zone of aeration is kept moist by constant applications of water. The average annual discharge by evapotranspiration in the stream-valley lowlands (less than 5 feet to water) was determined to be 2.5 feet per acre per year. The data for the quantity of groundwater underflow through the alluvial deposits were taken from table 6.

TABLE 2.—*Summary of the hydrology along the Arkansas River valley between the Nepesta and La Junta gaging stations October 1949 to October 1960*

Depletions from the total water supply	*Acre-feet per year (rounded)*
Surface water (measured)[1]:	
Arkansas River at La Junta	124,000
Canal diversions	418,000
Ground water (computed):	
Pumpage	40,000
Outflow, Arkansas River valley at La Junta	2,000
Evapotranspiration (estimated): Stream-valley lowlands (10,000 acres at 2.5 ft per year)	25,000
Total	609,000
Accretions to total water supply	
Surface water inflow (measured):	
Arkansas River near Nepesta[1]	440,000
Apishapa River near Fowler[2]	22,000
Timpas Creek near Fowler[3]	34,000
Ground water (computed):	
Inflow, Arkansas River valley at Fowler	3,200
Inflow, Apishapa River valley near Fowler	400
Inflow, Timpas Creek valley near Swink	1,300
Inflow, Patterson Hollow	200
Direct recharge from precipitation (90,000 acres st 0.2 at per yr)	18,000
Gain between Nepesta and La Junta (36 mi): unmeasured tributary flow, ground-water seepage from canals and irrigation, and return water to the river by exchange from Lake Meredith, Holbrook Reservoir, and Dye Reservoir	89,900
Total	609,000

[1] Average.
[2] Average. Waste-water and seepage return from lands irrigated by Rocky Ford High Line. and Oxford Farmers Canals included in this record.
[3] Average discharge for 10-yr period of record (October 1940 to October 1950). Waste-water and seepage return from lands irrigated by Rocky Ford High Line, Otero, and Rocky Ford Canals included in this record.

Although it is impossible to measure the amounts of ground-water inflow and outflow, evapotranspiration, and recharge from precipitation, the computed values in table 2 are probably of the right magnitude. The difference between the amount of depletion from, and accretion to, the total water supply represents the gain or loss of water in an area. As shown in table 2, the average yearly gain along the main valley of the Arkansas between Nepesta and La Junta during the period 1949–60 was 90,000 acre-feet. Of this amount, 10,000 acre-feet per year is estimated to be unmeasured tributary flow. The remaining 80,000 acre-feet is return water from irrigation diversions. About 270,000 acre-feet per year is diverted, and about 40,000 acre-feet per year is pumped for irrigation of lands within the main valley of the area. Therefore, about 26 percent of all the water diverted for irrigation within the area (80,000÷310,000) becomes available for reuse either through seepage and return streamflow or by pumping from the valley aquifers.

TABLE 3.—*Annual flow of streams and diversions of canals from the Arkansas River, in acre-feet, October 1949–October 1960*

Water years	Colorado Canal (acres irrigated 51,000) [1]	Rocky Ford High Line Canal (acres irrigated 23,000) [2]	Nepesta gaging station, Arkansas River	Oxford Farmers Ditch (acres irrigated 5,250)	Otero Canal (acres irrigated 6,600)	Catlin Canal (acres irrigated 18,660)	Apishapa gaging station Apishapa River	Holbrook Canal (acres irrigated 16,000)	Rocky Ford Canal (acres irrigated 7,850)	Ft. Lyon Storage Canal	Ft. Lyon Canal (acres irrigated 92,000) [3]	La Junta gaging station Arkansas River
1950	64,900	69,300	355,500	32,800	12,700	88,300	27,030	22,800	53,200	7,400	223,000	80,130
1951	78,300	73,900	354,000	30,500	11,400	77,900	31,140	32,500	48,900	10,200	207,000	89,420
1952	99,300	82,900	546,300	27,600	18,700	105,100	8,900	34,700	52,300	1,200	235,000	139,200
1953	68,200	70,500	384,600	20,900	7,100	74,900	10,060	23,800	49,800	2,100	190,300	100,300
1954	39,300	50,300	232,700	12,300	5,000	47,000	10,120	17,500	48,000	1,200	108,700	55,860
1955	51,000	60,500	349,100	19,800	2,100	47,300	53,090	24,800	49,200	10,000	150,300	159,600
1956	44,300	63,000	319,300	17,600	3,100	65,600	12,140	11,300	47,100	1,800	155,000	74,010
1957	110,500	110,100	1,081,000	26,800	14,200	86,800	31,890	73,500	47,500	120,700	350,700	395,500
1958	131,900	87,900	507,500	25,000	3,500	100,800	41,150	60,700	40,900	15,300	318,400	142,200
1959	71,700	65,700	297,800	19,800	800	74,800	6,340	19,900	43,600	0	190,400	41,970
1960	106,200	68,300	416,100	21,200	5,900	76,600	14,180	42,200	43,600	8,400	224,100	84,960
Average	78,690	72,950	440,350	23,120	7,680	76,830	22,460	33,060	47,640	16,210	213,900	123,920

[1] Includes 200 acres in Pueblo County.
[2] Includes 2,000 acres in Pueblo County.
[3] Includes 86,000 acres east of the project area, 6,000 acres within the project area.

THE GROUND-WATER SYSTEMS

Ground water in Otero and the southern part of Crowley Counties is largely either confined or unconfined, but in places it is semiconfined.

ARTESIAN CONDITIONS

Water in an aquifer that is overlain by a relatively impermeable bed is under pressure and will rise above the top of the aquifer if it is tapped by a well. Such water is called artesian water. If the pressure is great enough, the water flows at the land surface, and the well is termed a flowing well. The imaginary surface to which the water will rise under artesian pressure is called the piezometric surface.

Some of the rock units in Otero and Crowley Counties contain beds of relatively permeable sandstone that alternate with beds of relatively impermeable shale. The beds dip generally northward, so that water entering the more permeable beds in their areas of outcrop to the south and west moves downdip between the confining layers of shale and saturates the sandstone. Under these conditions the water in the sandstone is under artesian pressure.

The principal artesian aquifers in the area are the Cheyenne Sandstone Member of the Purgatoire Formation and the Dakota Sandstone. The Cheyenne is underlain by the relatively impermeable siltstone and shale of the Morrison Formation and overlain by the Kiowa Shale Member of the Purgatoire Formation. The Dakota overlies the Kiowa and is overlain in turn by the Graneros Shale. Water in these two aquifers is under artesian pressure everywhere in the area except in part of southeastern Otero County, where the aquifers have been eroded away, and in areas where they crop out along the Purgatoire River and its tributaries. In these last areas the Dakota may contain little or no water, although the Cheyenne is saturated. The configuration of the piezometric surface, as determined from wells tapping the Dakota, is shown in figure 7. The hydraulic gradient is much steeper in the southwestern part of the project area (about 50 ft per mile) than it is in the northeastern part (about 8.3 ft per mile). In general, the ground water moves northeastward, perpendicular to the structure shown in figure 5.

WATER-TABLE CONDITIONS

The water table is an irregular sloping surface, which conforms roughly to the land surface and which marks the upper limit of water that is available to wells. In some places, lenses of clay or tightly cemented sand and gravel confine the zone of saturation and thus produce a slight artesian effect; however, this effect is negligible in the project area.

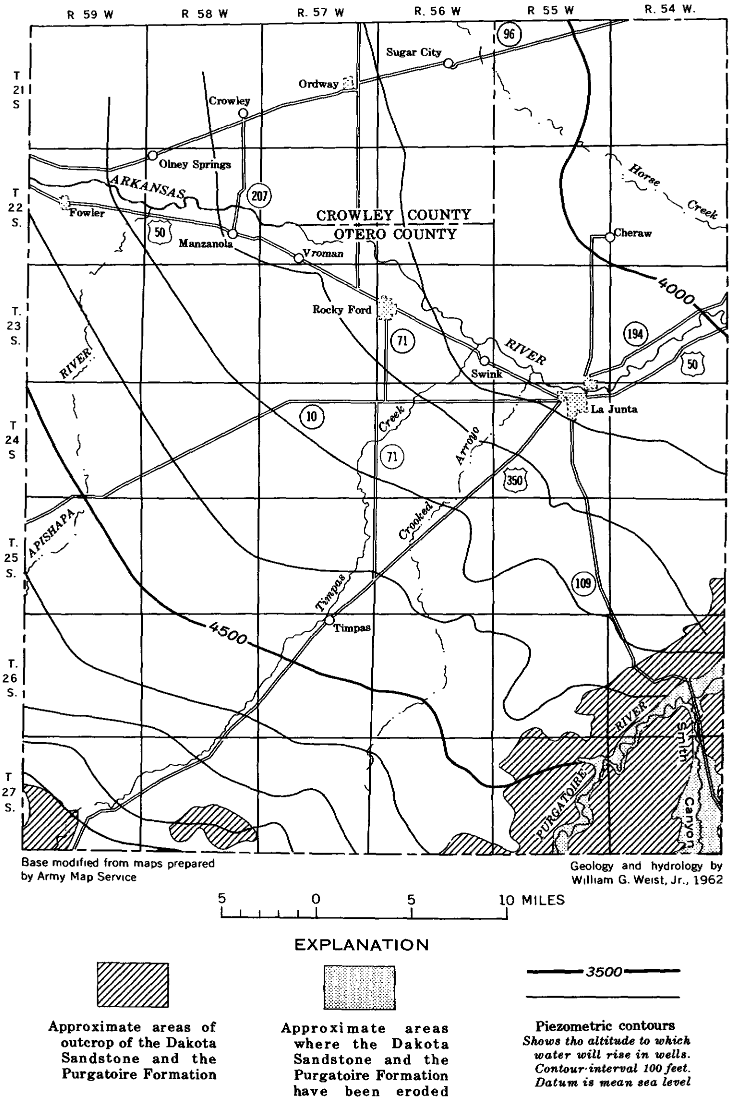


FIGURE 7.—Piezometric surface in the Dakota Sandstone in Otero County and part of Crowley County, 1962.

Most of the water-table wells are in four areas: (1) the Arkansas River valley and its tributaries, notably Timpas Creek, (2) the valley around Cheraw, (3) an area extending from Olney Springs east to Sugar City, and (4) on top of the Nebraskan deposits west of Olney Springs. Plate 2 shows the configuration of the water table based on measurements made in April 1960. In the last three areas, it was necessary to use some measurements made at other times during the fieldwork, but the water table probably does not fluctuate enough in these areas to affect the configuration of the contour lines appreciably.

Although water-table wells are scattered throughout the rest of the project area, the water table is probably discontinuous throughout much of the upland, and information is insufficient to prepare contour lines. In general, however, the water table slopes toward, and downstream along, the Arkansas River, and ground water moves toward the river.

The configuration of the water table reflects changes in the bedrock surface and in the saturated thickness and permeability of the water-bearing deposits. A higher bedrock surface or a decrease in saturated thickness or in permeability restricts the flow of ground water and thus causes an increase in the hydraulic gradient so that the flow is accommodated. This increase in hydraulic gradient is reflected on the map by more closely spaced contour lines.

Ground water in the Arkansas River valley and its tributaries moves from the sides of the valleys toward the river in a downstream direction. On the map, the upstream flexures of the contour lines indicate that the aquifers are being recharged near their edges, probably from the irrigation canals, and are discharging into the streams. The closer spacing of the contour lines along most of the southern side indicates a steeper hydraulic gradient, which is probably caused by a thinner saturated zone due to a higher bedrock surface. Along the Arkansas River flood plain, the water table has a gradient of about 9 feet per mile. This gradient steepens away from the river.

Ground water in the valley around Cheraw generally moves northeastward to Horse Creek and then flows southeastward into Bent County and the Arkansas Valley. On the map, the closed contour lines in the immediate vicinity of Cheraw Lake indicate a water-table lake.

Ground water in the Olney Springs-Sugar City area flows generally southeastward. The western part of this area is probably hydrologically connected with the Arkansas River valley, and the ground water as far east as Manzanola flows into the Arkansas River valley. East of Manzanola, however, the two areas are separated by bedrock highs, and the ground water seems to flow into Lake Meredith. In the Sugar City area most of the ground water flows into Horse Creek. The slight upstream flexures in the vicinity of Bob Creek, near Crowley, probably indicate some discharge from the aquifer to the creek. The stronger flexures west of Crowley are probably caused by pumping from several irrigation wells. The gradient here is 25 to 30 feet per mile.

Ground water in the Nebraskan deposits flows generally southwestward, although a small component in the eastern part flows southeastward, supplying the discharge of springs along the eastern edge of the terrace. The hydrologic gradient in these deposits ranges from less than 10 to about 50 feet per mile.

Depth to water is related to topography and is generally least in the low-lying areas. Depth to water in the valleys of the Arkansas River and its tributaries is generally less than 30 feet. Where the depth to water is less than 5 feet, the land is likely to be waterlogged, and considerable amounts of ground water is evaporated and transpired.

HYDRAULIC PROPERTIES OF THE WATER-BEARING MATERIALS

By Edward D. Jenkins

AQUIFER TESTS

Hydraulic properties of the principal aquifers were determined at 23 test sites. During the tests, the wells were pumped at a nearly uniform rate for several hours or days. The discharge of the wells and the depths to water were measured periodically during the pumping. Observation wells were measured during some of the tests to determine the drawdown at different distances from the pumping well. For some tests, water levels were measured periodically after the pump was turned off to determine the rate of recovery of the water table.

From the data gathered during the tests, the coefficients of transmissibility and storage were computed by the Theis nonequilibrium formula (Theis, 1935), the modified nonequilibrium formula described by Jacob (1947) and Cooper and Jacob (1946), and the Thiem equilibrium formula. The derivation of the general Thiem formula was discussed by Wenzel (1942, p. 81), and a graphic method for solving the Thiem formula was described by Jacob (1944). The coefficient of storage also was computed by dividing the volume of water pumped by the volume of the cone of depression.

The apparent coefficient of storage of an unconfined aquifer increases with duration of pumping: rapidly at first, and then more and more slowly until the true coefficient of storage is approached. The length of pumping time necessary to obtain a reasonable approximation of the coefficient of storage is governed by the time required to completely drain the sediments within the cone of depression. Many days or weeks of pumping may be required for fine-grained sediments to become largely drained, whereas only a few hours of pumping may be needed for very coarse-grained sediments. The true coefficient of storage can be estimated from the projection of a curve where the apparent coefficient of storage has been plotted against time.

The specific capacity of a well is its rate of yield per unit of drawdown and is generally determined by dividing the yield, in gallons per minute, by the drawdown, in feet. It is a function of factors other than transmissibility. These factors include coefficient of storage, duration of pumping, the diameter of the well, how far the well penetrates the aquifer, the effectiveness of the casing perforations or well screens, the extent and effectiveness of well development, and the distance of the well from nearby wells that are being pumped. Under water-table conditions, the specific capacity of even a fully developed well is nearly constant only when the drawdown is a small fraction of the saturated thickness of the aquifer. In general, high specific capacity indicates high transmissibility, and low specific capacity indicates low transmissibility. According to a method developed by Theis and others (1954), as used by Back (1957, p. 4–6, 30–32), transmissibility can be estimated by multiplying the specific capacity, in gallons per minute per foot of drawdown, by 2,000.

The results of the aquifer tests made in the project area are given in table 4.

The coefficients of transmissibility ranged from 15,000 to 200,000 gpd (gallons per day) per ft for the unconsolidated deposits and from 110 to 800 gpd per ft for the consolidated Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation. Fractured Fort Hays Limestone Member of the Niobrara Formation had a coefficient of transmissibility of 10,000 gpd per ft at one site. A wide range in transmissibility of the unconsolidated deposits is to be expected because the deposits differ widely in saturated thickness and in size, shape, and degree of interconnection of interstices. The sandstone consists of cemented fine-grained sand, which has a low permeability. The field coefficients of permeability for the saturated unconsolidated deposits ranged from 520 to 8,900 gpd per sq ft, but were from less than 1 to 8 gpd per sq ft for the consolidated Dakota and Cheyenne. Fractured Fort Hays had a coefficient of permeability of 330 gpd per sq ft at one site.

The apparent coefficient of storage of the unconsolidated water-table aquifers, as determined in seven of the tests, ranged from 0.03 to 0.17. The coefficient of storage for the artesian aquifers in the sandstone, as determined from one test, was 0.0001. The coefficient of storage for the semiconfined aquifer of the Fort Hays was 0.009.

The apparent coefficients of storage for the unconsolidated deposits are probably conservative for the following reasons: (1) The water may be semiconfined in some areas by extensive layers of material

TABLE 4.—*Summary of the results of aquifer tests*

[Principal aquifer: Kpc, Cheyenne Sandstone Member of the Purgatoire Formation; Kd, Dakota Sandstone; Knf, Fort Hays Limestone Member of the Niobrara Formation; Qtw, Wisconsin terrace]

Location	Owner or user	Principal aquifer	Depth of well (feet)	Total saturated thickness (feet)	Distance to water level below or above (+) land surface (feet)	Average pumping rate (gpm)	Drawdown (feet)	Specific capacity (gpm per ft of drawdown)	Duration of pumping (hours)	Coefficient of transmissibility (gpd per ft)	Coefficient of permeability of entire aquifer (gpd per sq ft)	Apparent coefficient of storage	Apparent radius of influence (feet)	Temperature (°F)	Specific conductance in micromhos at 25°C (field determination)	Kilowatt-hours per acre-foot of water	Date of test
C21-56- 2bdb	F. Hagan	Qvf	28.7	20	8.5	440	10	44	4	30,000	1,500				6,300	53	9-27-60
C21-58-22aab	L. Kiefer	Qvf	32.2	21	11.3	420	9	47	3	50,000	2,400			60	2,300	47	9-26-60
22daa	W. Bronner	Qvf	28.7	18	10.2	160	6	27	3	30,000	1,700			58	2,100	85	9-27-60
27daa	F. Tanabe	Qvf	41.0	29	11.8	120	17	7	25	15,000	520	0.15	170	58	3,000	167	9-26-60
C22-54-17ddd	O. Bay	Qvf	46.4	20	30.1	300	7	43	96	50,000	2,500	.13	900	57	2,700	90	8-26-60
C22-58-28cac	The Valley Water Co.	Kd, Kpc	1,506	220	85	40	198	.20	48	120	.5			82			2-10-62
C22-59- 7daa	E. Jensen	Qtw	35.3	24	10.8	430	8	54	33	120,000	5,000	.12	800	55	3,700	106	9-25-60
16acb	C. Stauder	Qtw	39.8	29	11.2	940	19	49	28	160,000	5,500			56	2,200	69	9-15-60
16dcc	do	Qtw	30.6	9	21.3	310	8	39	10	80,000	8,900	.16	300	57	2,400	71	9-16-60
C23-54-13bac	J. Dutton	Qtw	32	19	9.8	490	17	29	16	80,000	4,200			58	2,400		8- 3-60
20aac	Bent's Fort Water Co.	Kd, Kpc	[1] 800	227	69.0	75	550	.14	25	110	.5			70			3- 4-61
29daa	J. Dutton	Qtw	32.4	24	8.3	730	12	61	23	90,000	3,800			56	3,300	57	8- 4-60
30cdd	W. Glasco	Qtw	34.5	23	11.0	620	7	89	10	200,000	8,700	.11	600	56	3,600	50	8- 3-60
C23-55-30bcc	Western Alfalfa Co.	Qtw	34.0	28	6.1	670	15	45	94	120,000	4,300	[2] .17	1,700	56	3,500		9- 9-60
33bad	A. Bair	Qtw	36.1	31	7.2	690	16	43	5	100,000	3,200		500	55	1,700	52	8- 6-60
36bbc	Bent'sFort Water Co.	Kd, Kpc	820	202	91	47	488	.10	24	150	.7	.0001		57	2,000	89	8- 8-60
36bda	Wunsch Bros	Qtw	40.2	16	24.0	760	10	76	12	140,000	8,800			57	2,000	89	8- 8-60
C23-56- 8ddc	D. Reynolds	Qtw	32.2	18	13.7	400	11	36	25	50,000	2,800			57	2,800	59	9- 1-60
C23-57- 2ddc	W. Woodside	Qtw	34.7	12	22.6	200	7.5	27	48	50,000	4,200			56	2,200	100	8-30-60
C24-56- 4cdc	B. Malott	Qvf	41.7	20	21.0	500	13	38	5	80,000	4,000			55	2,200	70	8-10-60
12abb	C. Lusk	Knf	41	30	10.6	125	19	7	69	10,000	330	.009	2,500	54	4,200	63	8-26-60
18acb	W. Caldwell	Qvf	47.4	20	27.4	700	13	54	20	110,000	5,500	.03	1,200	55	3,200	96	9-12-60
C24-58-19abd	Arnold-Harriman Co., Inc.	Kd, Kpc	[3] 1,131	102	+84	9.4	84	.11	3	800	8			77	1,200		9-28-60

[1] Casing perforated 450 to 800 ft.
[2] Coefficient of storage projected for 20 days may exceed 0.25.
[3] Casing perforated 1,110 to 1,130 ft.

having a comparatively low permeability, and the tests in these areas were not long enough for the water level to decline below the confining layer; (2) because of a variety of physical limitations, it was not possible to pump many wells long enough to allow the cone of depression to become largely drained.

