# Geology and Ground-Water Resources of Washington County Colorado

*By* HAROLD E. McGOVERN

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# GEOLOGY AND GROUND-WATER RESOURCES OF WASHINGTON COUNTY, COLORADO

By Harold E. McGovern

## ABSTRACT

Washington County, in northeastern Colorado, has an area of 2,520 square miles. The eastern two-thirds of the county, part of the High Plains physiographic section, is relatively flat and has been moderately altered by the deposition of loess and dune sand, and by stream erosion. The western one-third is a part of the South Platte River basin and has been deeply dissected by tributary streams. The soils and climate of the county are generally suited for agriculture, which is the principal industry.

The rocks that crop out in the county influence the availability of ground water. The Pierre Shale, of Late Cretaceous age, underlies the entire area and ranges in thickness from 2,000 to 4,500 feet. This dense shale is a barrier to the downward movement of water and yields little or no water to wells. The Chadron Formation, of Oligocene age, overlies the Pierre Shale in the northern and central parts of the area. The thickness of the formation ranges from a few feet to about 300 feet. Small to moderate quantities of water are available from the scattered sand lenses and from the highly fractured zones of the siltstone. The Ogallala Formation, of Pliocene age, overlies the Chadron Formation and in Washington County forms the High Plains section of the Great Plains province. The thickness of the Ogallala Formation ranges from 0 to about 400 feet, and the yield from wells ranges from a few gallons per hour to about 1,500 gpm. Peorian Loess, of Pleistocene age, and dune sand, of Pleistocene to Recent age, mantle a large part of the county and range in thickness from a few inches to about 120 feet. Although the loess and dune sand yield little water to wells, they absorb much of the precipitation and conduct the water to underlying formations. Alluvium, of Pleistocene and Recent age, occupies most of the major stream valleys in thicknesses of a few feet to about 250 feet. The yield of wells tapping the alluvium ranges from a few gallons per minute to about 3,000 gpm, according to the thickness of saturated material.

Development of ground water for irrigation has been generally restricted to the South Platte, Arikaree, and Beaver valleys. There were 134 irrigation wells, 3 industrial wells, and 10 municipal wells in the county in 1959. The annual ground-water pumpage from Washington County is estimated to be 18,000 acre-ft; about 10,000 acre-ft is from the High Plains ground-water province.

Although some ground water enters the county as underflow, most of the recharge to ground-water reservoirs is from precipitation on the land surface. Recharge to the Ogallala Formation in the county is assumed to be approximately equal to the natural discharge from the county by underflow because ground-water withdrawals are from storage, and no other significant amount of natural discharge is apparent. Underflow in the Ogallala was calculated to be 83,000 acre-ft per year and the rate of recharge from precipitation to be about

0.95 inch per year. Neither recharge nor discharge was calculated for that part of the county in the South Platte River basin.

All ground water in Washington County has a high proportion of bicarbonate and is classed as hard to very hard. The sodium-adsorption-ratio for all samples analyzed was below the limit recommended for irrigation water. All the water from the Ogallala Formation and most of the water from the Chadron Formation is suitable for domestic use. Some water from the alluvial deposits overlying the Pierre Shale was exceptionally high in calcium, magnesium, and sodium sulfates.

Ground water has been heavily developed for irrigation in the South Platte valley and in some parts of the Beaver and Arikaree valleys. Some additional areas, however, could be developed in the latter two valleys. Large quantities of ground water in the Ogallala Formation are available for future development. The quantity of water in storage in the High Plains ground-water province in Washington County is about 6.5 million acre-ft. It may be feasible to utilize only 1 million acre-ft of the stored water for agriculture.

Some excess surface runoff in the playa lakes in the High Plains and in the Arikaree valley is available for artificial recharge. Water-level records show that the seasonal demand for water in some areas of the Arikaree valley probably exceeds the aquifer capability, but 8-year records indicate that the aquifer is not being rapidly depleted. Both water-spreading and injection-well techniques could be used in the Arikaree valley, although additional data on availability of water and rate of sedimentation would be needed to determine the economic feasibility.

## INTRODUCTION

### LOCATION

Washington County is in northeastern Colorado and extends about 60 miles north-south and 48 miles east-west. (See fig. 1.) The area of the county is about 2,520 square miles. Akron, the county seat, is 95 miles northeast of Denver.

### PURPOSE AND SCOPE

The purpose of the investigation was to determine the character, thickness, and extent of the geologic formations and the occurrence, quantity, and quality of ground water within these formations. Additional purposes were to determine the extent of present ground-water development, the possibilities of further development, and the feasibility of utilizing artificial recharge.

The investigation was begun in July 1957, as a part of the cooperative program between the U.S. Geological Survey and the Colorado Water Conservation Board. Credit is given D. L. Coffin for his assistance in the collection of data during the first 2 years of the project and V. M. Burtis, who determined all altitudes for wells and test holes. The compilation of the data and completion of the report were under the direct supervision of T. G. McLaughlin and E. A. Moulder, successive district geologist and district engineer, in charge of ground-water investigations in Colorado.