The test at the site of well C23–55–30bcc lasted 94 hours, and water-level measurements were made in eight observation wells. Discharge from the pump was piped more than a quarter of a mile away from the well so that recharge effects were minimized. The apparent coefficient of storage was computed by dividing the volume of water pumped by the volume of the cone of depression and by the Theis and the Thiem formulas. As shown on figure 8, the apparent coefficient of storage increased from 0.08 after 5 hours of pumping to 0.17 after 4 days of pumping. By projection, the coefficient of storage after 20 days of pumping may exceed 0.25. The results of this test together with other tests indicate that the coefficient of storage of the unconsolidated deposits probably exceeds 0.20, but 0.20 is used in computations throughout the report.

The relation between the specific capacity of wells (for the length of test) and the coefficient of transmissibility was studied. Data from 19 aquifer tests were used to construct a curve (fig. 9) showing this

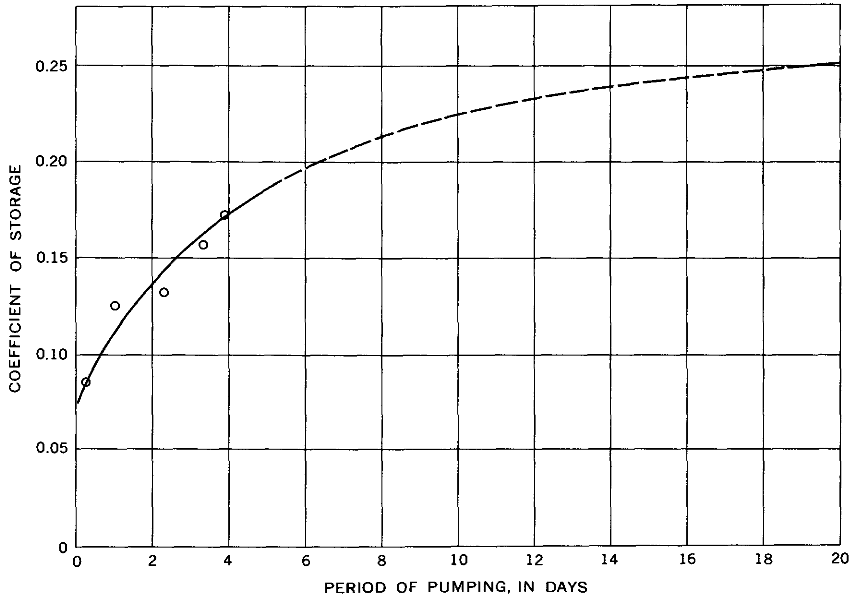


FIGURE 8.—Increase in coefficient of storage with duration of pumping from well C23–55–30bcc.

relation. The scatter of the data on figure 9 can be attributed to changes in the ratio of the drawdown to the total saturated thickness, duration of pumping, screen efficiency, and the effectiveness of well development. The Theis and Thiem formulas indicate that the specific capacity is directly proportional to the coefficient of transmissibility. The graph showing the relation is, therefore, a straight line. The slope of the line in figure 9 was computed, and the equation was found to be

$$T=1{,}920C,$$

where

T=coefficient of transmissibility
C=specific capacity

A pumping period of about 12 hours is suggested for general use with the equation.

Data for the calculation of specific capacity were obtained for several wells. The coefficient of transmissibility of the aquifer in the vicinity of a well can be estimated from the curve or the equation. The curve in figure 9 and the preceding equation indicate that a well having a specific capacity of 50 taps an aquifer having a coefficient of transmissibility of about 100,000 gpd per ft. High coefficients of transmissibility generally indicate deposits of sand and gravel in buried river channels; low coefficients of transmissibility generally indicate thin deposits of sand and gravel interbedded with silt and

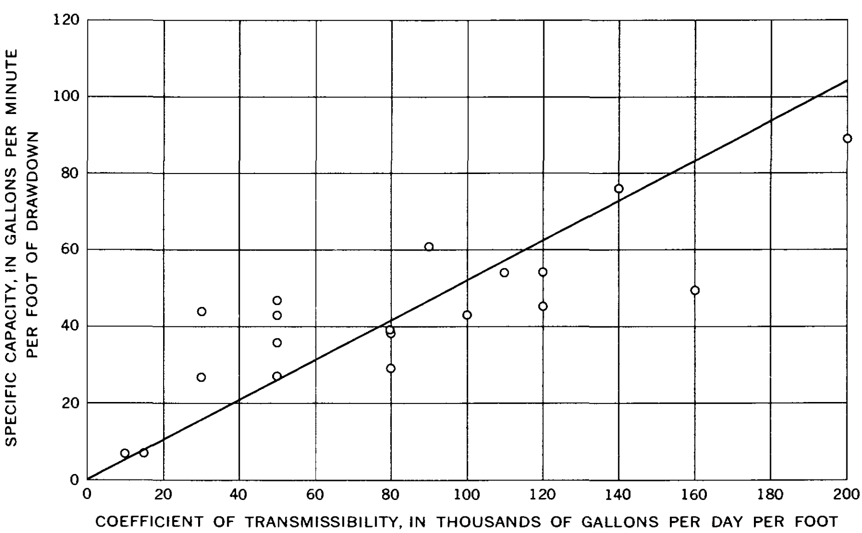


FIGURE 9.—Relation of specific capacity of wells tapping the unconsolidate deposits to transmissibility of the unconsolidated deposits in the vicinity of the wells.

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clay. The large-producing wells, naturally, are in the areas of high transmissibility.

The apparent radius of influence of a pumping well is defined in this report as the farthest distance at which a drawdown of 0.1 foot can be measured on the cone of depression. During testing, this distance ranged from 170 to 2,500 feet, but would vary in any given test with the rate and duration of pumping, the permeability, and the coefficient of storage. When a well is pumped, the water level is lowered in and near the well and takes the form of an inverted cone, which is called the cone of depression. This situation causes water to flow into the well from all directions. If wells are located too closely, their cones of depression overlap—a condition causing a lowering of the water level, greater pumping lifts, and reduction in yield. Cones of depression continue to increase in size with continued pumping: rapidly at first and then more slowly. They diminish in size after pumping has stopped. In the project area, irrigation wells that are spaced 1,000 feet apart would interfere little with one another because of intermittent pumping. Wells used for other purposes and pumped continuously for months could have a noticeable effect on one another if spaced within 1,000 feet.

The power consumption for most of the large-capacity electrically powered wells was measured by timing the electric watt-hour meters with a stop watch. An average of about 80 kilowatt hours of energy was required to lift 1 acre-foot of water to the land surface. The average pumping lift was 26 feet; therefore, an average of 3 kilowatt hours of energy was required to lift 1 acre-foot of water 1 foot. These values can be used to make estimates of pumpage where the wells are powered by electricity, as shown by the following formulas:

$$\text{Acre-feet pumped} = \frac{\text{kilowatt hours}}{80}$$

or

$$\text{Acre-feet pumped} = \frac{\text{kilowatt hours}}{3 \times \text{pumping lift}}.$$

LABORATORY TESTS

The results of laboratory tests of 22 samples of water-bearing materials from the unconsolidated deposits are shown in table 5. These results are somewhat misleading because of the difficulty in reconstructing the sample in the laboratory as it was in the field. The packing and sorting was changed, the coarsest material was not recovered in many samples, and some drilling mud may have been in the samples at the time of the tests. The specific yield of these samples ranged from 14.1 to 32.1 percent and averaged 25.1 percent, the specific

TABLE 5.—*Summary of laboratory-analysis data*

[Analyses by the Hydrol. Lab. of the U.S. Geol. Survey, Denver, Colo.]

Geologic source: Qn, Nebraskan deposits; Qtw, Wisconsin terrace deposits; Qvf, valley-fill deposits.
Specific retention: The ratio of the volume of water retained after a saturated rock has been drained by gravity to the bulk volume of the rock.
Porosity: Ratio of the aggregate volume of the voids in a rock or soil to its bulk volume.
Specific yield: The ratio of the volume of water in a saturated rock that will drain by gravity to the bulk volume of the rock. Porosity minus specific retention equals specific yield.
Coefficient of permeability: Amount of water that will flow through a unit cross section of material in a unit of time under a unit hydraulic gradient at a given temperature. The tabulated values are for a temperature of 60°F.

Location	Depth (feet)	Geologic source	Size of grain (percent by weight)											Specific retention (percent)	Porosity	Specific yield	Coefficient of permeability
			Clay and silt sizes (millimeter less than 0.0625)	Sand sizes (millimeters)					Gravel sizes (millimeters)								
				Very fine (0.0625–0.125)	Fine (0.125 0.25)	Medium (0.25–0.5)	Coarse (0.5–1.0)	Very coarse (1.0–2.0)	Very fine (2.0–4.0)	Fine (4.0 8.0)	Medium (8.0–16.0)	Coarse (16.0–32.0)	Very coarse (32.0–64.0)				
C21-58-36ccc	22- 54.5	Qvf	8.2	1.0	2.7	4.7	14.8	24.0	27.8	11.3	3.0	2.5	--------	7.51	36.2	28.7	150
C21-60-25aaa	27- 54	Qn	.6	.3	.6	1.9	4.6	12.6	25.1	37.6	16.7	--------	--------	5.26	33.8	28.0	1,360
C22-57-26dad	11- 38.5	Qtw	1.2	.1	.5	4.0	10.5	13.7	23.4	37.2	9.4	--------	--------	8.51	33.1	24.6	700
36bbb	11- 42.5	Qtw	.0	.1	.3	3.0	12.3	15.4	19.7	15.7	33.5	--------	--------	2.05	28.2	26.1	1,600
C22-58-23dbb	--------	Qtw	2.0	.8	2.3	5.8	8.5	17.4	40.0	21.6	1.6	--------	--------	7.62	35.4	27.8	300
C22-59-34caa	35- 46	Qvf	5.7	1.5	3.7	5.3	3.3	2.6	6.2	26.0	39.5	6.2	--------	14.42	29.7	15.3	25
C23-54-13add	3- 19	Qtw	.9	.4	1.6	11.6	21.0	22.3	25.1	13.2	3.9	--------	--------	5.09	32.2	27.1	1,300
20add	30- 55	Qtw	.3	.0	.2	1.0	4.8	9.1	14.7	21.5	46.5	1.9	--------	3.29	29.8	26.5	7,800
28cbc	15- 34	Qtw	1.1	.1	.3	1.9	9.8	24.0	20.2	33.7	8.9	--------	--------	4.31	31.6	27.3	1,950
29aaa	13- 44	Qtw	1.8	.3	1.0	5.9	22.9	29.5	33.9	4.5	.2	--------	--------	6.44	33.6	27.2	1,080
C23-56-11bcc	16- 29	Qvf	6.1	1.9	4.1	16.1	31.0	16.5	15.5	7.3	1.5	--------	--------	8.09	31.2	23.1	185
16dda	10½- 28	Qtw	2.9	.6	1.2	9.5	19.9	30.0	24.9	8.0	3.0	--------	--------	7.29	35.2	27.9	980
21daa	10- 43	Qtw	.5	.3	.7	3.2	12.5	24.5	32.0	23.1	3.2	--------	--------	4.89	32.6	27.7	1,920
22dba	6- 42	Qtw	1.2	.3	1.4	6.9	9.3	29.9	24.9	12.3	11.2	2.6	--------	7.79	32.6	24.8	2,120
24cdd	19-425	Qtw	1.0	.4	.9	7.7	22.7	30.9	32.1	4.3	--------	--------	--------	6.37	38.5	32.1	230
26ccc	29- 45	Qtw	4.9	.7	1.4	3.4	10.3	17.5	28.8	22.1	8.7	2.2	--------	10.22	30.7	20.5	700
36acb	31- 53	Qtw	.5	.1	.2	.0	5.6	16.7	30.0	33.6	12.4	--------	--------	3.72	33.5	29.8	2,120
C23-57- 2aaa	0- 34	Qtw	1.4	.5	2.4	11.0	16.9	23.3	29.3	15.0	.2	--------	--------	6.16	31.9	25.7	630
11add	27- 37	Qtw	6.5	.8	2.5	9.0	17.4	20.0	22.0	16.2	5.6	--------	--------	9.10	32.2	23.1	170
C24-55- 2aab	5- 34	Qtw	1.1	.4	1.8	7.2	15.9	32.5	34.1	6.1	.9	--------	--------	4.65	32.7	28.0	2,320
C24-56- 5cdd	15½- 41	Qvf	4.5	1.0	4.0	14.2	11.7	5.9	10.4	21.3	19.5	7.5	--------	10.32	24.4	14.1	50
8aaa	23- 36	Qvf	3.4	.3	.6	1.2	2.0	3.3	11.4	33.2	43.3	1.3	--------	18.19	34.1	15.9	500

retention ranged from 2.05 to 18.19 percent and averaged 7.3 percent, the porosity ranged from 24.4 to 38.5 percent and averaged 32.4 percent, and the coefficients of permeability ranged from 25 to 7,800 gpd per sq ft and averaged 1,280 gpd per sq ft.

A comparison of the field and laboratory determinations is as follows:

	Field determinations	Laboratory determinations
Number of determinations	18	22
Coefficient of permeability (gpd per sq ft)	520–8, 900	25–7, 800
Average do	4, 300	1, 280
Coefficient of storage	0. 03–0. 17	0. 14–0. 32
Average	. 12	. 25

The difference in averages is due not only to the difference in condition of the samples in the laboratory but also to the fact that the samples were collected from areas different from those where the field tests were made.

In addition to the hydrologic properties mentioned, the particle-size distribution of the samples was determined in the laboratory. These results are given in table 5, and some are shown graphically in figures 24, 26, and 27. The distribution of the grain sizes, or sorting, is a good indication of permeability. In general, the better sorted material has the higher permeability. When a sample has a wide range of grain sizes, the finer material partly fills the voids between the coarser material, thus blocking off some of the flow of water. For example, the sample from test hole C23–54–20add consisted of nearly 94 percent gravel and very coarse sand and only 0.3 percent silt. Its coefficient of permeability was 7,800 gpd per sq ft. In contrast, the sample from test hole C22–59–34caa consisted of about 80 percent gravel and very coarse sand and of about 6 percent silt, and its coefficient of permeability was only 25 gpd per sq ft.

UNDERFLOW

Estimates of the underflow at several places along the Arkansas River valley and its tributaries were made by use of the modified form of Darcy's Law, which may be written as:

$$Q=PIA\ (\cos\alpha).$$

in which

Q=quantity of water passing through the cross section, in gallons per day;

P=coefficient of permeability, in gallons per day per square foot;

I = hydraulic gradient of the water table, in feet per mile;
A = area of cross section, in mile feet (width, in miles, times thickness, in feet); and
α = angle between the given cross section and a cross section oriented normal to the valley.

The coefficient of permeability was determined by means of aquifer tests (table 4) near the selected cross section; the hydraulic gradient and the angles were determined from plate 2, and the areas were determined from the sections shown on plate 3.

The rates of underflow in the alluvial deposits are given in table 6. The underflow along the Arkansas River valley ranged from 1,010 to 3,250 acre-feet per year, and that along the tributary valleys ranged from 190 to 1,340.

Calculations based on field and laboratory measurements of hydrologic properties indicate that water moves downstream through the alluvial deposits of the main valley at about 5 feet per day, or about one-third mile per year. This figure represents an average value; actual values may vary somewhat in local areas where gradients are different from the average gradient of 9 feet per mile.

QUANTITY OF GROUND WATER AVAILABLE FOR WITHDRAWAL

A large amount of ground water is stored in the unconsolidated deposits of the project area. The approximate quantity of ground water available for withdrawal from these deposits was determined by multiplying the volume of saturated material by a coefficient of storage of 0.20. The volume of saturated material was determined from the saturated thickness map (pl. 5). Not all the ground water could be removed immediately by pumping under ideal conditions; a considerable amount would remain in the aquifer between cones of depression. Given enough time, however, this water would move downgradient along the surface of the bedrock to deeper channels in the bedrock, where most of it would become available to the more advantageously located wells. The quantity of ground water represented by each foot of rise or decline of the water table was estimated and is shown in the following table together with the estimated quantity of ground water available for withdrawal. The quantity of ground water that could theoretically be removed by pumping from the unconsolidated deposits is equal to the quantity of water in a surface reservoir 1⅕ times the size of John Martin reservoir, which has a capacity of 645,500 acre-feet.

Although more ground water can be pumped from the valley-fill deposits, additional study is needed to evaluate the effect on surface-

TABLE 6.—*Rate of underflow*

Line of section shown on pl. 3	Valley	Pf (field coefficient of permeability, gpd per sq ft)	I (gradient, feet per mile)
	Arkansas Valley:		
A–A′	Fowler	6,000	10
D–D′	Manzanola	5,000	10
E–E′	Rocky Ford	4,000	10
F–F′	Swink	4,500	10
J–J′	La Junta	6,000	8
K–K′	Casa siding	6,000	8
L–L′	Hadley siding	5,000	8
B–B′	Apishapa River near Fowler	2,000	15
M–M′	Patterson Hollow	500	17
	Timpas Creek:		
G–G′	Near Swink	4,000	15
N–N′	Near Hawley	4,500	15

water appropriators. An increase in ground-water pumpage will reduce the flow of the Arkansas River in some areas.

The Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation underlie about 946,000 acres and have an average thickness of 200 feet in the project area. The quantity of water stored in these aquifers is estimated to be 200,000 acre-feet, if one assumed a coefficient of storage of 0.001.

Estimated quantity of ground water that could be removed from storage of the unconsolidated deposits by pumping under ideal conditions

[Based on an assumed coefficient of storage of 0.20]

Area	Quantity of ground water represented by a 1-ft rise or decline of the water table (acre-feet)	Quantity of recoverable ground water in storage (acre-feet)
Arkansas River valley	15,000	300,000
Cheraw area	6,000	120,000
Olney Springs to Sugar City	10,000	300,000
Nebraskan deposits	4,000	40,000
Total	35,000	760,000

WATER-LEVEL FLUCTUATIONS

Water levels in wells in the shallow unconsolidated aquifers seem to respond fairly closely to precipitation and ditch diversions. The wells closest to the ditches usually have the strongest response. According to measurements made twice a year by the Agricultural Experiment Station of Colorado State University, water levels in several *along the Arkansas River*

A (area, mile-feet)	α	Cos α	Underflow			
			Gallons per day	Cubic feet per second	Acre-feet per day	Acre-feet per year
48	0	1	2, 900, 000	4½	9	3, 250
37	0	1	1, 900, 000	3	6	2, 130
80	30	.87	2, 800, 000	4½	9	3, 140
38	30	.87	1, 500, 000	2½	5	1, 680
33	0	1	1, 600, 000	2½	5	1, 790
40	30	.87	1, 700, 000	2½	5	1, 900
25	30	.87	900, 000	1½	3	1, 010
15	30	.87	390, 000	½	1	440
25	35	.82	170, 000	¼	½	190
28	45	.71	1, 200, 000	2	4	1, 340
21	45	.71	1, 000, 000	1½	3	1, 120

wells in the Arkansas River valley declined during the midfifties, but recovered to about their 1950 levels by 1960.

Periodic water-level measurements were made in 19 observation wells. These measurements were published in the basic-data report for this area (Weist, 1962). Figures 10–13 are hydrographs comparing the changes in the water level of observation wells with precipitation at the nearest weather station and with the amount of water diverted into nearby irrigation canals.

Water levels in the area from Olney Springs to Sugar City are lowest during the late winter and early spring (fig. 10). During May or June they rise abruptly. This rise seems to correlate fairly well with the greatest ditch diversions and the highest precipitation. The water levels start declining during August or September, when precipitation is usually low, as are ditch diversions.

Well C21–59–16ccb (fig. 11) is on top of the Nebraskan deposits west of Olney Springs. There is no irrigation in this area, and the water level shows little or no immediate response to precipitation. The water level has remained almost stationary since September 1959.

Well C22–59–27daa3 (fig. 11) is on a rise southeast of Fowler and is about half a mile below the Rocky Ford High Line Canal. The water level is generally lowest in May or June and highest during the winter or early spring. This seems to reflect a slow response to precipitation and to diversions for the Rocky Ford High Line Canal. On the other hand, the level in well C22–58–25cba, about half a mile east of Manzanola, seems to show a very close correlation with diversions for the Catlin and Otero Canals (principally the Catlin) and a fairly close response to precipitation.

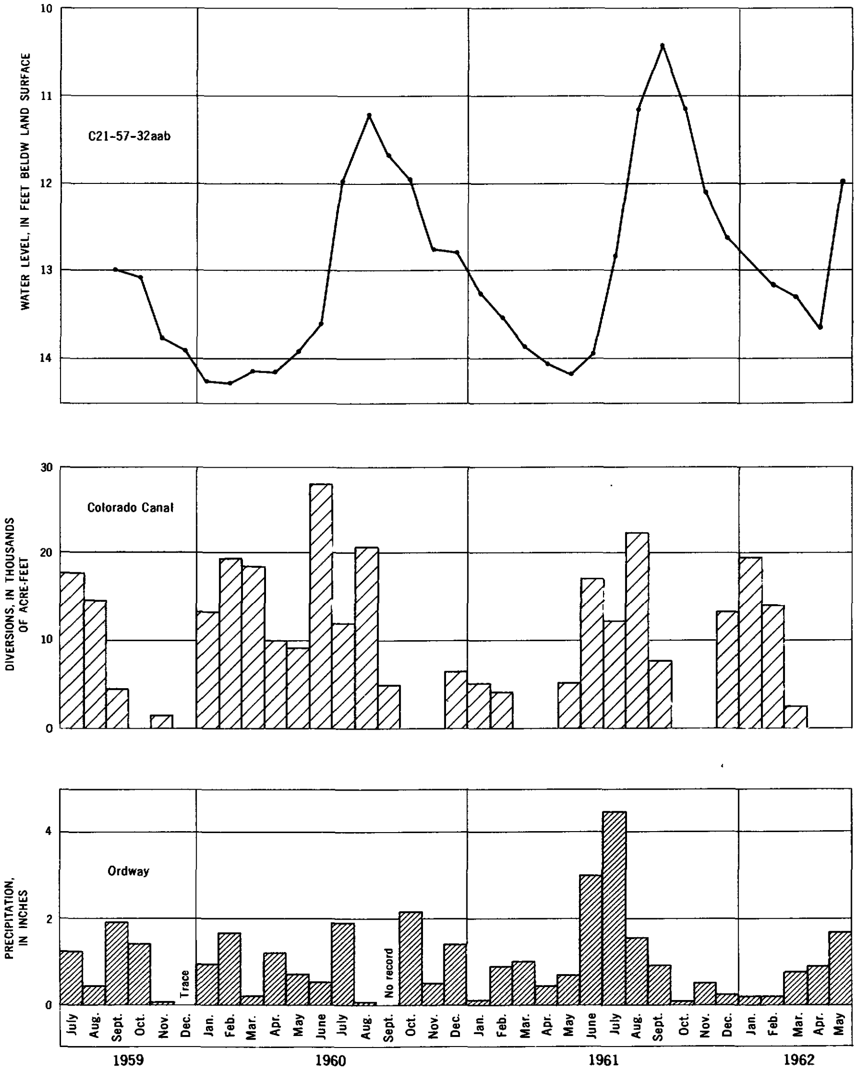

FIGURE 10.—Fluctuations of water level in a well near Ordway, diversions for the Colorado Canal, and precipitation at Ordway, 1959–62.

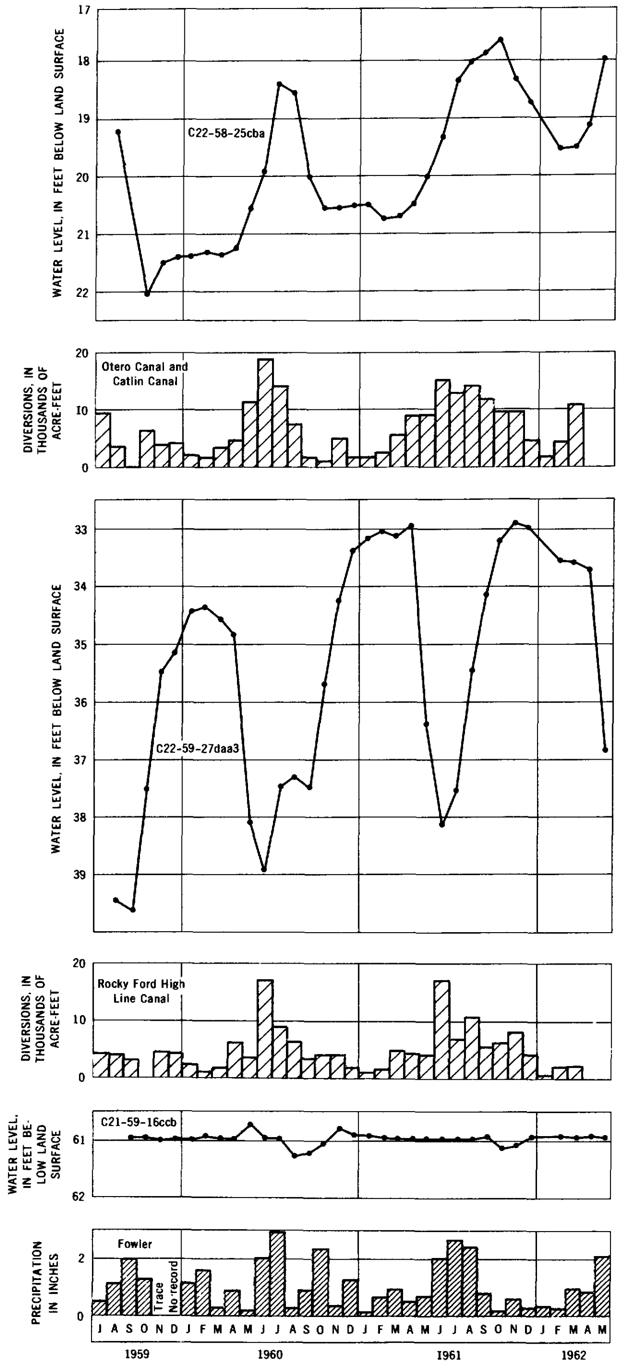

Figure 11.—Fluctuations of water levels in wells near Fowler and Manzanola, diversions for the Otero, Catlin, and Rocky Ford High Line Canals, and precipitation at Fowler, 1959–62.

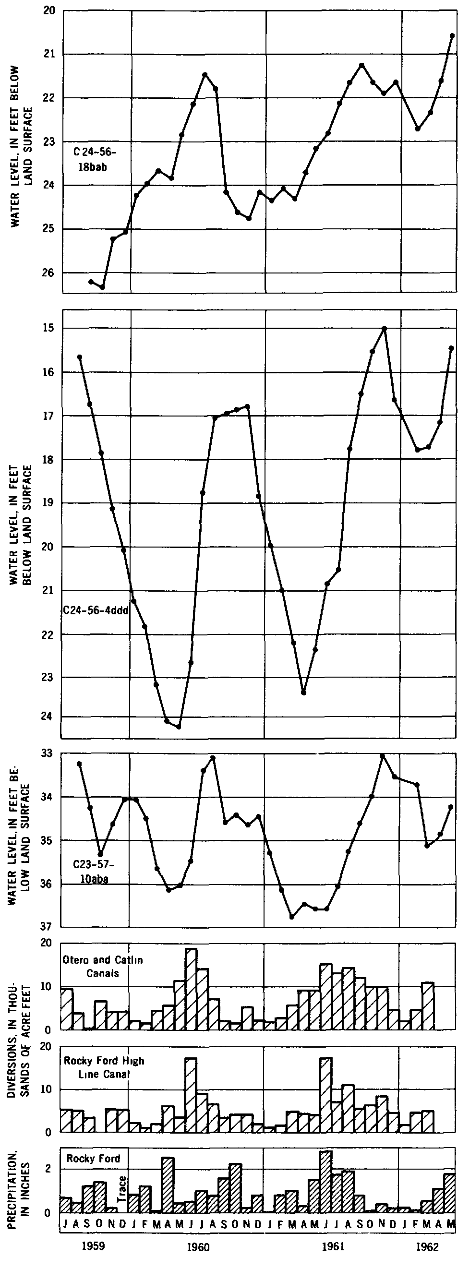

Figure 12.—Fluctuations of water levels in wells near Rocky Ford, diversions for the Otero, Catlin, and Rocky Ford High Line Canals, and precipitation at Rocky Ford, 1959–62.

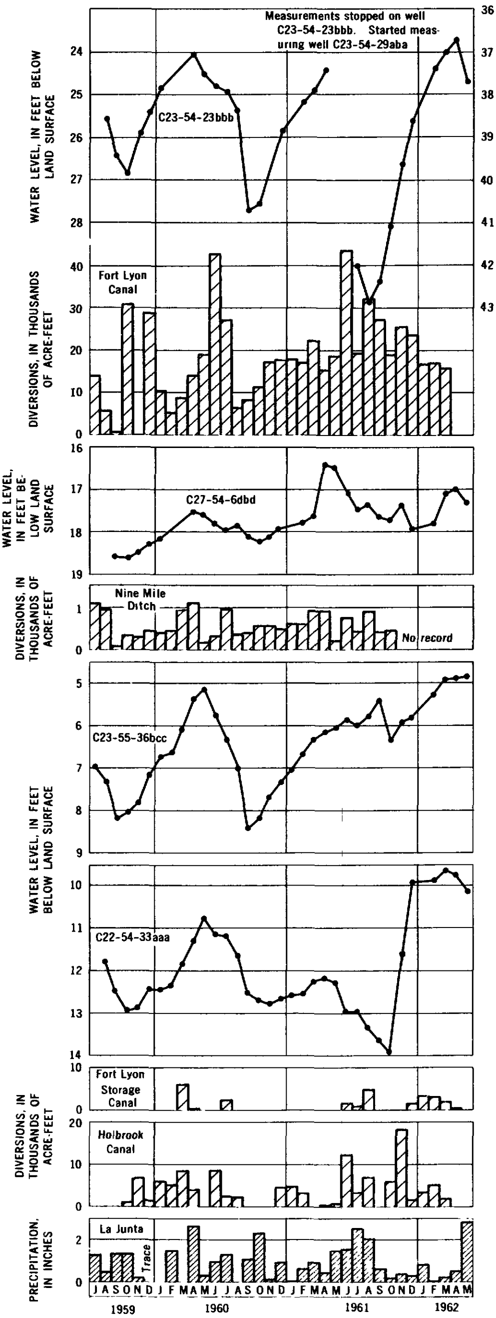

FIGURE 13.—Fluctuations of water levels in wells near La Junta and diversions for the Fort Lyon, Fort Lyon Storage, and Holbrook Canals and for the Nine Mile Ditch, and precipitation at La Junta, 1959–62.

Figure 12 shows that water levels in the vicinity of Rocky Ford and Roberta (wells C23–57–10aba and C24–56–4ddd) have a delayed reaction both to precipitation and to canal diversions. Levels are lowest during the spring and highest during the late summer and fall. The level in well C24–56–18bab, south of Hawley, shows a more immediate response to canal diversions—probably because it is located next to the Catlin Canal.

Hydrographs of wells in three different areas are shown on figure 13. Levels in wells C22–54–33aaa and C23–55–3bcc, in the Cheraw area, show response to diversions for the Holbrook and Rocky Ford Storage Canals but little or no response to precipitation. On the other hand, the level in well C27–54–6dbd, in the Purgatoire River valley, shows no relation to diversions for the Nine Mile Ditch. Wells C23–54–23bbb and C23–54–29aba are in the heavily pumped area on the Wisconsin terrace deposit east of La Junta. The cyclic pattern of their levels is probably related to pumping from irrigation wells in the area—levels are lowest in late summer or fall near the end of the irrigation season. The levels rise during winter and spring until pumping starts again.

Levels also change in artesian wells owing to changes in pressure caused by increasing or decreasing the amount of water withdrawn from the aquifer. Hydrographs of two artesian wells are shown in figure 14. Well C24–55–35bca, about 2 miles south of La Junta, taps the Dakota Sandstone. Many artesian wells tap the Dakota Sandstone in this general area, and the piezometric surface is declining. Well C27–56–35bcc, near the southern edge of Otero County, taps the Cheyenne Sandstone. Few wells pump water from the aquifer in this area, and the piezometric surface is rising.

RECHARGE

All the ground-water reservoirs in the project area receive some recharge, but the amount varies. Ground-water reservoirs along the Arkansas River and its tributaries receive recharge from three sources: subsurface inflow, precipitation, and irrrigation return water from ditches and wells. Most of the subsurface inflow comes from Pueblo County into the alluvial deposits along the Arkansas River. Smaller amounts enter the valley-fill deposits aong the Apishapa River and Timpas and Horse Creeks and their tributaries, but these deposits are not extensive and their permeability is relatively small. Line *A–A′* (pl. 3) represents a saturated cross-sectional area of 48 mile-feet at Fowler. The average coefficient of permeability of the aquifers, as determined from aquifer tests in the area, is 6,000 gpd per sq ft, and the average hydraulic gradient is about 10 feet per mile. Calculations

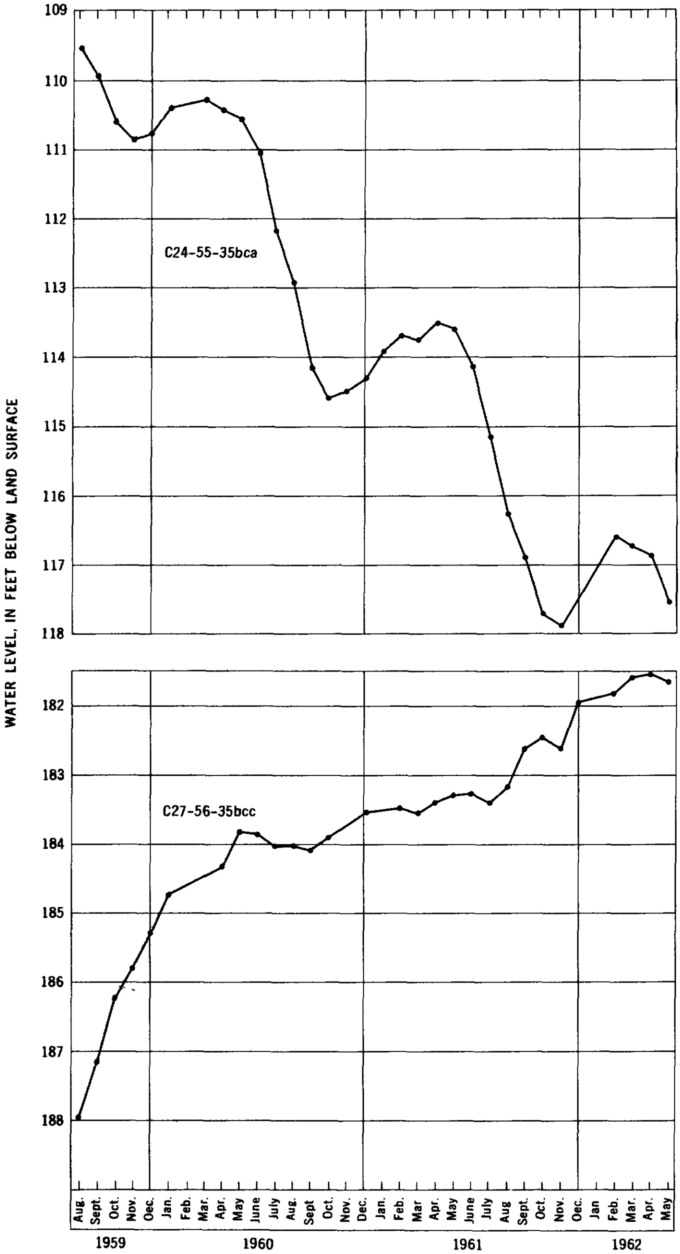

FIGURE 14.—Fluctuations of water levels in two artesian wells.

using these figures indicate the underflow into the area along the Arkansas River to be 2,900,000 gpd (table 6).

Recharge from precipitation is much more difficult to calculate. The average annual precipitation along the Arkansas River is 12 inches. About a quarter of an inch runs off into the river. The greater part of that left is evaporated or transpired, leaving only a fraction of a foot to replenish the soil moisture and to recharge the aquifers.