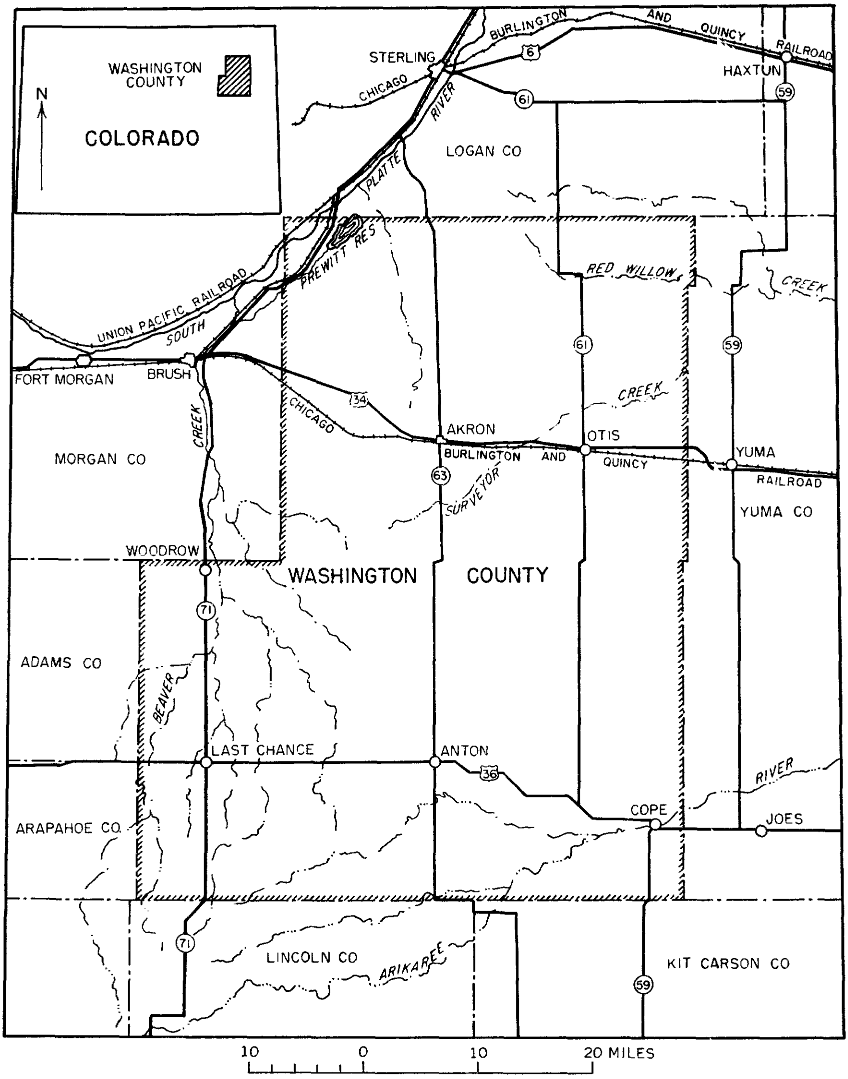


*FIGURE 1.—Map showing the location of Washington County, Colo.*

## PREVIOUS INVESTIGATIONS

The geology and ground-water resources of Washington County were first described by Darton (1905) as a part of a comprehensive report of the central Great Plains. Cardwell (1953) discussed the area in a reconnaissance of irrigation-well development in the Kansas River basin of eastern Colorado. The part of Washington County that lies in the South Platte River valley was studied in detail by Bjorklund and Brown (1957), and the northeastern part of the county was included in the detailed study of the Frenchman Creek basin by Cardwell and Jenkins (1963). A detailed study has also been made in Yuma County by Weist (1964).

## METHOD OF INVESTIGATION

Information on ground-water conditions in Washington County was collected from 360 selected wells representative of the area. The depth to water below the land surface was measured in these wells, and the altitude of the land surface at the wells was determined by planetable leveling. The wells were located with the aid of U.S. Department of Agriculture aerial photographs. Data on the yield and performance of most of the large-capacity wells were obtained to ascertain the present rate of pumping and the potential yield of the water-bearing materials.

The surface geology was mapped on aerial photographs and transferred to a base map prepared by the Topographic Division of the U.S. Geological Survey. Mapping of the dune-sand and loess areas in the northern half of the county was greatly facilitated by a soils map of the Akron area prepared by E. W. Knobel and others (1947).

Information on the subsurface geology was obtained from several thousand logs of wells, test holes, and seismograph shot holes. Supplemental information was obtained from sample logs of 54 test holes drilled for the U.S. Geological Survey in strategically selected areas.

The hydrologic properties of some sand and gravel deposits were determined by means of acquifer tests. Samples of material taken from the flood plain of the Arikaree River were tested by the Hydrologic Laboratory, U.S. Geological Survey, Denver, Colo.

Water samples were collected from 12 selected wells, each representative of a particular locality and water-bearing formation. The samples were analyzed by the Quality of Water Branch, U.S. Geological Survey, Denver, Colo.

The records of wells, logs, water-level measurements, test holes, and chemical analyses collected during this investigation have been published by the Colorado Water Conservation Board (McGovern, 1961).