Return water from irrigation also recharges the aquifers. Most irrigation water evaporates or transpires, but 20 to 30 percent percolates down through the soil to the water table. Figures 10–13 show that the water table rises when irrigation canals contain water. This rise is due in part to recharge from water spread on the fields, but some recharge is probably contributed directly from the canals to the water table. Officials of the canal companies report that 15 to 20 percent of the water diverted from the river is lost through evaporation and seepage along the canals before reaching the irrigated fields.

The valley-fill deposits in the Cheraw area do not receive recharge by subsurface underflow. They are recharged entirely by precipitation and return of irrigation water. Average annual precipitation in the area is 11.5 inches. As surface drainage out of the area is negligible except for Horse Creek at the eastern end, most surface water drains into the series of lakes in the center of the valley. A small amount of water percolates down to the water table from these lakes, but most of it is evaporated. The relation between water levels and canal diversions, as shown on figure 13, indicates that most of the recharge around Cheraw comes from return of irrigation water.

The valley-fill deposits in the Olney Springs-Sugar City area may be recharged slightly by subsurface inflow along Bob and Horse Creeks, but they are recharged mainly by precipitation and return of irrigation water. As in the Cheraw area, surface drainage is not well developed. Most precipitation drains through drainage ditches to Lake Meredith. Most of the remainder evaporates and transpires; very little percolates to the water table. Recharge in this area comes chiefly from return of irrigation water (fig. 10).

The Nebraskan deposits receive some subsurface inflow from the north and west, but they and the minor unconsolidated aquifers in the project area, such as the upland deposits, are probably recharged mainly by precipitation.

The Dakota Sandstone and the Cheyenne Sandstone Member of the Purgatoire Formation are artesian aquifers recharged in areas to the southwest where they crop out, as discussed in an earlier report (Weist, 1963).

Artificial recharge, the practice of adding water to a ground-water reservoir through wells and spreading grounds, is not planned for the project area at the present time (1962) nor is any surplus water, except spring runoff, available for artificial recharge.

DISCHARGE

Water in the zone of saturation moves in the direction of the hydraulic gradient toward areas of discharge. Discharge includes evapotranspiration, seeps, springs, and drainage ditches, underflow, and pumping from wells.

EVAPOTRANSPIRATION

Water evaporates both from exposed water surfaces and from the soil. Plants take water from the soil, from the capillary fringe above the water table, and from the zone of saturation and transpire it into the air. The depth to which plant roots extend in search of water ranges from a few inches for most grasses and field crops to several tens of feet for some desert plants and alfalfa. The greatest amounts of water in the project area are probably consumed by alfalfa, cottonwood trees, and saltcedar (tamarisk). Transpiration cannot usually be measured separately from evaporation, and the two processes together are termed "evapotranspiration."

Evapotranspiration in Otero and Crowley Counties is concentrated in the low areas along the Arkansas River and its tributaries, where the water table is very close to the land surface and where water-loving plants are numerous. Dense growths of saltcedar may consume as much as 8 feet of water per year (Robinson, 1958, p. 75). No attempt has been made to determine evapotranspiration in the project area, but it undoubtedly is large. The U.S. Geological Survey and Colorado State University are currently making a water management study of the Arkansas River valley between La Junta and Las Animas. This study will include an investigation of evapotranspiration.

SPRINGS AND SEEPS

Springs and seeps discharge wherever the land surface intersects the water table. Springs and seeps in the project area are of two types: contact springs at the exposed contact of a permeable deposit overlying a relatively impermeable deposit and depression springs where the land surface intersects the water table. Contact springs are more common in this area.

Springs at the contact with the underlying Pierre Shale discharge from the Nebraskan deposits. They supply water for the towns of Fowler and Olney Springs as well as for many farms near Olney Springs and Crowley. Yields from these springs are small but steady.

East of Cheraw the discharge of a spring flowing into Horse Creek was measured at 100 gpm (gallons per minute). This spring is at the contact of the valley-fill deposits and the underlying Smoky Hill Marl Member of the Niobrara Formation.

Other contact springs discharge west of Fowler from the Wisconsin terrace deposits above the flood plain, southwest of Manzanola from the base of the Nebraskan deposits (Arnold Springs), and along the north side of the Arkansas River valley from the base of the older Wisconsin terrace deposits.

In southeastern Otero County, several springs flow from the Dakota and Cheyenne where the Purgatoire River and its tributaries have cut through these formations.

Most of the depression springs and seeps are in low areas along the Arkansas River flood plain and its tributaries and in the center of the valley near Cheraw.

WELLS

Water pumped from wells undoubtedly is the largest ground-water discharge in Otero and Crowley Counties. (See table 2.) About half the wells in the area are large-diameter irrigation, industrial, and municipal wells having yields of as much as 2,000 gpm. Records of nearly 800 wells are included in the basic-data report on this area (Weist, 1962). The estimated withdrawal of ground water in the area is discussed on page 44.

SUBSURFACE OUTFLOW

The principal subsurface outflow in the project area is in the Arkansas River valley at the Bent County line. Approximately 900,000 gpd flows out of the area, as computed in table 6.

Subsurface outflow is much less along Horse Creek valley and the Purgatoire River valley at the Bent County line.

The piezometric contour map (fig. 7) shows that water in the artesian aquifers is moving northeastward out of the project area.

RECOVERY OF GROUND WATER

SPRINGS

Gravity contact springs are those in which water moves by the force of gravity and flows out at the contact of a permeable bed with a less permeable bed. All springs inventoried in the project area seem to be gravity contact springs, except possibly Iron Springs (C27–58–16cbc), which may be artesian. Most of the springs inventoried flow from the Nebraskan deposits, but a few flow from the other unconsolidated formations and from the Dakota Sandstone and Cheyenne

Sandstone Member of the Purgatoire Formation (Weist, 1962, table 4).

Springs in the Nebraskan deposits have the most elaborate improvements. According to residents, they were first developed about 1902. Trenches were dug to the top of the Pierre Shale, the bottoms were lined with tile pipe, which was then covered with fine gravel, and the trenches were filled in. These tile lines feed into manholes, where the water is collected and piped into the distribution system. The manholes enable the tile lines to be cleaned out periodically. Other springs have been improved either by excavation or piping the water to stock tanks or reservoirs.

DUG WELLS

Where the water table is shallow, especially near Fowler, many wells were dug, either by hand or by mechanical means. These large-diameter (generally 6 feet or more) wells are usually cased with bricks. Because dug wells do not usually go more than a few feet below the water table, they are subject to failure during drought. Dug wells usually are poorly sealed and therefore are more susceptible to surface contamination than drilled wells.

DRILLED WELLS

Most of the wells in the project area were drilled by cable-tool, rotary, or reverse-rotary methods. They are usually cased with iron or steel casing that ranges in diameter from 4 to 10 inches for stock and domestic wells to as much as 24 inches for many municipal and irrigation wells. The casing is usually perforated opposite the water-bearing materials, but some wells penetrating the Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation are cased through only the first few feet of the sandstone; the rest of the hole is left uncased.

Maximum yields can be obtained by drilling a well through all the water-bearing materials, by using the proper size gravel pack and well screen or perforations in the casing and placing it opposite the water-bearing materials, and by properly developing the well. Increasing the depth of a well usually has a greater effect on increasing the yield than increasing the diameter, provided that additional water-bearing materials are penetrated.

UTILIZATION OF GROUND WATER

Nearly 800 wells and 35 springs were inventoried during the investigation (Weist, 1962), including all the municipal and public supply wells and most of the irrigation and industrial wells. Of these, 22 wells and 7 springs are used for public supplies, 33 wells and 17

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springs for municipal supplies, 25 wells and 3 springs for industrial supplies, 390 wells for irrigation, and 251 wells and 7 springs for domestic and stock supplies. The rest were not in use at the time the inventory was made.

Not all the water withdrawn from the aquifers is consumed; some of the excess irrigation water and waste water from other uses returns to the aquifers. The quantities of water estimated in this section represent withdrawal rather than consumptive use, which is less. The following table summarizes the estimated withdrawal of ground water in the project area during 1962.

Use	Number of wells	Number of springs	Acre-feet withdrawn
Domestic and stock	251	7	2, 200
Industrial	25	3	1, 300
Irrigation	390	----------	53, 400
Public supply:			
Municipal	33	17	3, 500
Other	22	7	300
Total	721	34	60, 700

DOMESTIC AND STOCK SUPPLIES

Most domestic and stock supplies in Otero and Crowley Counties are obtained from ground-water sources; some stock water is obtained from streams and by ponding surface runoff. Nearly all stock water and many domestic water supplies are obtained from wells of small diameter equipped with cylinder pumps powered by windmills. Wells supplying the more modern rural homes and some stock wells have a variety of pump types, mostly powered by electric motors. Yields from these wells are generally less than 5 gpm, although some wells are capable of much larger yields. In areas with a shallow water table, a few dug wells are in use, but most wells were drilled. Most springs used for stock water flow only a few gallons per minute, but the flow of a spring northeast of Cheraw was measured at 100 gpm (Weist, 1962, table 4). The water is generally of good quality if the wells are properly constructed and maintained, but the water from the shallow aquifers is usually very hard.

INDUSTRIAL SUPPLIES

Of the 25 wells that yield water for industrial purposes, 10 were drilled into the Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation. These are discussed in another report (Weist, 1963). The rest were drilled into the Wisconsin terrace deposits along the Arkansas River.

The Fowler Creamery uses water from a shallow well for cleaning equipment and for cooling. The Divan Packing Co. of Fowler uses about 60 acre-feet a year from two wells. In La Junta, the Santa Fe Railway Co. uses about 680 acre-feet a year from four wells. At Swink, eight wells behind the old American Crystal Sugar Co. plant are capable of pumping 650–750 gpm each but are probably no longer used (1962).

The Korinek Trout Farm uses water from three springs along the base of the older Wisconsin terrace deposits north of the Arkansas River. The springs have a combined flow of 240 gpm.

IRRIGATION SUPPLIES

The greatest use of ground water in Otero and Crowley Counties is for irrigation. Most of the irrigation is done on the Wisconsin terrace deposits and flood-plain deposits along the Arkansas River. Other areas irrigated by ground water are along Timpas Creek south of Roberta, and in the Olney Springs to Sugar City area (especially just west of Crowley). Minor areas include the Wisconsin terrace deposits south of Swink and along Crooked Arroyo west of La Junta.

The oldest known, still operating, irrigation wells in the area were completed in 1909. Irrigation from ground water developed slowly until 1950, when there were about 100 irrigation wells. During the next 7 years at least 176 irrigation wells were drilled. Only 16 irrigation wells are known to have been drilled during 1958–61. Drilling dates for the other wells are not known.

Of the 390 irrigation wells in the project area in 1962, 336 were located either on the Wisconsin terrace deposits or on the flood-plain deposits along the Arkansas River. Yields were as much as 2,200 gpm and averaged about 700 gpm. About 46,600 acre-feet was pumped for irrigation in 1960 from the aquifer along the Arkansas River.

In 1960, 16 irrigation wells pumped from the valley-fill deposits along Timpas Creek upstream from Roberta. Yields of these wells ranged from 50 gpm (estimated) to 800 gpm (reported). About 1,600 acre-feet was pumped for irrigation in 1960.

Yields of the 18 wells in the Olney Springs-Sugar City area ranged from 50 to 440 gpm. Most of the 700 acre-feet pumped in 1960 was used to supplement ditch water.

Yields of the 6 wells tapping the valley-fill deposits in the Cheraw area ranged from 100 to 400 gpm, and about 600 acre-feet was withdrawn in 1960. The 6 wells tapping the Wisconsin terrace deposits south of Swink yield from 100 to 300 gpm, and about 400 acre-feet was withdrawn in 1960. Yields of the 5 wells in the valley-fill deposits along Crooked Arroyo west of La Junta ranged from 300 to 600 gpm, and about 500 acre-feet was withdrawn.

Estimates of the acre-feet pumped from the various areas during 1958–60 are given in the following table:

Estimates of ground water pumped for irrigation

	Acre-feet pumped		
	1958	1959	1960
Arkansas Valley	29, 300	48, 700	46, 600
Timpas Creek valley	700	1, 700	1, 600
Olney Springs to Sugar City	500	800	700
Cheraw valley	500	800	600
Older Wisconsin terrace deposits	100	400	400
Crooked Arroyo valley	300	900	500
Others	1	4	34
Totals	31, 401	53, 304	50, 434

Most irrigation wells are 12 to 24 inches in diameter and are equipped with electrically driven turbine pumps. In the Fowler area, several dug wells are as much as 120 inches in diameter.

PUBLIC SUPPLIES

MUNICIPAL SUPPLIES

The following paragraphs summarize the municipal water-supply systems in the project area in 1962. Additional information can be found in the report on the public water supplies of Colorado (Gregg, and others, 1961).

Cheraw.—At the time fieldwork was done for this study, Cheraw obtained its water from a well, 850 feet deep, tapping the Cheyenne Sandstone Member of the Purgatoire Formation. The well is capable of pumping 65 gpm, averages 12 million gallons per year. The town has since drilled a well, which is reported to yield 85 gpm, 735 feet into the Dakota Sandstone.

Crowley.—Crowley gets its water for domestic use from a well 1,432 feet deep tapping the Dakota Sandstone. This well pumps 4 gpm, and consumption averages 3,000 gpd. The town gets water for other uses from the Colorado Canal.

Fowler.—Fowler has two water systems—a hard-water supply for sanitation and irrigation and a softer supply for washing and cooking. (See Weist, 1963, for a discussion of "hard" and "soft" as applied to water in this area.) The soft water is supplied by eight or nine springs along the southern edge of the Nebraskan deposits north of the Arkansas River. The springs have a combined flow of about 100 gpm, and the town uses an average of 45,000 gpd. The hard water is supplied by six wells drilled into the Wisconsin terrace deposits in or near the town limits; all are less than 35 feet deep. One well is used for the town cemetery, and one is used primarily for the swimming pool. The yield of the wells ranges from 250 to 450 gpm; no information is available on the amount of water withdrawn.

La Junta.—La Junta has 12 wells (in 3 well fields) tapping the Wisconsin terrace deposits. The wells are all about 40 feet deep and yield from 400 to 1,000 gpm. About 2½ million gallons is used daily.

Manzanola.—Manzanola has a soft-water supply for cooking and washing and a hard-water supply for sanitation and irrigation. The softer water comes from two wells: one is 1,365 feet deep and pumps 45 gpm from the Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formations; the other well is 1,113 feet deep and pumps 50 gpm from the Dakota Sandstone. The town uses an average of 70,000 gpd from the two wells. In addition, water is hauled from the wells to supply 550 to 600 people outside the town. In 1962 a third deep well was being drilled to meet increased demands. The hard water comes from a 37-foot well, which pumps 600 gpm from the Wisconsin terrace deposits.

Olney Springs.—Olney Springs owns 10 springs along the east edge of the Nebraskan deposits west of town. Nine of these springs are in use and have a combined yield of about 20 gpm. The average use is about 3,300 gpd. Hard water for irrigation and sanitation is supplied by the Colorado Canal.

Ordway.—Ordway gets a supply of soft water from two wells in the alluvium along Horse Creek north of the project area. Hard water for irrigation and sanitation is supplied by the Colorado Canal.

Rocky Ford.—Rocky Ford gets most of its water from the Arkansas River by way of the Catlin Canal and the Rocky Ford Ditch. This supply is supplemented by two 45-foot wells drilled into the Wisconsin terrace deposits. Each well is capable of pumping 900 gpm.

Sugar City.—Sugar City gets its water supply from two batteries of two wells each in the valley-fill deposits along Horse Creek north of town. The wells are about 30 feet deep and pump 150 gpm from each battery. The town uses an average of 74,000 gpd.

Swink.—Swink gets a supply of soft water from two wells. One well is 547 feet deep and pumps 30 gpm from the Dakota; the other is 769 feet deep and pumps 30 gpm from the Dakota and Cheyenne. The town uses an average of 30,000 gpd. Three wells about 50 feet deep in the Wisconsin terrace deposits yield 200 to 250 gpm each for sanitation and irrigation.

OTHER SUPPLIES

Included in the category of "other supplies" are wells and springs belonging to private water associations and wells from which water is hauled to nearby farms and ranches. In the basic-data report by Weist (1962), these wells are called public-supply wells.

At present (1962), 14 private water associations in the project area obtain water from 18 wells and 7 springs. The wells pump water from both the Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation or from the Dakota Sandstone alone. Most of these wells were discussed in another report (Weist, 1963). The seven springs are owned by the Crowley County Water Association. They have a combined flow of 45 gpm from the Nebraskan deposits and supply water to 125 farms in Crowley County.

At least four wells in the project area are primarily used to provide water to be hauled to nearby farms and ranches. The wells pump water from the Cretaceous sandstones and yield as much as 45 gpm. In addition, water is hauled from several of the private water association wells and from some of the municipal supplies.

OUTLOOK FOR FURTHER DEVELOPMENT

Of the 14 known aquifers in Otero and Crowley Counties, only 5 contribute significantly to the water supply. The rest (upland deposits, Illinoian terrace deposits, Kansan deposits, Smoky Hill Marl Member, Fort Hays Limestone Member, Codell Sandstone Member, Bridge Creek Limestone Member, Lincoln Limestone Member, and Morrison Formation) may yield small amounts of water of differing quality for stock and domestic uses. These units do not yield water everywhere in the project area, and a more reliable water supply can usually be obtained from one of the five major aquifers. Fewer than 80 wells inventoried obtain their water from the minor aquifers, mostly from the upland deposits.

About 90 percent of the water withdrawn from the ground-water reservoirs in the project area comes from the Wisconsin terrace deposits along the Arkansas River. The well-location map included in the basic-data report by Weist (1962, pl. 1) shows the concentration of large-capacity wells. Already some wells interfere with the performance of nearby wells. During a prolonged drought, the poorer wells will probably fail, and the yields of the other wells will decline. Even in fairly wet years, the yields of some wells decline during the pumping season.

Locally, as between Rocky Ford and Swink and northwest of Rocky Ford, a few large-capacity wells could be drilled without serious interference with other wells. But large-capacity wells drilled elsewhere in the area will probably interfere with other wells.

The best sites for developing large yields are those over buried channels, as in the Swink area. A deep well drilled at the old sugar factory penetrated only 8.5 feet of sand and gravel before reaching bedrock. Half a mile southwestward, the town of Swink has three wells nearly 50 feet deep in sand and gravel that yield 200 to 250 gpm each. At the school, a few blocks south of these wells, bedrock was penetrated at 23 feet, and a quarter of a mile south of the school, bedrock was penetrated at 53 feet. Thus there are two buried channels that carry large quantities of water and which are separated by bedrock highs with little or no water (line *F–F′*, pl. 3). The bedrock contour map (pl. 4) delineates most of the channels in the project area.

The deposits mapped as valley-fill deposits on plate 1 have a lower transmissibility and permeability than the Wisconsin terrace deposits. They also show considerable variation in lithologic characteristics from place to place (see page 81), as well as within an area. They are not capable of extensive development.

Most promising of the three major areas of valley-fill deposits is along Timpas Creek north of the Rocky Ford High Line Canal. The area already has several good irrigation wells, and test-drilling showed water-bearing gravel beds that could support additional irrigation wells.

The valley-fill deposits from Olney Springs to Sugar City are not as promising a source of water for large-capacity wells. Although there are several irrigation wells in the area, yields are generally less than 300 gpm. Test-drilling did not locate any well-sorted beds of gravel in this area, but additional low-yield irrigation wells probably can be developed. The best places to drill are those underlain by the greatest saturated thickness, as shown on plate 5. If this material is mostly clay and silt, however, an irrigation well could probably not be developed. When planning a large-capacity well, several test holes should be drilled, and the one penetrating the greatest thickness of saturated coarse materials should be selected as the well site.

The area around Cheraw is the least promising of the three major areas of valley-fill deposits. The lack of irrigation wells in most of the area and the fact that test-drilling did not reveal any well-sorted gravel make it seem doubtful that the area could support many, if any, more irrigation wells.

No large-capacity wells are on the Nebraskan deposits in the project area. It is extremely doubtful that large yields could be obtained because the saturated thickness is generally less than 10 feet (pl. 5), and only a very small area has more than 30 feet. Nevertheless, these deposits constitute one of the major aquifers in the project area because they supply water for two towns and a private water association.

The Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation are sources of water throughout most of the project area. Maximum yield of a well tapping both aquifers is about 150 gpm, but maximum sustained yield is closer to 75 gpm. Although the aquifers cannot furnish enough water for large-scale irrigation, they are important sources of water for industrial and municipal supply. Although declining water levels may locally indicate overdevelopment (such as around Cheraw and La Junta), the two sandstones are capable of further development in the rest of the project area. Of the 171 wells known to be drilled into these formations, 102 tap only the Dakota and 27 tap only the Cheyenne. The rest tap both units. Because fewer wells tap the Cheyenne, it would seem better for new wells to be drilled into the Cheyenne to take advantage of the yields from both aquifers.

Continuing studies of the area should be made, including periodic measurements of water levels in the various aquifers, calculation of the amount of water withdrawn each year, better estimation of the recharge, and the amount of interference between wells.

QUALITY OF THE GROUND WATER

By C. Albert Horr

Otero and southern Crowley Counties largely depend on irrigation agriculture for economic support. The utilization of water is closely related to its chemical quality. Water-quality requirements differ according to use, and water of suitable quality for one user may not meet requirements of another. Hardness, iron, manganese, magnesium, chloride, sulfate, nitrate, fluoride, and dissolved solids concern the domestic consumer. Dissolved-mineral content, calcium magnesium to sodium ratios, and boron and bicarbonate content concern irrigators. Dissolved-mineral content and the concentration of nitrate, fluoride, chloride, and others concern stock growers. Water-quality requirements for industrial users differ according to use and the particular industry.

Samples collected from representative wells in the project area were analyzed by personnel of the Geological Survey according to methods described by Rainwater and Thatcher (1960), and the analyses are given in table 8 of the basic-data report (Weist, 1962). The dissolved-mineral content of the ground water calculated from the determined constituents ranged from 566 to 7,350 ppm (parts per million). On the basis of percentage composition, the water may be roughly classed as sodium calcium sulfate bicarbonate. Sodium and sulfate are the predominate ions in solution and make up more than half of the dissolved material in 43 of the 61 samples analyzed. The calcium in the water may be derived from gypsum or limestone in the aquifer, which also would contribute sulfate and bicarbonate. High sodium content is generally associated with ground water in arid and semiarid regions.

DEFINITION OF TERMS

The terminology of water chemistry generally is straightforward. A few terms, however, may convey a variety of meanings and as an aid to clarity are defined below.

Parts per million (ppm) is a unit expressing the concentration of constituents on a weight-to-weight basis, usually in milligrams of constituent per kilogram of solution. For most water, the unit is nearly equal to milligrams of constituent per liter of solution.

Equivalents per million (epm) is a unit expressing the concentration of chemical constituents in terms of chemical equivalence and more closely describes the composition of a water and the relations of ions in solution. One equivalent of a positively charged ion (cation) will react with one equivalent of a negatively charged ion (anion). Parts per million are converted to equivalents per million by multiplying by the reciprocal of the combining weight of the ion. The following factors, based on 1961 atomic weights, are used:

Cation	*Factor*	*Anion*	*Factor*
Calcium (Ca^{+1})	0.04990	Carbonate (CO_3^{-2})	0.03333
Magnesium (Mg^{+2})	.08226	Bicarbonate (HCO_3^{-1})	.01639
Sodium (Na^{+1})	.04350	Sulfate (SO_4^{-2})	.02082
Potassium (K^{+1})	.02557	Chloride (Cl^{-1})	.02821
		Fluoride (F^{-1})	.05264
		Nitrate (NO_3^{-1})	.01613

Specific conductance is a measure of the capacity of water to conduct an electric current and is expressed as micromhos per cm at 25°C. Specific conductance is directly related to the concentration of ions in solution and can be used as an empirical measure of the dissolved-solids content. For most water the following relations apply:

$$\text{Specific conductance} \times (0.65 \pm 0.05) = \text{ppm of dissolved solids,}$$

and

$$\frac{\text{Specific conductance}}{100} = \text{total epm cations} = \text{total anions.}$$

Salt is a generic term that includes all ionizable material in solution and does not refer to common table salt ($NaCl$) alone. Examples of salts are: gypsum ($CaSO_4 \cdot 2H_2O$), epsomite ($MgSO_4 \cdot 7H_2O$), and sylvite (KCl).

Sodium-adsorption-ratio (SAR) is a measure of the suitability of irrigation water and relates to the adsorption of sodium by a soil from water. The ratio is calculated by dividing the concentration of sodium, expressed in epm, by the square root of half the concentration of calcium plus magnesium, also expressed in epm.

Leaching requirement (D percent) is a ratio, expressed as a percentage, of the amount of water that must pass through the root zone to the amount of water applied to maintain soil productivity for satisfactory crop yields.

FACTORS AFFECTING WATER QUALITY

Water falling on the earth absorbs gases from the atmosphere and the soil. This process enables that part entering aquifers to form compounds that react with and thus dissolve minerals. The chemical quality of ground water differs from place to place and is the result of several interdependent factors. The most important of these factors are: direction of ground-water movement, source and amount of recharge, and physical and chemical properties of the material through which the water moves. Regional patterns of chemical quality may exist, but the quality of the water from each well is influenced more by local conditions.

WATER QUALITY IN RELATION TO GEOLOGY

The chemical quality of ground water is determined by the physical and chemical properties of the rocks in contact with the water. The aquifers in Otero and southern Crowley Counties may be divided into two groups: shallow aquifers, which include unconsolidated deposits of gravel, sand, silt, and clay of Pleistocene and Recent age; and deep aquifers, which include limestone and sandstone of Late and Early Cretaceous and Late Jurassic age. (See p. 61–83 for complete description.)

As precipitation infiltrates the ground and becomes ground water, it dissolves material from the rock. The amount dissolved is dependent upon the temperature and dissolved-gas content of the water, the length of time of contact, and the mineral solubility. The chemical nature is dependent on the rock type with which the water is in contact.

Figure 15 shows, in general, the chemical quality representative of ground water from geologic sources in Otero County and southern Crowley County. The bar graphs indicate the approximate average composition of ground water in each of the formations represented. Examination of the chemical analyses (Weist, 1962, table 8) shows a wide variation in composition of the ground water from a particular geologic source. Attempts to isolate the effect of one rock type on water quality have been inconclusive.

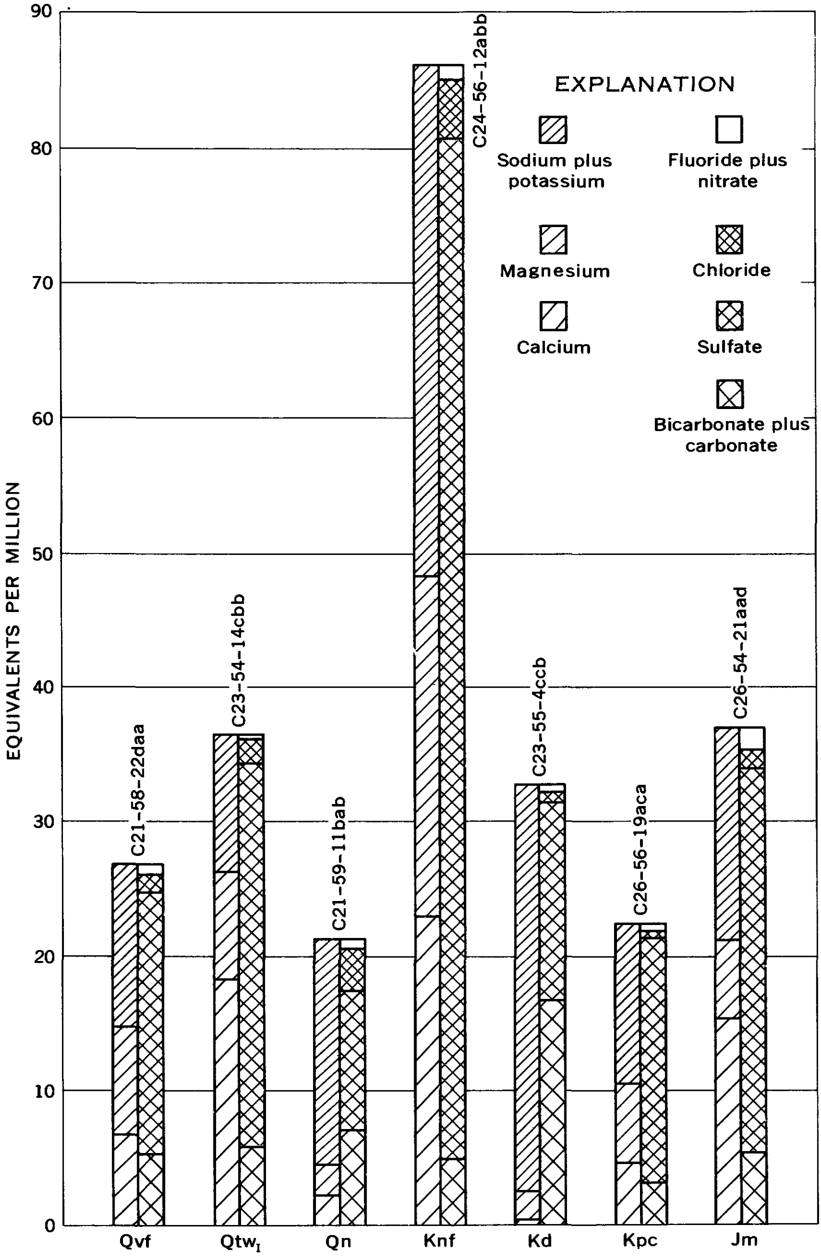

FIGURE 15.—Chemical quality representative of water from geologic sources in Otero County and southern Crowley County. Qvf, valley-fill deposits; Qtw, upper Wisconsin terrace deposits; Qtn, Nebraskan terrace deposits; Knf. Fort Hays Limestone Member of Niobrara Formation; Kd, Dakota Sandstone; Kpc, Cheyenne Sandstone Member of Purgatoire Formation; Jm, Morrison Formation.

WATER QUALITY IN RELATION TO GROUND-WATER MOVEMENT

Shallow ground water north of the Arkansas River generally moves southeastward, whereas shallow ground water south of the river moves northeastward. Little overall difference in the specific conductance of the ground water exists from west to east in the project area. Locally, however, changes in the degree of mineralization of the ground water are related to the distance from the Arkansas River and areas of recharge.

In the Fowler, Manzanola, Rocky Ford, and Swink areas, mineralization of the ground water increases southward away from the river. This increase indicates recharge into the terrace deposits from upland deposits farther south. In the area east and north of La Junta bounded by the Fort Lyon Canal and the Arkansas River, the degree of mineralization increases toward the river. Here, seepage from the canal and irrigation water is the source of recharge.

RELATION OF WATER QUALITY AND USE

Ground water in the project area is generally of fair to good quality for most uses. Water-quality criteria differ according to use.

DOMESTIC USE

Water for domestic use should be clear, colorless, free of objectionable odor, taste, and disease-causing micro-organisms, and of reasonable temperature. Several State health departments have established quality standards, but the only nationwide standards for potable water are those established by the U.S. Public Health Service (1962). These standards apply only to culinary water used in railroad cars, aircraft, and vessels engaged in interstate commerce. The American Water Works Association has adopted these standards as recommended limits for public water supplies. Standards for some of the chemical constitutents are listed below:

Allowable limits for public water supply

Constituent	*Concentration (ppm)*	*Constituent*	*Concentration (ppm)*
Iron (Fe)	0.3	Fluoride (F^{-1})	[1]
Manganese (Mn)	.05	Nitrate (NO_3^{-1})	45
Chloride (Cl^{-1})	250	Dissolved solids	[2] 500
Sulfate (SO_4^{-2})	250		

[1] Latest recommendations (1962) give lower, optimum, and upper control limits for fluoride based on the annual average of maximum daily air temperatures. For the project area these limits are: 0.7 ppm (lower), 0.9 ppm (optimum), and 1.2 ppm (upper). Fluoride concentrations greater than 1.8 ppm constitute grounds for rejection of the supply.

[2] 1,000 ppm permitted, if no other supply is available.

Whereas few permanently disabling diseases or harmful effects are attributable to water (other than diseases of bacterial origin), concentrations of chemical constituents that exceed the recommended limits may render a water undesirable for domestic use. High magnesium concentrations in combination with sulfate (epsom salts) have laxative effects. Excess chloride imparts a characteristic salty taste to water. Fluoride in water at concentrations of about 1.0 ppm has been shown to prevent dental caries (Dean, 1936). Greater concentrations, however, give rise to chronic fluorosis of bone tissue and teeth, which appears as mottled enamel in the teeth of children. Excessive nitrate is particularly hazardous to infants because it causes methemoglobinemia or cyanosis. Excessive nitrate also may be an indication of contamination from sewage, decaying vegetation, or fertilizers.

Hardness in water is manifested by the formation of soap curd or scum. Hardness is caused principally by calcium and magnesium, although barium, strontium, aluminum, iron, and free acid, if present, contribute to hardness. The adjective ratings of hardness are subject to variation. The hardness classification of water used by the U.S. Geological Survey (S. K. Love, written comm., 1962) is as follows:

Hardness (ppm)	*Rating*
<60	Soft.
61–120	Moderately hard.
121–180	Hard.
>181	Very hard.

The ground water sampled in the project area ranges from soft to very hard, depending on the aquifer tapped. In general, water from the Dakota Sandstone and Cheyenne Sandstone Member of the Purgatoire Formation is soft to moderately hard. Water from other aquifers in the area is hard to very hard.

STOCK USE

Although animals can tolerate water having higher dissolved-solids content than human beings can, water that meets the standards for domestic use should be used for maximum production of eggs, meat, and milk. Prolonged periods of drinking highly mineralized water may result in physiological disturbances such as wasting, gastrointestinal disturbances, disease, and eventual death of the animal. Other effects are reduction in lactation and rate of reproduction.

The Western Australia Department of Agriculture (1950) lists the following threshold salinities (dissolved solids):

	Ppm		*Ppm*
Poultry	2,860	Cattle, dairy	7,150
Swine	4,290	Cattle, beef	10,000
Horses	6,440	Sheep, adult dry	12,900

The California State Water Pollution Control Board (1952, p. 155) reports that Colorado water containing as much as 2,500 ppm of dissolved solids is acceptable for stock use. Montana rates water containing less than 2,500 ppm salts as good, 2,500 to 3,500 ppm as fair, 3,500 to 4,500 ppm as poor, and greater than 4,500 ppm as unfit. Apart from total salt concentrations, certain salts—particularly the nitrates, fluorides, and salts of selenium and molybdenum—are specifically toxic to animals even in low concentrations.

It should be recognized, however, that the critical factor in the animal's metabolism is the total quantity of salts ingested. Salt intake depends on the daily water consumption, which, in turn, depends on the water content of feed, the temperature and humidity, and the degree of exertion of the animal. On the basis of the Colorado limit of 2,500 ppm of dissolved solids, most ground water in the area is rated acceptable for stock use.

IRRIGATION USE

Otero and Crowley Counties, which rank among the 100 most productive agricultural counties in the Nation, depend on large-scale highly developed irrigation for support of their agrarian economy.

The success or failure of any irrigation project depends on the quality of the water that is to be applied. Interpretation of water quality in relation to irrigation has been largely based on field observations and studies of plant tolerances. However, recent investigations by Eaton (1954), the U.S. Salinity Laboratory Staff (1954), and others are providing a better understanding of the subject.

The suitability of water for irrigation is determined by the total salt concentration, ratios of certain salts, the chemical reactions between salts in the applied water and the soil, and the increase in soil salt concentration after application. Water rated as good for irrigation may, under poor irrigation practices, cause deterioration and eventual destruction of the soil. Conversely, poor-quality water applied on well-drained soil in sufficient quantity so that injurious concentrations of salt are leached beyond the root zone will maintain good productivity with little damage to the soil, if soil amendments are used. The calcium to sodium ratio in irrigation water is an important consideration because of ion-exchange reactions in the soil. Water that is high in sodium in relation to calcium will cause alkalinization of, and consequently poor tilth in, soils that contain silt, fine clay, or organic fractions. In general, however, the sodium concentration must be more than half the soluble cations before exchange is significant. Because the exchange equilibrium favors calcium in the reaction, water that contains high calcium relative to sodium will maintain soil permeability and texture.

The U.S. Salinity Laboratory Staff (1954) has constructed a diagram for rating irrigation water on the basis of salinity and sodium (alkali) hazards. This diagram is interpreted as follows:

SALINITY HAZARD

*   *   *   *   *   *   *

Low-salinity water (C1) can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

Medium-salinity water (C2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

High-salinity water (C3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.

Very high salinity water (C4) is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

SODIUM [HAZARD]

The classification of irrigation waters with respect to SAR is based primarily on the effect of exchangeable sodium on the physical condition of the soil. Sodium-sensitive plants may, however, suffer injury as a result of sodium accumulation in plant tissues when exchangeable sodium values are lower than those effective in causing deterioration of the physical condition of the soil.

Low-sodium water (S1) can be used for irrigation on almost all soils with little danger of the devlopment of harmful levels of exchangeable sodium. However, sodium-sensitive crops such as stone-fruit trees and avocados may accumulate injurious concentrations of sodium.

Medium-sodium water (S2) will present an appreciable sodium hazard in fine-textured soils having high cation-exchange-capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability.

High-sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management—good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

Very high sodium water (S4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible.

*   *   *   *   *   *   *

In the classification of irrigation waters, it is assumed that the water will be used under average conditions with respect to soil texture, infiltration rate, drainage, quantity of water used, climate, and salt tolerance of crop. Large deviations from the average for one or more of these variables may make it unsafe to use what, under average conditions, would be a good water; or may make it safe to use what, under average conditions, would be a water of doubtful quality.

Suitability of ground water in Otero and Crowley Counties for irrigation was determined on the basis of the aforementioned criteria. The ratings, listed in table 7, show the ground water to be high (C3) to very high (C4) with respect to salinity hazard. The sodium (alkali) hazard of these samples include the entire range from low (S1) to very high (S4). The C3–S4 ratings of water from three wells (C21–58–26add, C22–54–27cdc, and C23–55–22cbc) are questionable because of their high sodium-adsorption-ratios. Water from two wells, C24–56–12abb and C26–54–24dbd, not rated because of excessively high conductance and sodium-adsorption-ratio, are assumed to be unfit for irrigation use.