## WELL-NUMBERING SYSTEM

The numbering system used in this report is based on the U.S. Bureau of Land Management system of land subdivision. The number shows the location of the well or test hole by quadrant, township, range, section, and position in the section. A graphical illustration of this method of location is shown in figure 2. The capital letter at the beginning of the location number indicates the quadrant in which the well is located. Four quadrants are formed by the intersection of the

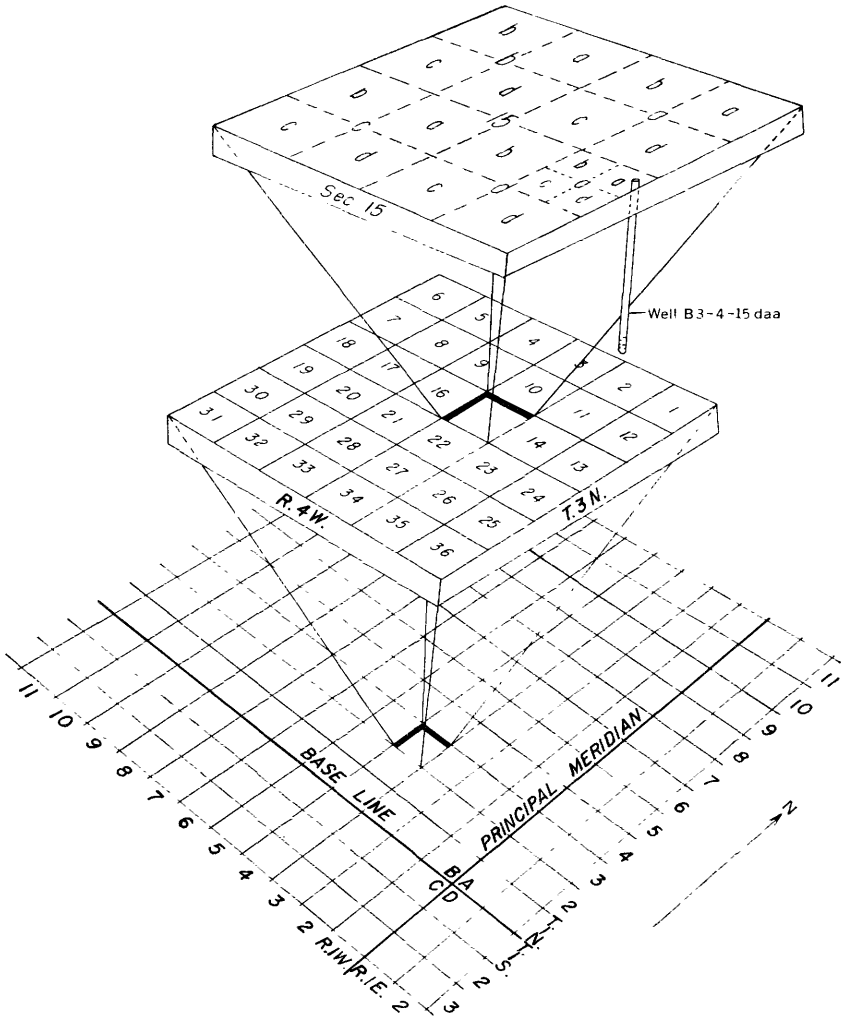


FIGURE 2.—System of numbering wells and test holes in Colorado.

base line and the principal meridian—A indicates the northeast quadrant B, the northwest quadrant; C, the southwest quadrant; and D, the southeast quadrant. The first numeral indicates the township, the second indicates the range, and the third indicates the section in which the well is located. Lowercase letters following the section number locate the well within the section. The first letter denotes the quarter section, the second letter denotes the quarter-quarter section, and the third letter denotes the quarter-quarter-quarter section. The letters are assigned in the section in a counterclockwise direction, beginning with (a) in the northeast quarter of the section. Letters are assigned in each quarter section and in each quarter-quarter section in the same manner. Where two or more locations are in the smallest smallest subdivision, consecutive numbers beginning with 2 are added to the letters in the order in which the wells or test holes were inventoried. For example, C4–55–12abc2 indicates a well in the southwest quarter of the northwest quarter of the northeast quarter of sec. 12, T. 4 S., R. 55 W., and shows that this is the second well inventoried in the quarter-quarter-quarter section. The capital letter C indicates the township is south of the base line and that the range is west of the principal meridian.

### ACKNOWLEDGMENTS

This report was made possible through the cooperation and contributions of many people and agencies. Gratitude is extended to the people of Washington County who permitted access to their property and provided information on their wells. The writer also is indebted to the officials of Washington County for permission to drill test holes on county rights-of-way, to the officials of Akron and Otis for information on the municipal water systems, and to the Y. W. Electric Assoc., U.S. Soil Conservation Service, Colorado Agricultural Experiment Station, Wrape and Payne Drilling Co., D. W. Venrick and Son, Amerada Oil Co., California Co., Lion Oil Co., Ohio Oil Co., Skelly Oil Co., and Texas Co. for additional information.

## GEOGRAPHY

### TOPOGRAPHY AND DRAINAGE

Washington County is in the Great Plains physiographic province. The eastern two-thirds of the county is a part of the High Plains section and the western one-third is in the South Platte River basin and is part of the Colorado Piedmont section.

The High Plains part of the county is chiefly a plain that has been moderately altered by deposition of dune sand and loess, and by stream erosion. Sand dunes cover an area of approximately 240 square miles in the east-central part of the county. The dunes form a series of northwest-southeast-trending ridges, which reach a maximum thickness of more than 100 feet. However, the valleys formed between the ridges may have only a few feet of sand cover. Most of the remaining area of the High Plains in the county is covered by loess, which ranges in thickness from a mantle of several feet to ridges of more than 100 feet. The ridges are oriented in the same general direction as the sandhills.