Evapotranspiration, water drained from the root zone, and some harvesting practices result in a soil solution that may be many times more concentrated than the applied irrigation water. To keep irrigated croplands productive, salts must be prevented from accumulating in the soil by applying sufficient quantities of water to leach the soil and to carry excess salts beyond the root zone. An excessive amount of applied water, however, results in waste, in leaching of required plant nutrients, and probably in drainage problems.

Eaton (1954) proposed a method for the characterization and interpretation of analyses of irrigation water based on the leaching requirement and the amount of calcium, as gypsum, that should be added to irrigation water. Estimates of the leaching percentages and required calcium have been made, by use of Eaton's formulas, for ground water in the project area. These values, given in table 8, are tentative because an assumed value for mean soil-solution salinity was used in the calculations. Actual measurements, in the field, should be made to determine final percentage values of leaching and calcium requirements.

Eaton (1950) in a study of black alkali soils defined the concept of residual sodium carbonate as the excess of bicarbonate over calcium and magnesium expressed in milliequivalents per liter. He pointed out that when water contains residual sodium carbonate, calcium and magnesium are precipated in the soil with a corresponding increase in the sodium-adsorption-ratio. Therefore, even though sodium is originally not the predominate cation, it becomes so, causing an increase in the sodium hazard of irrigation water. Water that contains residual sodium carbonate in excess of 2.5 milliequivalents per liter is classified as unfit for irrigation. Water containing from 2.5 to 1.5 milliequivalents per liter is marginal, and that containing 1.5 milliequivalents per liter or less is safe. Marginal water may be safely used with proper use of soil amendments and good management practices.

TABLE 7.—*Suitability of ground water for irrigation*

Well	Specific conductance (micromhos per cm at 25° C)	Sodium-adsorption-ratio	Classification	Residual sodium carbonate (epm)	Boron (ppm)
C21-54-21aaa	2,240	8.3	C3-S2	8.05	---
55-12ddd	2,260	9.6	C4-S3	3.47	---
56- 2baa	1,770	10	C3-S3	2.81	---
58-22daa	2,220	5.0	C3-S2	.00	0.61
58-26add	1,920	32	C3-S4	4.33	---
59-11bab	1,990	11	C3-S3	2.58	---
59-33cdc	1,760	6.6	C3-S2	.00	---
59-35bbc	906	7.6	C3-S2	3.77	---
C22-54-15ccc	2,730	2.7	C4-S1	.00	---
54-27cdc	1,470	39	C3-S4	5.19	---
55-25add	1,340	24	C3-S4	4.20	---
57-30cca2	2,460	1.7	C4-S1	.00	.35
58-14bab	1,430	4.0	C3-S1	.00	.91
58-18cbd	1,430	1.8	C3-S1	.00	.11
58-21cbd2	2,020	1.8	C3-S1	.00	.23
58-26bdb	1,970	25	C3-S4	5.12	---
58-26bdd	1,750	22	C3-S4	3.18	---
59- 6ccc	3,240	4.1	C4-S2	.00	.28
59-20aaa	3,240	3.4	C4-S2	.00	---
59-23bba	2,120	1.8	C3-S1	.00	.22
59-29cbb	3,570	2.8	C4-S1	.00	.38
C23-54-13abb	2,490	3.1	C4-S1	.00	.37
54-14cbb	2,780	2.7	C4-S1	.00	.33
54-23ada	2,350	4.2	C4-S2	.00	.35
54-27bcc	4,290	5.3	C4-S2	.00	---
54-28adb	2,860	3.9	C4-S2	.00	.29
54-29dda	3,440	3.5	C4-S2	.00	---
55- 4ccb2	2,850	25	C4-S4	14.10	---
55-22cbc	2,160	41	C3-S4	6.87	---
55-31abc	3,110	2.4	C4-S1	.00	---
55-34dca	1,980	2.4	C3-S1	.00	---
55-36cda	2,970	3.7	C4-S2	.00	.34
55-36ddc	2,500	2.9	C4-S1	.00	---
56- 6baa	1,780	2.0	C3-S1	.00	.23
56-22bcb	3,070	3.1	C4-S1	.00	.39
56-25cac	1,420	17	C3-S4	3.00	---
56-25cad	1,530	22	C3-S4	6.54	---
57- 3bda	2,060	2.1	C3-S1	.00	.25
57- 4add	1,770	14	C3-S3	.00	---
C24-55- 1bbc2	2,330	2.9	C4-S1	.00	---
56- 4ccc	3,120	2.9	C4-S1	.00	.53
56- 6dcd	1,240	12	C3-S3	1.83	---
56-12abb	6,370	7.7	---	.00	---
57-24abd2	4,110	4.1	C4-S2	.00	.69
58-19abd	1,360	18	C3-S4	7.16	---
C25-54- 2cda	3,380	15	C4-S4	.00	---
57- 6dad	1,640	6.7	C3-S2	.00	---
58-13ddb	1,770	3.7	C3-S1	.00	---
C26-54-21aad	3,120	5.1	C4-S2	.00	---
54-24dbd	8,960	86	---	6.81	.27
55-22bbb	2,390	8.4	C4-S2	.00	.27
56-19aca	1,950	4.9	C3-S2	.00	.21
57-19adc	1,520	3.5	C3-S1	.00	---
58-17bbb	2,370	3.6	C4-S1	.00	---
C27-54-17caa	3,590	16	C4-S4	.30	---
55-30bdd	1,090	4.0	C3-S1	.00	.24
57-30dda	3,730	1.8	C4-S1	---	---
58-28bca	1,930	2.8	C3-S1	.00	.22
59-27dcd	1,340	2.3	C3-S1	.00	---
C28-54- 3bbb	2,600	7.2	C4-S2	.00	---

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TABLE 8.—*Leaching and gypsum requirements for reasonable crop yields*

[Gypsum requirement: Asterisk (*) indicates excess]

Well	Leaching requirement (D percent)	Gypsum requirement (pounds per acre-foot)	Well	Leaching requirement (D percent)	Gypsum requirement (pounds per acre-foot)
C21-54-21aaa	25	3,860	C23-55-34dca	15	(*)
55-12ddd	24	2,900	55-36cda	27	(*)
56- 2baa	22	2,000	55-36ddc	19	(*)
58-22daa	16	(*)	56- 6baa	13	(*)
58-26add	20	2,720	56-22bcb	28	(*)
59-11bab	19	2,110	56-25cac	14	2,050
59-33cdc	16	380	56-25cad	15	2,980
59-35bbc	8.8	1,900	57- 3bda	15	(*)
C22-54-15ccc	23	(*)	57- 4add	24	1,720
54-27cdc	17	2,820	C24-55- 1bbc2	20	(*)
55-25add	13	2,200	56- 4ccc	32	(*)
57-30cca2	22	(*)	56- 6dcd	10	924
58-14bab	8.2	(*)	56-12abb	100	(*)
58-18cbd	8.9	(*)	57-24abd2	53	(*)
58-21cbd2	14	(*)	58-19abd	12	2,910
58-26bdb	16	1,880	C25-54- 2cda	34	2,000
58-26bdd	17	2,320	57- 6dad	13	489
59- 6ccc	30	(*)	58-13ddb	12	(*)
59-20aaa	33	(*)	C26-54-21aad	24	(*)
59-23bba	15	(*)	54-24dbd	100	(*)
59-29cbb	42	(*)	55-22bbb	19	543
C23-54-13abb	22	(*)	56-19aca	14	(*)
54-14cbb	26	(*)	57-19cdc	9.6	(*)
54-23ada	19	(*)	58-17bbb	18	(*)
54-27bcc	44	(*)	C27-54-17caa	17	2,810
54-28adb	28	(*)	55-30bdd	7.3	(*)
54-29dda	32	(*)	57-30dda	50	(*)
55- 4ccb2	36	5,780	58-28bca	14	(*)
55-22cbc	26	3,530	59-27dcd	8.1	(*)
55-31abc	29	(*)	C28-54- 3bbb	12	225

The following table, as adopted from Agricultural Engineering Fact Sheet SW10, University of Wyoming, 1956, presents the class limits for boron concentrations:

Boron hazard	Limits (ppm)		
	Sensitive crops	Semitolerant crops	Tolerant crops
Very low. No effect on crops	0.33	0.67	1.00
Low. Very slight effect on crops	0.33–0.67	0.67–1.33	1.00–2.00
Moderate. Significant yield depression	0.67–1.00	1.33–2.00	2.00–3.00
High. Large yield depression anticipated	1.00–1.25	2.00–2.50	3.00–3.75
Very high. Nonusable	1.25	2.50	3.75

Boron concentrations in water from wells in the project area are shown in table 7. In general, the water can be used for all but the most sensitive crops, such as most fruit trees. Water samples from wells C21–58–22daa, C22–58–14bab, C24–56–4ccc, and C24–57–24abd2 are the only ones that contain more than 0.4 ppm of boron.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES

JURASSIC SYSTEM

UPPER JURASSIC SERIES

MORRISON FORMATION

The Morrison Formation consists of interbedded variegated marl, siltstone, clay, and shale that contain thin beds of dense limestone and lenses of sandstone. Dinosaur bones have been found in the formation in many areas. The fine-grained materials are commonly gray, green, red, or maroon and exhibit shaly structure. Some of the beds are highly jointed and break up into blocks. The beds of fine-grained material generally form long slopes below the massive Cheyenne Sandstone Member of the Purgatoire Formation and are generally covered. Good exposures are found only in stream or roadcuts.

The limestone and sandstone beds are usually gray, tan, or white and are more resistant than the clay, marl, siltstone, and shale beds. The limestone is platy, dense, and silty. The sandstone is commonly friable and fine grained.

In this report, the Morrison Formation includes all the beds between the Entrada Sandstone and the Purgatoire Formation. However, the basal part—which contains white or light-gray gypsum, beds of red chalcedony, some conglomerate, varicolored marl, clay, and shale—is no longer considered part of the Morrison by some geologists and is called the middle unit of Jurassic age (Oriel and Mudge, 1956).

The Morrison is present throughout the project area but is exposed only along the Purgatoire River and some of its tributaries. It ranges in thickness from 125 to 175 feet. The Morrison is overlain by the Cheyenne Sandstone Member of the Purgatoire Formation, but the contact is not always definite. (See p. 62.)

The age of the Morrison is Late Jurassic. It is present throughout much of the Rocky Mountain and Great Plains region.

Water supply.—The Morrison is generally not considered an aquifer because it is fine grained. Several stock and domestic wells in the canyons along the Purgatoire River, however, tap small supplies of water of fair quality from some of the sandstone beds.

CRETACEOUS SYSTEM

LOWER CRETACEOUS SERIES

PURGATOIRE FORMATION

The Purgatoire Formation overlies the Morrison Formation and underlies the Dakota Sandstone. It consists of two members: the Kiowa Shale Member, and the underlying Cheyenne Sandstone Member. For many years the name Dakota Sandstone was used to designate both the Purgatoire Formation and the present Dakota Sandstone. Local residents refer to the Cheyenne as the "lower" or "second Dakota" and to the Dakota Sandstone as the "upper" or "first Dakota."

The Purgatoire Formation in many areas contains marine Comanchean fossils, which date it as Early Cretaceous. It is present throughout southeastern Colorado and western Kansas. The Kiowa Shale Member is equivalent to the Glencairn Shale Member of the Purgatoire along the Front Range to the west, and the Cheyenne Sandstone Member is equivalent to the Lytle Sandstone Member of the Purgatoire.

CHEYENNE SANDSTONE MEMBER

The Cheyenne Sandstone Member (fig. 16) is commonly a light-colored fine- to coarse-grained friable sandstone. In places, it contains a considerable thickness of shale and sandy shale. The lighter color and relatively easily erodable nature of the sandstone serve to distinguish it from the Dakota Sandstone.

The contact of the Cheyenne with the underlying Morrison Formation is difficult to distinguish in many places. The basal sandstone beds in the Cheyenne are not persistent and may end abruptly against variegated clay and shale similar to that of the Morrison Formation. Figure 17, a photograph taken just south of Otero County, shows a thick sandstone in the Cheyenne (at the right) ending abruptly against variegated shale. A deep test hole drilled at Las Animas, Colo., showed that the base of the Cheyenne contained 34 feet of variegated shale above another sandstone having typical Cheyenne lithology (James H. Irwin, oral commun., 1962). The base of the Cheyenne was picked at the bottom of the last sandstone having Cheyenne lithology. This same contact was used in the project area, and the variegated clay and shale exposed along the Purgatoire River were mapped as part of the Cheyenne. The contact of the Cheyenne with the overlying Kiowa

FIGURE 16.—The Cheyenne Sandstone Member of the Purgatoire Formation at locality C26–53–19cac.

FIGURE 17.—The Cheyenne Sandstone Member of the Purgatoire Formation showing variable lithology at locality C28–55–6cba.

Shale Member is generally not difficult to distinguish at an outcrop. It is difficult to distinguish, however, in well cuttings where the upper part of the Cheyenne is shaly or the Kiowa is very sandy. In general, the sandstone of the Cheyenne is white, compared with the yellowish-brown sandstone of the Kiowa.

The Cheyenne is present throughout the project area except where it has been removed by erosion along the Purgatoire River and its tributaries. The only outcrops of the Cheyenne are in the canyon walls of this area. The thickness of the Cheyenne as determined from drillers' logs ranges from 70 to 110 feet.

Water supply.—The Cheyenne is one of the two major artesian aquifers in the area, although it is not extensively developed. Yields from wells tapping just the Cheyenne are reported to be as high as 65 gpm. Because the lithologic characteristics of the formation may change within a short distance, the Cheyenne is not as good an aquifer in some places as it is in others. Figure 18 compares electric logs from 2 wells 4 miles apart. At well C23–54–20cac, the Cheyenne is very shaly, and most of the water comes from the Dakota Sandstone. At well C23–55–36bbc, the Dakota Sandstone is very shaly, and most of the water comes from the Cheyenne.

KIOWA SHALE MEMBER

The Kiowa Shale Member overlies the Cheyenne Sandstone Member and underlies the Dakota Sandstone. It consists of dark-gray to

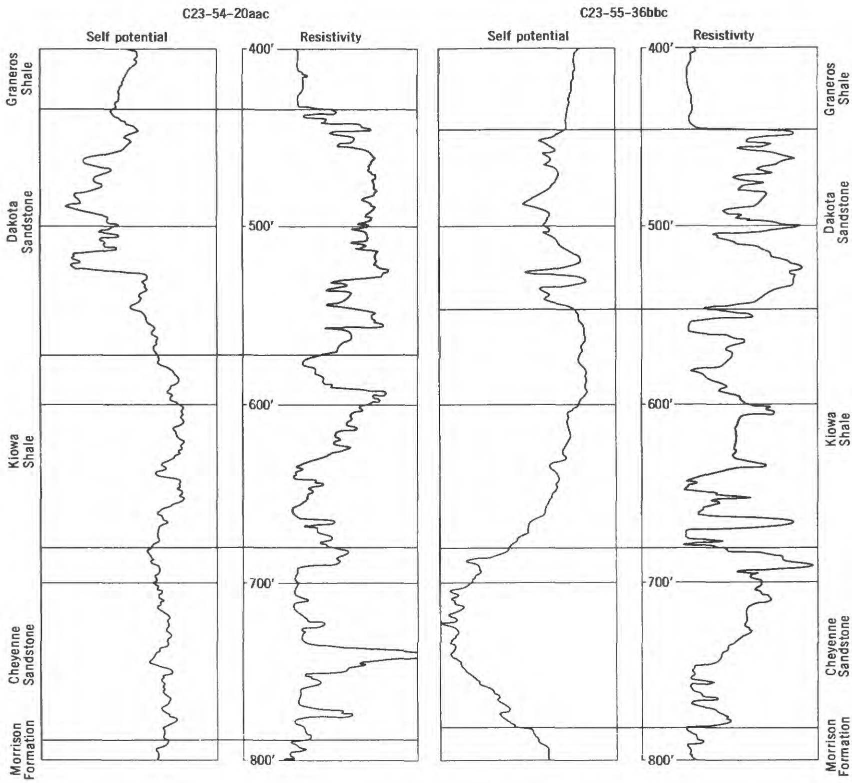

FIGURE 18.—Comparison of two electric logs, showing lateral change in lithology of the Dakota Sandstone and the Cheyenne Sandstone Member of the Purgatoire Formation.

black shale and sandy shale, which may be slightly calcareous. In places, the Kiowa becomes very sandy, having the appearance of a soft yellowish-brown sandstone. In such places the Kiowa may be mistaken for a part of the Dakota or Cheyenne.

Like the Cheyenne, the Kiowa underlies all the project area except southeastern Otero County, where it has been removed by erosion. It crops out along the Purgatoire River and its tributaries, and may crop out in Devil's Canyon in southwestern Otero County.

The thickness of the Kiowa, as determined from drillers' logs, ranges from 50 to 130 feet in the project area. Because the shale tends to mask the sandstone and the contact is difficult to determine from drillers' logs, this range is probably too high. True thickness is probably between 40 and 90 feet, as measured at outcrops in other areas.

Water supply.—The Kiowa is not known to yield water to wells in the project area, but it acts as a confining bed for water in the Cheyenne. Because of its shaly nature, the Kiowa is relatively impermeable and prevents any appreciable movement of water between the Dakota Sandstone and the Cheyenne.

DAKOTA SANDSTONE

The Dakota Sandstone overlies the Kiowa Shale Member of the Purgatoire Formation and underlies the Graneros Shale. This name was formerly applied also to the beds of the Purgatoire Formation and is still used in that way by many of the local residents.

The Dakota generally consists of two massive beds of sandstone separated by a sandy shale unit. The sandstone is commonly hard, fine to medium grained, and massive. It commonly breaks up into large angular blocks and is buff to tan or, rarely, light gray, white, or yellow. Weathered surfaces generally are heavily coated with desert varnish, and in places Indians have chipped away this coating to form pictographs. The sandstone is commonly crossbedded and fine grained but locally may be conglomeratic. The sandstone is generally resistant to erosion and forms steep ledges and cliffs, some as high as 50 feet.

The sandy shale in the Dakota is commonly dark gray to black, but it may have a yellowish-brown appearance. This shale is easily eroded and generally forms steep slopes between the sandstone beds. These slopes are generally covered with blocks of sandstone, which have broken off the overlying beds. In some areas, there is a transition zone at the top of the Dakota consisting of thin beds of sandstone and shale.

The Dakota underlies all the project area except where it has been removed by erosion in parts of southern Otero County. Outcrops of the Dakota are confined to the southern part of Otero County. The Dakota ranges in thickness from 75 to 140 feet, according to drillers' logs.

The Dakota Sandstone in southeastern Colorado is of Early Cretaceous age. It is recognized throughout much of the Rocky Mountains, Great Plains, the Colorado Plateau, and the San Juan Basin.

Water supply.—The Dakota Sandstone is one of the two major artesian aquifers in Otero and Crowley Counties. Yields as high as 85 gpm have been reported from wells tapping it in this area. It is commonly overlain by the impermeable Graneros Shale, and, consequently, the water is under artesian pressure, which in some areas is sufficient to produce flowing wells. Along the deep canyons in southern Otero County, the Dakota may have been drained, and a well must be drilled into the Cheyenne Member of the Purgatoire Formation to obtain water. As shown in figure 18, the lithology of the Dakota varies laterally, and the formation will not everywhere yield enough water. In such areas, however, it is usually possible to obtain a good supply from the Cheyenne.