The drainage pattern of the High Plains is poorly defined owing to the preponderance of loess and dune-sand cover. The numerous small drains end abruptly in depressions or merely disappear in the porous soil. The Arikaree River and Red Willow Creek are the only continuous streams in this area. The drainage system of the High Plains generally trends northeastward.

The Colorado Piedmont section of the county may be subdivided into three areas: The South Platte valley, the sandhills area, and Beaver valley. The South Platte River, which crosses the northwest corner of the county, forms a flat valley floor approximately 2 miles wide. Roughly parallel to the southeast side of the South Platte valley lies an area of sand dunes covering about 270 square miles. These dunes form northwest-southeast ridges as much as 80 feet thick. The sand dunes extend southeastward approximately 18 miles before they grade into the low escarpment of the High Plains. Beaver valley is typified by meandering streams in a gently undulating terrain in the northern part and by narrow and deeply entrenched streams among rolling hills in the southern part.

All streams of the Colorado Piedmont section in Washington County drain into the perennial South Platte River. The flow is regulated by upstream reservoirs and is not subject to pronounced fluctuations. All other streams in the county are ephemeral and carry water only after a rain or snowmelt. Water in smaller streams is quickly absorbed by the very sandy bed material.

## CLIMATE

The climate of Washington County is semiarid, and dry farming is generally successful during years of normal and above-normal rainfall.

The average annual temperature is 48° F. and the average temperature during the growing season is 58° F. The average length of the growing season is 151 days.

The average annual precipitation, as recorded by the U.S. Weather Bureau station at Akron, is 17.49 inches. Precipitation averages 13 inches from March through August and is sufficient to mature the principal crops. However, crops may wither even during a year of high rainfall if showers are infrequent.

One of the greatest hazards to crops is the moderate to strong wind, common to the area. Wind blowing over dry soils in the early spring may remove new plants or cover them with so much sand that they require replanting. In the late summer, the hot, dry winds remove moisture very rapidly. Occasional hail storms are disastrous to small areas.

## POPULATION AND ECONOMY

Washington County has been almost exclusively an agricultural area until recent years, when oil production became economically significant. Consequently, its economy and growth have been dependent on adequate precipitation and the trend of the market for farm products. Trends suggest, however, that the oil industry will not become great and that agriculture will remain the principal industry in the foreseeable future.

The population of the county is sparse and has been gradually declining since 1940. The official census shows that the total population in the county was 8,336 in 1940, 7,520 in 1950, and 6,625 in 1960. During 1960, 37 percent of the population lived in the towns of Akron (1,890) and Otis (568).

Transportation needs are served by the Union Pacific Railroad; the Chicago, Burlington, and Quincy Railroad; U.S. Highways 6, 34, and 36; and by State Highways 59, 61, 63, and 71. Most of the farm products are transported by truck to the railroads for shipment to distant markets.

About 85 percent, or 1,400,000 acres, of the total land area in Washington County is farmland, of which approximately 50 percent, or 688,000 acres, is classified as suitable for growing crops. However, the 1959 agricultural census shows that only 401,000 acres was harvested while the remainder was in fallow, used for pasture, or left idle. The principal crop is winter wheat, which is raised on more than 69 percent of the cultivated acreage. The other major crops are corn, barley, rye, sorghums, and hay. The native hay, which grows abundantly on the sandy soils of the remaining 50 percent of the farmland, is ideal for pasture. At the end of 1959 more than 41,000 cattle and 12,000 sheep were being grazed in the county.

Irrigation has been limited owing to the success of dry farming. The use of surface water for irrigation is confined to the South Platte valley, where irrigation has been practiced since the late 1800's. The use of ground water for irrigation in this same area began in 1920, increasing slowly until the late 1930's, when a series of dry years and a shortage of surface-water supplies caused rapid development of ground water. There are now 134 irrigation wells in Washington County. Details concerning ground-water development are discussed in the section "Utilization of water." Ground water always has been a great asset to the economy of the county because adequate supplies for domestic and stock uses are available nearly everywhere. Since 1958, ground water also has been used for water-flooding operation to increase oil production.

Oil was discovered in this area in 1950, and by 1959 more than 1,600 wells were drilled throughout the county. Because water flooding is reported to be successful, it seems likely that greater amounts of ground water will be used for the production of oil. The only other important mineral resources in the county, besides water and oil, are sand, gravel, and caliche, which are used extensively for road metal.

# GEOLOGY

## SUMMARY OF STRATIGRAPHY

The rocks that crop out in Washington County are sedimentary and range in age from Late Cretaceous to Recent. The age, thickness, physical character, and water-bearing properties of these rocks are summarized in table 1, and their areas of outcrop are shown on plate 1. A more detailed description of lithologic characteristics is included in the section "Geologic formations" as an aid to future exploratory drilling.

Rocks older than the Pierre Shale do not crop out in the area. Some of them contain oil and presently are of economic importance. Others contain large amounts of saline water that may be of economic value in the future. However, evaluation of the saline-water resources is beyond the scope of this study, so details concerning the occurrence of the older rocks will not be discussed.

## GEOLOGIC HISTORY

Washington County is underlain by about 8,000 feet of sedimentary rocks ranging in age from Cambrian to Recent. These rocks overlie granite of Precambrian age. The brief description of the geologic history in this report is based largely on data obtained from the numerous oil tests throughout the county and on geologic data collected during this investigation.

### PALEOZOIC ERA

The history of the Paleozoic Era is first marked by a period of erosion that removed a part of the Precambrian granite. Near the end of Cambrian time, deposits of sandstone were laid down in the shallow sea that invaded the area. A marine limestone was deposited before the sea retreated in Early Ordovician time. During the remainder of the Ordovician and the ensuing Silurian and Devonian Periods, the area was subjected to erosion, which may have removed much of the limestone. The seas returned in Early Mississippian time and deposited a marine limestone before withdrawing. At the beginning of the Pennsylvanian Period the rise of the Rocky Mountains was accompanied by the formation of a parallel trough, which extended throughout most of eastern Colorado. Seas rapidly invaded the trough and deposited nearly 1,300 feet of interbedded limestone and mudstone before retreating in Late Pennsylvanian time.

Continental sediments from the Rocky Mountains were deposited in this region during most of Permian time. By the close of the Paleozoic Era, approximately 1,100 feet of Permian red beds had been deposited in the area.

TABLE 1.—*Generalized section of the geologic units exposed in Washington County, Colo.*

| System | Series | Geologic unit | Thickness | Physical character | Water supply |
|---|---|---|---|---|---|
| Quaternary | Recent and Pleistocene | Dune sand | 0–100± | Reddish-orange windblown sand | Serves as catchment area for recharge but does not yield water to wells. Generally above water table. |
| | | Alluvium | 0–250+ | Pink, brown, and gray sand, gravel, clay, and silt. | Yields small to large quantities of water to wells. |
| | Pleistocene | Peorian Loess | 0–120+ | Massive yellowish-brown eolian silt. Well sorted and slightly cemented. | Yields no water to wells. Generally above water table. |
| Tertiary | Pliocene | Ogallala Formation | 0–350 | Gray to red sand, gravel, silt, and clay containing abundant caliche. Has caprock of algal limestone. | Yields small to large quantities of water to wells. |
| | Oligocene | Chadron Formation | 0–300± | Massive olive to tan siltstone containing lenses and channels of sandstone. | Yields small to moderate quantities of water from channel deposits and fractures. |
| Cretaceous | Upper Cretaceous | Pierre Shale | 2,000–4,500± | Thin-bedded, gray to dark-gray shale and sandy shale containing limestone and limonite concretions. | Yields small quantities of water to wells from the upper weathered zone. Forms the lower confining layer for water in overlying unconsolidated deposits. |

### MESOZOIC ERA

The Mesozoic Era began under environmental conditions similar to those at the end of the Paleozoic; therefore, some additional continental deposition may have continued during Early Triassic time.

Renewed uplift of the Rocky Mountains during Late Jurassic time revived the streams that carried the sand and clay of the Morrison Formation into this area. This deposition was followed by a short period of erosion before seas began to spread into the area near the middle of Cretaceous time. The shoreline fluctuated back and forth leaving the interfingering beds of marine and nonmarine sandstone and shale that constitute the Dakota Sandstone. During Late Cretaceous time, the sea spread over the land, depositing a thick sequence of marine limestone and shale of the Greenhorn, Carlile, Niobrara, and Pierre Formations. As the sea withdrew at the close of the Cretaceous Period, the Fox Hills Sandstone probably was deposited over part of the area, although it has been removed by subsequent erosion.

By the end of the Mesozoic Era, the sea had retreated and the uplift of the Rocky Mountains had begun again.

### CENOZOIC ERA

Paleocene and Eocene sediments that probably were being transported eastward as the mountains continued to rise are not present as recognizable deposits in the area. Either they were not deposited as far east as Washington County or they were removed by subsequent erosion. By the beginning of Oligocene time, a large basin had formed to the north and northwest in which the sand, silt, and clay of the Chadron Formation were laid down as stream or lake deposits. Some evidence indicates that fine-grained volcanic material also was brought into the area and laid down in the form of eolian deposits. The extent of deposition during Oligocene time is not known. More recent erosion has removed all Oligocene rocks except in a relatively small wedge-shaped area in the northern half of the county (pl. 1).

The period of erosion that followed Oligocene deposition lasted until mid-Pliocene. The Rocky Mountains began to rise again, and the increased gradient caused streams to cut deep channels into the underlying Oligocene and Cretaceous rocks. As downcutting in the mountains continued during Pliocene time, stream gradients decreased and the coarser materials were deposited in the valleys. When the valleys became filled, the streams meandered back and forth across the upland until the whole region was covered with the thick deposit of sand, gravel, and clay of the Ogallala Formation. At the end of Ogallala deposition, the area was a broad, flat plain with meandering streams and many shallow lakes in which fresh-water limestone was formed.

Intermittently through the early Pleistocene Epoch uplift in the mountains and abrupt climatic changes revived stream activity. Many small streams cut channels into the Pliocene surface and filled them with material, generally of local origin. The ancestral South Platte River cut to its maximum depth and deposited material transported from the mountains. Downcutting streams in the Beaver Creek area removed much of the Chadron Formation and deeply incised the Pierre Shale.