UPPER CRETACEOUS SERIES

GRANEROS SHALE

The Graneros Shale overlies the Dakota Sandstone and underlies the Greenhorn Limestone. As originally defined by Gilbert (1896), it included units now called the Lincoln Limestone and Hartland Shale Members of the Greenhorn Limestone.

The Graneros consists chiefly of dark-gray to black fissile noncalcareous shale. Locally, the shale may be calcareous. The middle part of the formation is generally darker than the upper or lower parts. At the base there is generally a transition zone of several feet of interbedded thin sandstone and shale. A concretionary zone 30 or 40 feet above the base of the formation is common, and a hard black dense clayey concretionary limestone occurs about 40 feet below the top in southwestern Otero County. This limestone weathers orange brown and forms a slight bench. The Graneros contains several thin beds of bentonite, called "talc" by the drillers, and thin stringers of gypsum crystals. The shale is soft and easily eroded and is commonly covered by slope wash and vegetation.

Although the Graneros underlies most of the project area, good outcrops may be found only in southwestern Otero County along Timpas Creek and in south central Otero County along Sheep Canyon Arroyo and its tributaries. According to drillers' logs the Graneros ranges in thickness from 90 to 200 feet and appears to thicken to the west.

The Graneros is of Late Cretaceous age and is recognized throughout eastern Colorado and western Kansas. It is the equivalent of the lower part of the Mancos Shale of western Colorado and Utah.

Water supply.—The Graneros is relatively impermeable and is not known to yield water in the project area. It acts as a confining bed for water in the Dakota Sandstone.

GREENHORN LIMESTONE

The Greenhorn Limestone, which overlies the Graneros Shale and underlies the Carlile Shale, consists of three members. From the base upward, the members are: the Lincoln Limestone, the Hartland Shale, and the Bridge Creek Limestone. The Greenhorn contains so much shale that it is hard to distinguish it from the Carlile and Graneros Shales in drillers' logs. Commonly, only part of the Bridge Creek Limestone Member is recognized as Greenhorn; the rest of the Greenhorn is mistaken for the Graneros or Carlile, and therefore an erroneous thickness for the formations is indicated.

Because there are few good exposures of the Greenhorn in most of the area, no attempt was made to map the members separately except east of La Junta, where only the Bridge Creek Limestone Member crops out (pl. 1).

The Lincoln Limestone Member consists mainly of calcareous shale and thin beds of platy clayey limestone. It is generally dark gray to black and may contain a few thin beds of bentonite. The limestone is highly fossiliferous and has a petroliferous odor when broken. It resembles the Codell Sandstone Member of the Carlile Shale in this area but is grayer and finer grained, and the beds are not as wavy. The Lincoln forms a slight bench in the southern part of Otero County.

The Hartland Shale Member is not well exposed in the project area. It consists mostly of gray limy shale, which contains a few thin beds of limestone and bentonite.

The Bridge Creek Limestone Member consists of interbedded chalky limestone, limy shale, a few thin layers of bentonite, and in places a thin bed of limestone conglomerate. The limestone beds are 1 inch to 1 foot thick and are separated by a few inches to a few feet of shale. The limestone is hard, dense, and gray and weathers to chalky white; it contains numerous fossils, especially in the upper part of the section. The limestone is resistant to erosion and forms a series of benches, which are especially well formed east of La Junta, where some are capped by Illinoian and older Wisconsin terrace deposits (fig. 19).

FIGURE 19.—Benches formed by limestone beds in the Bridge Creek Limestone Member of the Greenhorn Limestone east of La Junta (C23–54–33b). The bench in the foreground is capped by older Wisconsin terrace deposits, that in the background by Illinoian terrace deposits.

The Greenhorn Limestone crops out south of the Arkansas River east of La Junta and in a strip across southern Otero County. It underlies all the project area north of its outcrops. The Lincoln Limestone Member is 25 to 50 feet thick, the Hartland Shale Member is 10 to 30 feet thick, and the Bridge Creek Limestone Member is 30 to 85 feet thick, as determined from drillers' logs.

The Greenhorn Limestone is of Late Cretaceous age. It is recognized in eastern Colorado, western Kansas, the Oklahoma panhandle, and eastern New Mexico. It is equivalent to part of the Mancos Shale in western Colorado and New Mexico.

Water supply.—The Lincoln Limestone Member is not usually considered an aquifer, but it may yield small quantities of water to wells in some parts of Otero County. The Hartland Shale Member is relatively impermeable and is not known to yield water any place in the project area. The Bridge Creek Limestone Member yields small amounts of water to a few stock wells in southern Otero County.

CARLILE SHALE

The Carlile Shale overlies the Greenhorn Limestone and underlies the Niobrara Formation. It consists of three members, in ascending order: the Fairport Chalky Shale, the Blue Hill Shale, and the Codell Sandstone. Except for a few isolated outcrops of the Fairport south of the Arkansas River east of La Junta and some scattered outcrops of the Codell along the contact with the Fort Hays Limestone Member of the Niobrara Formation, the Carlile was mapped as a unit.

The Fairport Chalky Shale Member consists of tan to dark-gray fissile chalky shale at the base, which grades upward into blue-black to black calcareous shale. It contains some thin beds of limestone, which become less numerous in the upper part of the section, and a few thin layers of bentonite. The contact with the underlying Bridge Creek Limestone Member of the Greenhorn Limestone can be accurately determined only on the basis of fossils, but the approximate contact can be determined from changes in the lithologic character of the limestone beds. The Fairport grades upward into the Blue Hill Shale Member; it is not well exposed in the project area.

The Blue Hill Shale Member is generally a noncalcareous fissile black or blue-black shale, which contains some calcareous shale near the base. From 15 to 30 feet below the top of the Blue Hill is a zone of large septarian concretions. These concretions are generally tan or gray and are as much as 6 feet in diameter. The center of the concretions commonly contains brown and white calcite crystals and may contain some barite crystals. Cone-in-cone structure is commonly present in the outer shell of the concretions.

The Codell Sandstone Member is actually a slightly sandy limestone throughout most of the project area. It is hard, brown, and very fossiliferous. A fresh surface emits a strong petroliferous odor and exhibits crystal faces, which weather to form a rough surface. The bedding is generally very wavy (fig. 20). The Codell thickens to the west and east of the project area and grades to sandstone. As shown on figure 20, the contact with the overlying Fort Hays Limestone Member of the Niobrara Formation generally is distinct. Where the Fort Hays is thick, the Codell crops out as a bluff, with the Blue Hill exposed below it. Where the Fort Hays forms a rubbly slope, the underlying Codell generally forms a bench, which is covered with

FIGURE 20.—Contact of the Codell Sandstone Member of the Carlile Shale and the Fort Hays Limestone Member of the Niobrara Formation (C24–55–25abc).

fragments of Codell, and the Blue Hill is poorly exposed. Where the Fort Hays forms only a slight slope, the Codell appears only as rubble on the land surface, and the Blue Hill is generally not exposed.

The Carlile Shale occurs throughout most of the project area except in parts of southern Otero County, where it has been removed by erosion. The Fairport Chalky Shale Member and the Blue Hill Shale Member are both about 75 feet thick; the Codell ranges from 3 to 12 feet in thickness.

The numerous fossils in the Carlile have established it as Late Cretaceous in age. The Carlile is recognized throughout much of the region east of the Rocky Mountains. It is equivalent to part of the Mancos Shale of western Colorado and Utah.

Water supply.—Both the Fairport Chalky Shale Member and the Blue Hill Shale Member are relatively impervious and are not known to yield water to wells. The Codell Sandstone Member probably yields small amounts of water to a few stock wells in Otero County.

NIOBRARA FORMATION

The Niobrara Formation in this area was originally divided into the Timpas Limestone and the Apishapa Shale Members. The contact between these two members is not readily apparent everywhere and is virtually impossible to determine in well samples. Therefore, Dane, Pierce, and Reeside (1937) proposed that the subdivision used in

Kansas be applied to this area. The massive beds of limestone at the base of the formation are now called the Fort Hays Limestone Member, and the rest of the formation is called the Smoky Hill Marl Member.

FORT HAYS LIMESTONE MEMBER

The Fort Hays Limestone Member consists of a series of hard white to light-gray chalky limestone beds, 6 inches to 3 feet thick, separated by 1 to 6 inches of gray calcareous shale. A thin layer of bentonite was found in the shale north of the Arkansas River at the Bent County line, and bentonite may occur elsewhere. The limestone is strongly jointed and breaks into flakes parallel to the bedding. The Fort Hays is fossiliferous and contains numerous pyrite crystals and nodules of limonite near the base. It is generally very resistant and forms prominent bluffs along most of its outcrop. (See fig. 20 and p. 68.)

The Fort Hays ranges from 40 to 70 feet in thickness, according to drillers' logs, but is commonly about 55 feet thick. It crops out on both sides of the Arkansas River east of Swink and forms a high ridge across the central part of Otero County. It is present in the project area everywhere north of the Arkansas River.

On the basis of fossils, the Fort Hays has been dated as Late Cretaceous. It is recognized in eastern Colorado and western Kansas.

Water supply.—The Fort Hays supplies small quantities of water to stock wells in Otero County; an irrigation well south of Swink pumps 70 gpm. The water is carried in the joint system and in solution channels.

SMOKY HILL MARL MEMBER

The Smoky Hill Marl Member consists predominantly of gray, tan, or yellow limy shale and marl, which weathers a characteristic yellowish orange. There are several thin beds of limestone and layers of bentonite scattered through the member and at least one zone of limonite concretions. The beds are sparsely fossiliferous. Many of the bedding planes and joint surfaces are coated with gypsum or calcite crystals. A distinctive characteristic is the numerous white flecks of calcite that give the beds a "salted" appearance. Because the shale is easily eroded, the Smoky Hill is generally not well exposed. Low bluffs of Smoky Hill north of La Junta that exhibit the thin bedding of this member are shown on figure 21.

The Smoky Hill crops out near Timpas, east of the Apishapa River, south of the Rocky Ford High Line Canal, north of Swink and La Junta, and in a few other scattered areas. It is present in the subsurface north and west of its outcrops. On the basis of well logs, the Smoky Hill ranges from 400 to 700 feet in thickness in the project area. The Smoky Hill is of Late Cretaceous age and is recognized in eastern Colorado and western Kansas.

FIGURE 21.—The Smoky Hill Marl Member of the Niobrara Formation north of La Junta at locality C23–55–26bcc.

Water supply.—Although it is fairly impermeable, the Smoky Hill yields small quantities of water to a few stock wells. The water probably occurs along the bedding planes and joints.

PIERRE SHALE

The Pierre Shale in the project area consists principally of fissile dark-gray to black calcareous shale and some thin beds of limestone and layers of bentonite. Although the Pierre has been subdivided into several members in other areas, correlation is not certain, and these members are not used here. The Pierre can be divided into zones, however, to facilitate its description. The lower 300 to 350 feet in the project area consists of blue-gray thin-bedded shale, which contains abundant selenite crystals. Because it contains very few fossils, it is called the barren zone. Above this zone is a sequence of blue-gray shale, which contains very little selenite but abundant iron-stained concretions. This is the rusty zone, so called from the orange-brown color of the weathered concretions. This zone is overlain by a thinner zone consisting of light-gray very fossiliferous shale. Because of the large numbers of baculites in it, the zone is called the baculite zone. It is not certain that this zone occurs in the project area. North of Olney Springs there are about a dozen erosional features called tepee buttes. These low mounds are formed by a hard core of limy material and resemble the tepees of the plains Indians.

Although it is much thicker elsewhere, the Pierre Shale is probably not more than 600 feet thick in the project area. It occurs west of a line drawn from Lake Henry to the Apishapa River.

The Pierre is Late Cretaceous in age. It is recognized nearly everywhere east of the Rocky Mountains and is equivalent to the upper part of the Mancos Shale and the lower part of the Mesaverde Group of western Colorado and Utah.

Water supply.—The Pierre Shale is relatively impervious and is not known to yield water to wells in this area.

TERTIARY SYSTEM

OLIGOCENE(?) OR MIOCENE(?) SERIES

INTRUSIVE ROCKS

A dike extends for 3 or 4 miles in the northern half of T. 26 S., R. 59 W. The dike is a syenitic lamprophyre that is probably associated with the igneous activity of the Mesa de Maya region (Ross Johnson, oral commun., 1962). Because it is fairly soft, the dike does not form a ridge. Its occurrence is generally indicated by a line of rubble on the surface. The dike weathers readily into spheroidal blocks. The dike is about 15 feet thick and is of middle Tertiary age, probably late Miocene or early Oligocene.

QUATERNARY SYSTEM

PLEISTOCENE SERIES

The various Pleistocene deposits in the project area have not been definitely dated. Their stratigraphic relations and accumulation of caliche, however, indicate that they can probably be correlated with deposits of known age in other parts of Colorado, particularly those around Denver and along the South Platte River. The following table shows the correlation of these deposits with those of the Denver area and the South Platte valley near Greeley:

Correlation of Pleistocene deposits in eastern Colorado

Age	Arkansas River valley		Denver area [1]		South Platte River valley near Greeley [2]	
	Name	Height above river (feet)	Name	Height (feet)	Name	Height above river (feet)
Late Wisconsin	Younger Wisconsin terrace deposits	20–50	Broadway Alluvium	35–50	Kersey terrace	25–45
					Kuner terrace	10–20
Early Wisconsin	Older Wisconsin terrace deposits	60–80	Louviers Alluvium	50–70	Pleasant Valley terrace	50–60
Illinoian	Illinoian deposits	90–110	Slocum Alluvium	70–100	Timnath pediment	80–100
Kansan	Kansan deposits	150–200	Verdos Alluvium	150–200	Coalbank pediment	150
Late Nebraskan	Younger Nebraskan deposits	250–300	Rocky Flats Alluvium	350	Spottlewood pediment	200
Early Nebraskan	Older Nebraskan deposits	350		450		

[1] Scott (1962).
[2] Bryan and Ray (1940).

In general, the height of the deposits above the stream increases upstream with the distance between the deposits. In Otero and Crowley Counties this relation can be traced westward to the Front Range at Canon City (H. E. McGovern, oral commun., 1962). A generalized section of the Arkansas River valley in the project area, showing the relations of the various Pleistocene deposits, is given on figure 22. Illinoian, Kansan, and older Nebraskan deposits are not shown north of the river because they either do not occur or occur only in very small spots in the project area.

The Nebraskan deposits, particularly those northwest of Olney Springs, are out of the valley proper and probably represent sheet-type deposits predating the present Arkansas River drainage. The Kansan deposits are between the Nebraskan deposits and the valley proper and may represent the period during which the present drainage system was established. Both the Illinoian and the Wisconsin deposits are adjacent to and parallel to the present Arkansas River channel.

The occurrence of caliche in the various Pleistocene deposits also seems to be diagnostic. Generally, the youngest deposits contain the least caliche. Caliche or calcareous material was penetrated in all the test holes drilled into the Nebraskan deposits. Cemented zones were also penetrated in several holes, and a 4-inch bed of nearly pure caliche is exposed northwest of Olney Springs. Caliche occurs in the Kansan deposits as a grayish-white to light-pink cementing material and as a thick coating on much of the gravel. Caliche also occurs in the Illinoian deposits as cement or coating, but it is not as thick nor does it occur as extensively. Caliche forms only spotty accumulations in the Wisconsin deposits.

The only fossil found in Pleistocene deposits in the project area during the study is a horse tooth from a gravel pit in the older Wisconsin terrace deposits (C23–56–10cbc). This has been identified as an upper cheek tooth of *Equus* sp., probably of middle to late Pleistocene age, according to G. E. Lewis (written commun., 1961) and C. B. Schultz (written commun., 1961).

NEBRASKAN DEPOSITS

The oldest Pleistocene deposits in the project area are those of Nebraskan age. These deposits consist of generally unconsolidated moderately well sorted sand, gravel, clay, and silt, which contain some well-rounded cobbles. The materials are coarse at the bottom, are usually gray to pinkish, and contain considerable amounts of feldspar. The upper part of the deposits is generally white or gray and contains little or no gravel. The deposits contain much caliche; one bed 4 inches thick is exposed northeast of Olney Springs (C21–59–26add).

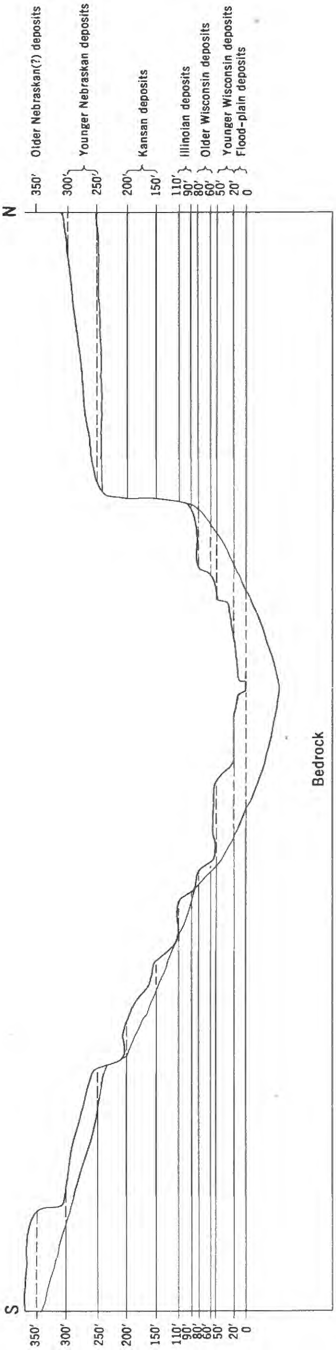

FIGURE 22.—Generalized section of the terraces.

The Nebraskan deposits lie on the Pierre Shale or the Smoky Hill Marl Member and commonly have a hard brown crossbedded conglomerate at the base (fig. 23).

FIGURE 23.—Hard crossbedded conglomerate at the base of the Nebraskan deposits (C22-59-3dba). A manhole for one of the springs flowing from the deposits is visible at the left of the photograph below the conglomerate.

Figure 24 shows a comparison of particle-size-distribution curves of samples collected from gravel pits in four of the Pleistocene deposits. It shows that the Nebraskan deposits consist of more than 70 percent sand and finer materials, whereas the other three deposits consist of 50 percent or less of these materials.

Nebraskan deposits form the high plateau north and west of Olney Springs and are 250 to 300 feet above the Arkansas River. These deposits extend westward into Pueblo County, and north and east to the Big Sandy Creek drainage. Nebraskan deposits also crop out south of the Arkansas River on the high buttes between Fowler and Rocky Ford. Deposits in sections 17–20, T. 23 S., R. 58 W., probably represent an earlier period of deposition in Nebraskan time (Glenn Scott, oral commun., 1962). They are about 350 feet above the river. Nebraskan deposits also crop out in a small area west of the La Junta airport. Thickness of the Nebraskan deposits in the project area ranges from 0 to about 100 feet.