By late Pleistocene time, stream activity had diminished, and wind became the dominant agent of deposition. Great masses of silt or loess were blown southeastward from the major stream valleys and were deposited over most of the county. Eolian deposition was interrupted by a short period of erosion, during which small streams dissected the loess deposits. Then the winds returned with even greater velocity and spread great quantities of dune sand over the area. The dune-sand deposits in Washington County probably are of very late Pleistocene to early Recent age. Recent activity in this area has been mostly limited to minor downcutting and deposition in the stream valleys.

## GEOLOGIC FORMATIONS

### CRETACEOUS SYSTEM—UPPER CRETACEOUS SERIES

#### PIERRE SHALE

The oldest formation that crops out in Washington County is the Pierre Shale of Late Cretaceous age. Although the Pierre crops out over a wide area in the western part of the county, it is commonly covered by deeply weathered soils or by the more recent alluvium, loess, or dune sand.

The formation may be described in general terms as a gray to dark-gray shale to sandy shale that contains an abundance of limestone concretions and concretionary limonite. The shale is thin bedded, only slightly calcareous, and is olive gray (5*Y* 4/1) to light olive gray (5*Y* 6/1) on the scale of the "Rock-Color Chart" (Goddard and others, 1948). Some fresh exposures are black. The material weathers to medium gray (*N* 5) or medium light gray (*N* 6) and has a blocky texture.

The abundant limestone in the formation occurs either in thin ledges or layers formed by a series of septarian concretions. The color of both fresh and weathered surfaces is medium gray (*N* 5) to medium light gray (*N* 6). The dense limestones are resistant to erosion and form thin ledges, which are from ½ to 3 inches thick and are persistent only over short distances. Concretionary zones are less persistent but far more common throughout the exposed areas. The concretions range from a few inches to 3 feet in thickness and from 6 inches to 6 feet in width. Many of the larger ones have a radial fracture pattern that has been filled with bright orange crystalline calcite. In some areas the concretions are highly fossiliferous, whereas in other areas fossils are notably absent.

The limonite, which is found throughout the area of outcrop, occurs in small veinlets along the bedding planes, in fractures, or occasionally as a concretionary cover for small pieces of gray shale. The abundance of limonite in the shale very commonly gives a yellow appearance to the weathered exposure; the wet clay penetrated in drilling was solid, yellow, and sticky. Calcite forms along the bedding of the limestone. In some areas, the crystals attain a length of 6 inches.

The Pierre Shale thickens across the county from 2,000 feet in the east to 4,500 feet in the west. Figure 3 is a map showing contours on the base of the Pierre Shale. The contours are based on information from several hundred oil tests in the area. The base of the Pierre dips northwestward as the formation thickens; the formation reaches a maximum thickness of about 9,000 feet near Denver. The part of the Pierre exposed in Washington County probably correlates with the upper part of the Lake Creek Shale Member of Elias (1931) in Wallace County, Kans.

The uppermost exposures of Pierre Shale in this area appear to be lower in the section than the exposures containing "teepees" and cone-in-cone structure about 15 miles southwest of Washington County. These two features are typical of the Salt Grass Shale Member of Elias (1931) in Wallace County, Kans.

### TERTIARY SYSTEM—OLIGOCENE SERIES

#### CHADRON FORMATION

The Chadron Formation, which unconformably overlies the Pierre Shale and unconformably underlies the Ogallala Formation, consists generally of siltstone of fluvial origin. The formation also contains local deposits of sand and gravel, limestone, and volcanic ash. The clayey silt is very compact, bentonitic, slightly calcareous, and weathers to a typical badland topography. Vertical cliffs alternate with rounded ledges, probably owing to the varying amounts of silt in the sequence of beds. In a weathered slope, the silt is highly fractured into small concoidal chips or blocks. The surface, where freshly exposed, is most commonly dark yellowish brown (10*YR* 4/2) to pale yellowish brown (10*YR* 6/2), and it weathers to very pale orange (10*YR* 8/2). However, the color may differ markedly both vertically and horizontally and may display varying shades of brown, red, yellow or quite commonly pale olive (10*Y* 6/2) to light olive gray (5*Y* 6/1). The siltstone of this area commonly contains numerous tiny balls of material similar in appearance to the matrix, although the balls are more calcareous.

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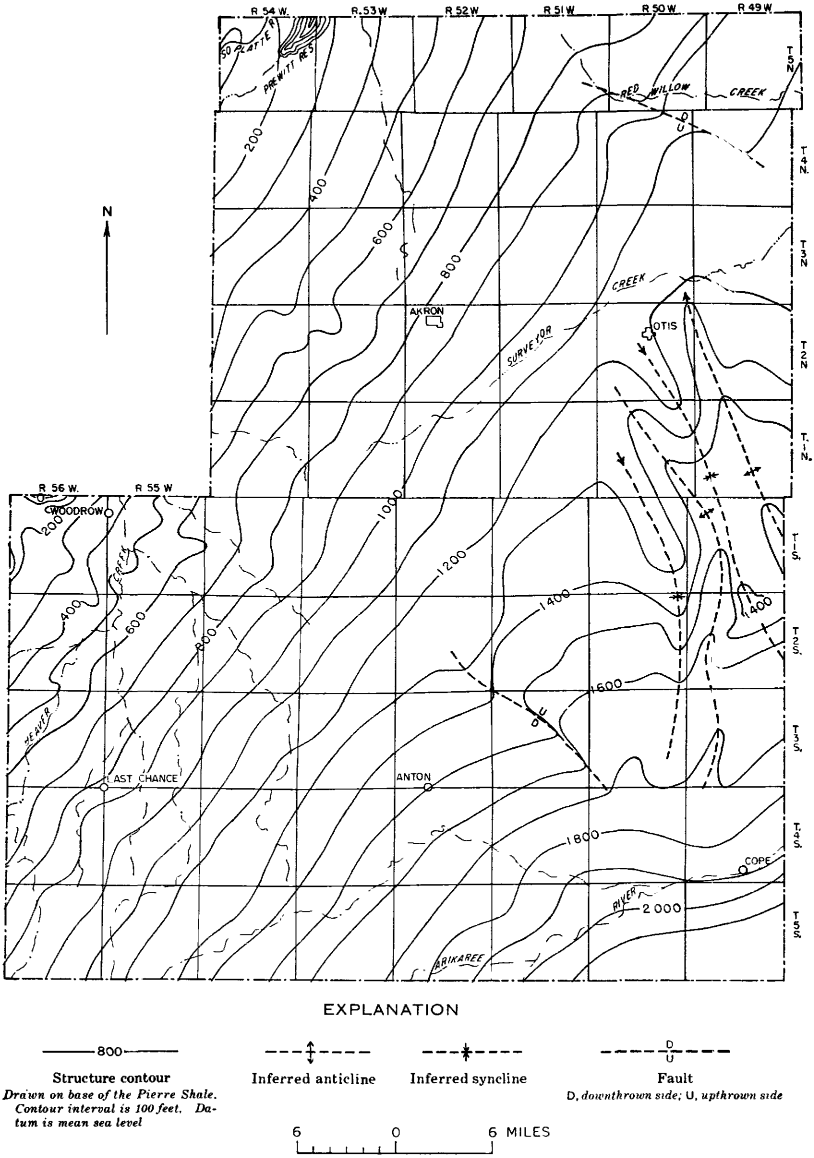


FIGURE 3.—Structure contour map of the base of the Pierre Shale in Washington County, Colo.

In some places the lowest part of the Chadron resembles the underlying Pierre Shale, both in color and texture. In these areas, the weathered part of the bluish-gray clay of the Pierre was probably moved only a short distance before being redeposited; thus, most of the original characteristics were retained. However, the clay has a slightly mottled appearance owing to numerous contained tiny particles of white, yellow, and red clay. A few channels have been cut into the lower clay and have been refilled with a red to brown clay containing a large quantity of chert nodules ranging in diameter from 1 to 5 inches.

The sand and gravel unit of the Chadron Formation generally occurs as a sinuous highly crossbedded channel deposit. Grain sizes range from very fine sand to fine gravel and colors vary from white to pink, gray, blue, green, or black. The sand and gravel unit may be loose or so tightly cemented with silica that it is difficult to break. Large blocks, 10 to 12 feet wide, are formed when the underlying material is removed by erosion and the beds collapse. The cemented sandstone is extremely resistant and forms prominent ridges throughout the northwestern part of the county. The ridge-forming sandstone in sec. 15, T. 3 N., R. 53 W., is 6 feet thick and 73 feet wide. Loose sand has been found at the base of the cemented zones. These observations indicate that some of the thicker deposits of sand are not entirely cemented.

The volcanic ash in the Chadron Formation was reworked and redeposited in streams or lakebeds. Most of the silt of the formation is bentonitic. One 3-foot ash bed was found at the contact between the Chadron Formation and the overlying Ogallala Formation in the NW cor. sec. 29, T. 3 N., R. 52 W. The age of this bed is unknown. Generally, beds of volcanic ash are rare in Washington County.

The Chadron Formation in Washington County correlates with the Chadron Formation (lower member of the White River Group) of Nebraska. Numerous titanothere fossils, for which the formation is noted, have been found throughout the area. Bone chips and fragments of turtle shells are common in the siltstone, and much of the cemented sandstone is highly fossiliferous on upper surfaces. A mandible of *Megacerops acer* Cope was identified by G. E. Lewis (written commun., 1957) as part of the Horsetail Creek fauna of Galbreath (1953), who reported the age to be middle or late Chadron. This fossil was found in the NW cor. sec. 10, T. 3 N., R. 53 W., less than 50 feet from the top of the formation.

Figure 4 shows the areal extent of the Chadron Formation in Washington County as determined from shothole logs and U.S. Geological Survey test holes. The greatest measured thickness was 234 feet in a test hole in the NW cor. sec. 6, T. 2 N., R. 52 W.