Most of the Nebraskan deposits in the project area were previously mapped as the Ogallala Formation. Although these deposits are similar to the Ogallala in color and mode of deposition, there are enough dissimilarities that the author and other geologists who studied the area believe that the deposits are younger than the Ogallala. The

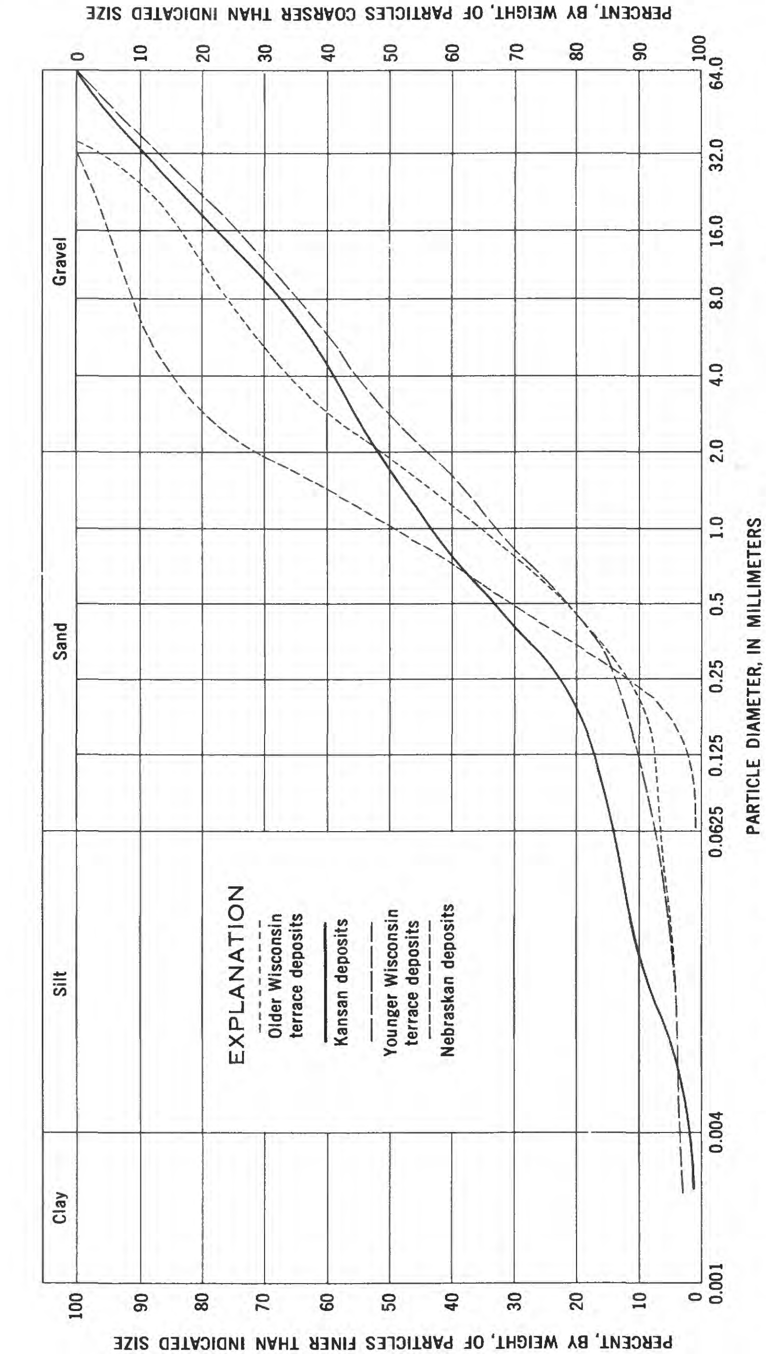

FIGURE 24.—Particle-size-distribution curves compared for samples from four of the Pleistocene deposits.

Ogallala north of Big Sandy Creek trends northeastward, whereas the Nebraskan deposits trend southeastward. An attempt to correlate the two units across Big Sandy Creek near Wild Horse, Colo., showed that the Nebraskan deposits are several hundred feet lower topographically. The algal limestone, which is fairly persistent at the top of the Ogallala throughout the High Plains, is conspicuously absent south and west of Big Sandy Creek. The Ogallala contains mostly granitic material from the Rocky Mountains, whereas the Nebraskan deposits contain finer-grained arkosic material, probably derived from the Black Forest and Castle Rock areas. These deposits are discussed further by Elkin (1958, p. 8–10), who also believes they are younger than the Ogallala.

Water supply.—Although the Nebraskan deposits in the southwestern part of the project area generally have less than 10 feet of saturation, as shown on plate 5, they are an important source of water for public supply. The towns of Fowler and Olney Springs, and the Crowley County Water Association obtain their supplies of soft water from springs flowing from these deposits. Elsewhere, small supplies of water for stock and domestic use are usually obtainable from wells. It is very doubtful that yields greater than 50 gpm can be obtained from these deposits in the project area. The Nebraskan deposits in the rest of the area are generally drained.

KANSAN DEPOSITS

Isolated deposits that may be of Kansan age cap high buttes, generally of the Smoky Hill Marl Member, on both sides of the Arkansas River. These deposits consist of poorly sorted clay, sand, gravel, and cobbles, which contain large amounts of caliche coating and cementing the particles. The larger fragments are commonly well rounded. As shown on figure 24, gravel makes up nearly 50 percent of the deposits. The gravel and cobbles are mostly fragments of granite, pegmatite, and dark igneous rocks.

The Kansan deposits are from 150 to 200 feet above the flood plain. They range in thickness from 0 to about 30 feet.

No fossils have been found in the deposits. These deposits have been assigned a Kansan age on the basis of their relation to other Pleistocene deposits in the area.

Water supply.—Throughout most of the project area the Kansan deposits are drained. In some areas, however, they yield small quantities of water to wells and springs.

ILLINOIAN TERRACE DEPOSITS

The Illinoian terrace deposits consist of generally unconsolidated poorly sorted clay, sand, gravel, and cobbles, which contain considerable caliche, although not as much as the Kansan deposits. The deposits are commonly crossbedded and may contain hard crossbedded conglomerate. The deposits do not seem to contain as great a percentage of coarse gravel and cobbles as the Kansan deposits, and most of the rocks are fragments of granite and pegmatite, containing very few fragments of dark igneous rocks, such as those in the Kansan deposits.

The major area of Illinoian terrace deposits is south of the Arkansas River from Patterson Hollow to about 2 miles east of Rocky Ford. They also cap scattered buttes near La Junta and along the Apishapa River. They range in thickness from 0 to about 50 feet.

Water supply.—The Illinoian deposits may yield small amounts of water to wells and springs. The isolated deposits are mostly drained.

WISCONSIN TERRACE DEPOSITS

The Wisconsin terrace deposits consist generally of unconsolidated clay, silt, sand, gravel, cobbles, and boulders, which have spotty accumulations of caliche. Locally, as in the area near Swink and north of Manzanola, there is a very hard conglomerate ½ to 5 feet thick at or near the base of the section (fig. 25). The larger particles are well rounded and consist mostly of fragments of granite and pegmatite. As shown on figure 24, they have a higher percentage of gravel than other Pleistocene deposits.

Two levels of Wisconsin deposits may be found along the Arkansas River. The older deposits lie 60 to 80 feet above the river. They range

FIGURE 25.—Hard crossbedded conglomerate near the base of the older Wisconsin terrace deposits north of Manzanola (C22–58–14ddb).

in thickness from 0 to 85 feet and are generally not as extensive as the younger deposits. The younger Wisconsin terrace deposits lie 20 to 50 feet above the river, where they are exposed, but they also are found under the flood-plain deposits. They range in thickness from 0 to 60 feet and extend the length of the Arkansas River valley in the project area.

Figure 26 shows particle-size-distribution curves for representative samples of the younger Wisconsin terrace deposits collected from six test holes drilled for this project.

Because these deposits are the lowest Pleistocene deposits in the area and because they have spotty accumulations of caliche, which is typical of other deposits of this age, these deposits were probably laid down during Wisconsin time.

Water supply.—The younger Wisconsin terrace deposits form the most important unconsolidated aquifer in the project area. Approximately 90 percent of the ground water used for irrigation comes from this aquifer as does all the water for La Junta and much of the water for Fowler, Manzanola, Rocky Ford, and Swink. The older Wisconsin terrace deposits yield as much as 300 gpm to irrigation wells in the area between Timpas Creek and Crooked Arroyo. Elsewhere, they are drained or yield only small quantities of water to wells and springs.

PLEISTOCENE AND RECENT SERIES

UPLAND DEPOSITS

The term "upland deposits" is used in this report to include all the unconsolidated deposits that are not associated with streams. Some of the material is weathered shale, some is slope wash, and a considerable amount seems to be wind deposited. Northeast of Cheraw, the deposits are clayey medium to fine sand containing some caliche, coarse sand, and very fine gravel. When dry, they are light tan and very hard; wet, they are yellowish brown and slippery. They rest on an irregular surface of the Smoky Hill Marl Member, which gives the material a yellow color where the marl is close to the surface. Along the outlet from Lake Meredith, the deposits are very sandy and have the appearance of loess. South of Hawley, they are a tan to light-brown sandy clay, containing some gravel and caliche that decrease in abundance with depth.

The upland deposits in the project area overlie the Smoky Hill Marl Member or the Pierre Shale. They crop out over a large area north of the Arkansas River valley east of Colorado State Highway 71, over much of the area south of the Arkansas River valley west of La Junta and north of Timpas, and in a few other small areas. They range in thickness from 0 to about 80 feet.

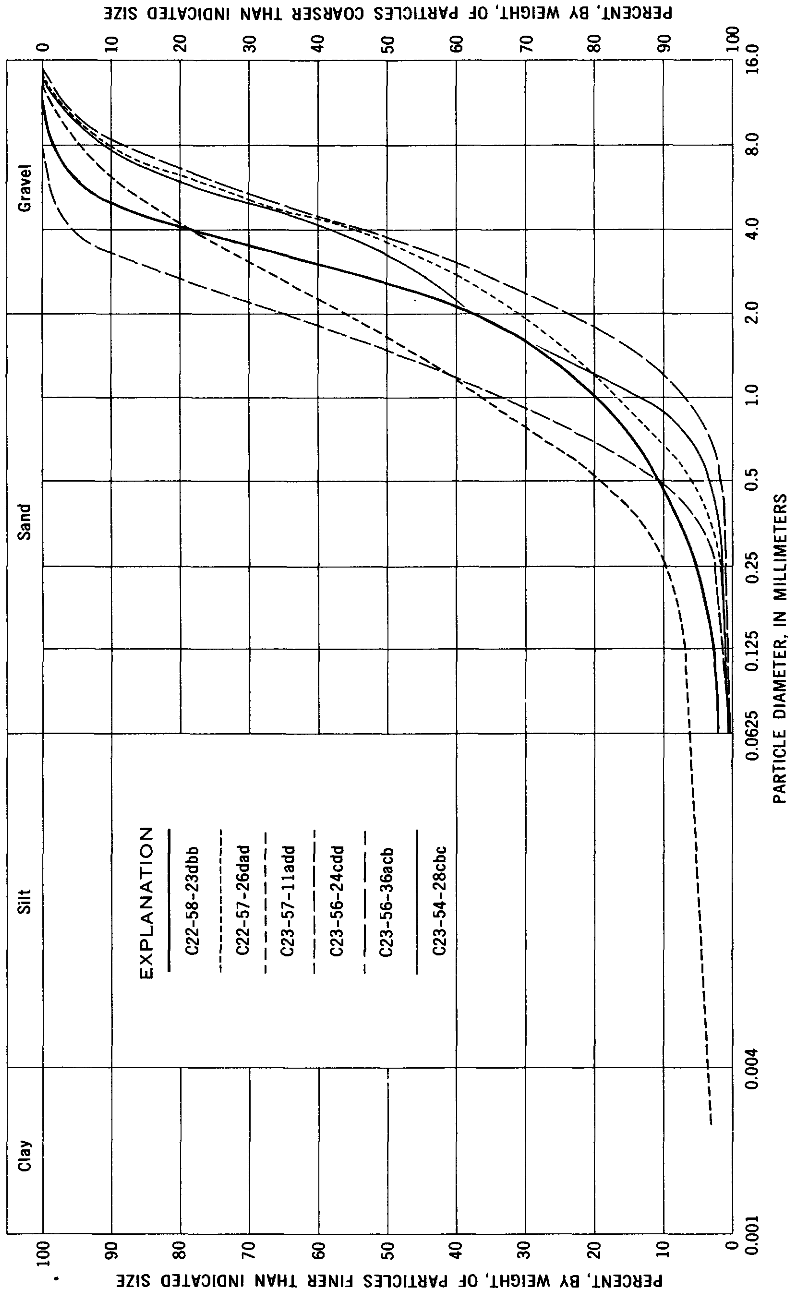

FIGURE 26.—Particle-size-distribution curves compared for six samples from the younger Wisconsin terrace deposits.

The age of the upland deposits is not definitely known, but from their appearance and relation to other deposits they are probably late Wisconsin to early Recent.

Water supply.—The upland deposits may yield small quantities of water for stock and domestic purposes where they are saturated.

VALLEY-FILL DEPOSITS

The term "valley-fill deposits," as used in this report, includes all alluvial deposits outside of the Arkansas River. In the Arkansas River valley, the flood-plain and terrace deposits are mapped separately. In general, the deposits consist of well- to moderately well sorted clay, sand, and gravel, which may in places contain some caliche. The gravel generally consists of flat pebbles of limestone and shale concretions—probably derived locally. There may be some cementation, especially at the contact with the underlying bedrock. Figure 27 compares particle-size-distribution curves for some of the cleaner gravel collected from test holes. The deposits along the Apishapa River (C22–59–34caa) and Timpas Creek (C24–56–5cdd and C24–56–8aaa) are better sorted and coarser than those in the Olney Springs-Sugar City area (C21–58–36ccc) and the Cheraw area (C23–56–11bcc).

In addition to the areas just mentioned, valley-fill deposits were also mapped along Horse Creek, along the Purgatoire River, and along some of the other tributaries of the Arkansas River. Although they may be as much as 75 feet thick, these deposits are commonly less than 50 feet thick.

Water supply.—The valley-fill deposits generally yield small quantities of water for stock and domestic wells throughout the project area. Where they are fairly permeable and have sufficient saturation, the deposits yield as much as 600 gpm for irrigation.

RECENT SERIES

FLOOD-PLAIN DEPOSITS

The flood-plain deposits consist primarily of unconsolidated clay, silt, and sand and some thin lenses of gravel. These deposits are generally gray or tan and crossbedded and overlie younger Wisconsin terrace deposits.

Flood-plain deposits are differentiated only along the Arkansas River on the geologic map (pl. 1). Elsewhere, they have been lumped with other alluvial deposits and mapped as valley-fill deposits. They range in thickness from 0 to 15 feet. The flood-plain deposits are Recent in age.

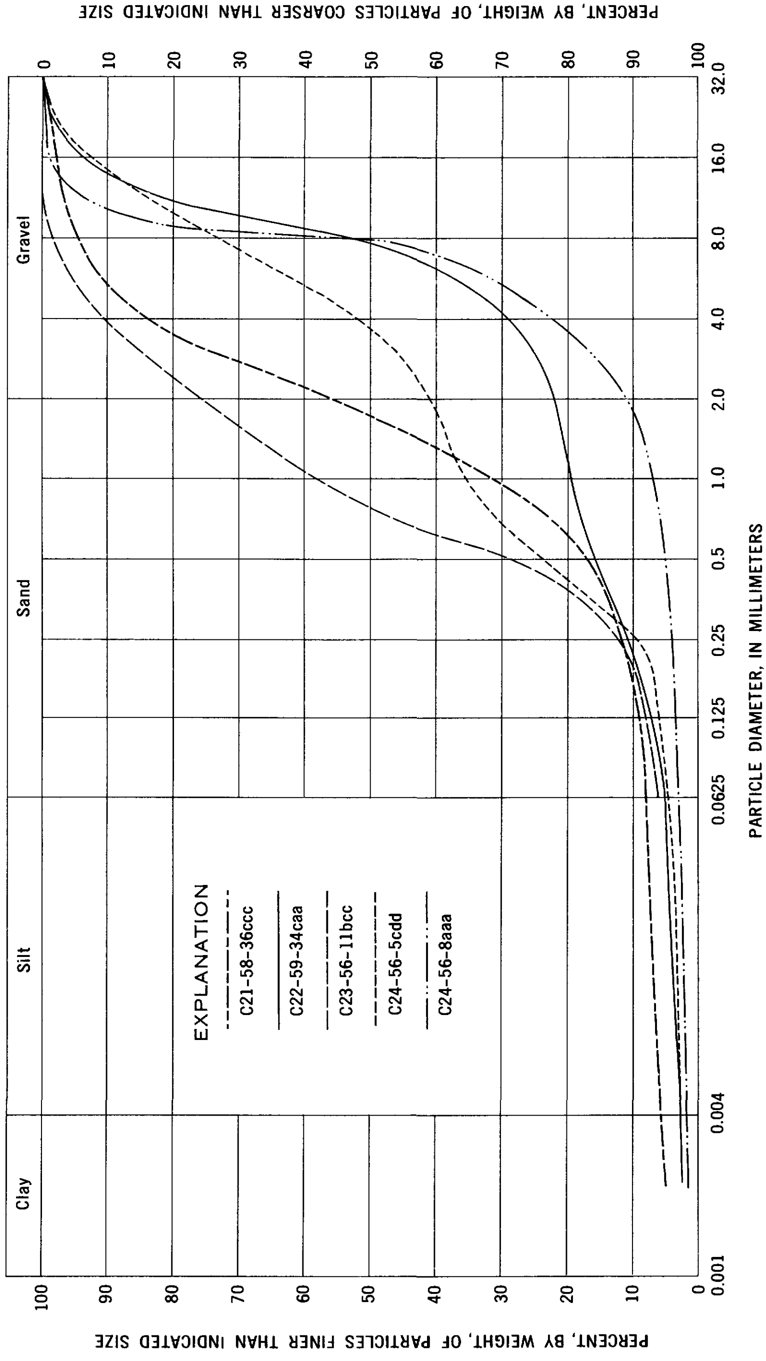

FIGURE 27.—Partcile-size-distribution curves compared for samples of valley-fill deposits.

Water supply.—The flood-plain deposits are not known to yield water to wells in the project area; however, because they are topographically low, the water table is high, and considerable amounts of water are evaporated and transpired.

DUNE SAND

Dune sand in the project area is composed chiefly of very fine to coarse subrounded to well-rounded grains of clear quartz. It commonly contains some feldspar, and the upper part is commonly silty or clayey. The dunes are generally yellow or white, and most of them have been stabilized by vegetation.

Large areas of dune sand were mapped northwest of Olney Springs and north of Rocky Ford. There are smaller areas of dune sand east of La Junta, north of Cheraw, and elsewhere. The dune sand northwest of Olney Springs ranges from 0 to 45 feet in thickness. No figures are available for the other areas, but the dune sand there is probably no thicker.

The dune-sand deposits were formed during Recent times; a deposit east of La Junta is not stabilized, and the sand still moves when the wind blows.

Water supply.—The dune sand is above the water table, and, hence, yields no water. The porosity of the dunes, however, makes them major catchment areas for recharging underlying aquifers.

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