## TERTIARY SYSTEM—PLIOCENE SERIES

### OGALLALA FORMATION

The Ogallala Formation unconformably overlies the Chadron Formation and the Pierre Shale and is composed chiefly of a hetero-

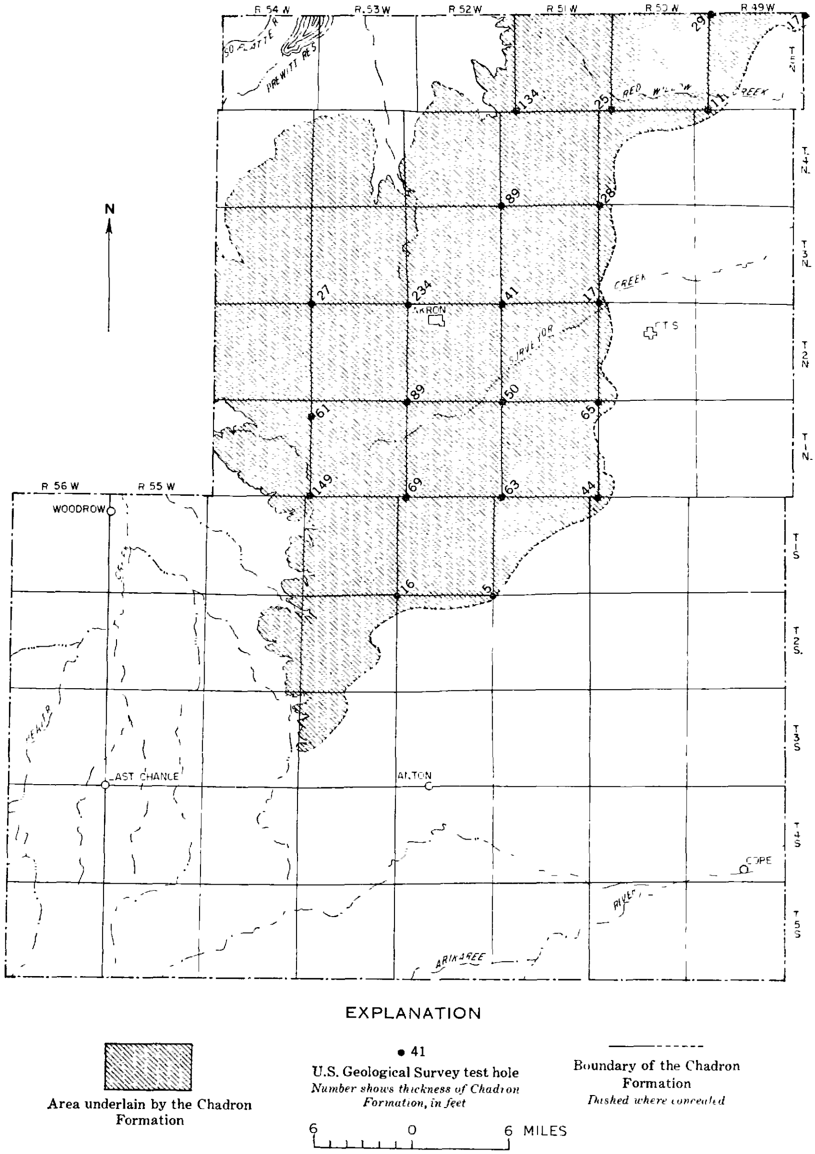


FIGURE 4.—Map showing the areal extent of the Chadron Formation in Washington County, Colo.

geneous mixture of clay, silt, sand, and gravel. The formation also contains local deposits of limestone, volcanic ash, opaline sandstone, bentonitic clay, and high concentrations of calcium carbonate. In general, the coarsest materials are near the base, and the finest (predominantly silt and clay) are in the upper part.

The sand and gravel may be clean to highly clayey and loose to tightly cemented with calcium carbonate. The grain size ranges from fine sand to coarse gravel, and the color is white to light gray or pink. The sand and gravel deposits that have been cemented with calcium carbonate are called mortar beds owing to their appearance on the outcrop. They are generally white to light gray, 1 to 5 feet thick, and are sufficiently resistant to form prominent ledges. Although most of the sandstone is highly calcareous, siliceous replacement has produced an almost pure opal in a few beds. Owing to their high resistance to weathering, the fragments commonly remain, whereas other materials are removed.

The silt is usually pink to red, massive, and contains a large quantity of calcium carbonate nodules or pipings. The silt is generally mixed with large quantities of clay and sand.

The clay is red to dark red, and is commonly calcareous, but contains only small amounts of caliche. The clay is generally massive and blocky, containing only small amounts of silt and sand.

Volcanic ash may be found in small lenses throughout the formation, but generally it occurs as reworked stream deposits. Lenses of pure volcanic ash are rare in this area. Bentonitic clay is rarely found in lenses but is mixed with the silt and other types of clay throughout the formation.

The fresh-water limestone of the Ogallala Formation is impure and contains considerable amounts of sand or silt. The limestone beds are generally thin and discontinuous. The algal limestone (Elias, 1931), which forms the caprock for the Ogallala Formation, is discontinuous in Washington County but is persistent elsewhere throughout the High Plains of Colorado. The name refers to the pink to brown concentric banding that is typical of algal structure. The material weathers to small biscuitlike cobbles and forms many prominent benches throughout the area. The best example of algal limestone is the caprock on Fremont Butte in sec. 9, T. 3 N., R. 53 W.

The highly irregular surface upon which the Ogallala Formation was deposited is an old erosion surface dissected by deep, narrow channels. The thickness of the Ogallala varies within short distances owing to deposition on this irregular surface.

The greatest measured thickness of the Ogallala Formation was 350 feet in a test hole in the SW cor. sec. 31, T. 1 N., R. 48 W., and in a test hole in the NW cor. sec. 6, T. 2 N., R. 48 W. The thinnest complete section measured, which also included the algal limestone, was only 17 feet thick.

The age of the Ogallala Formation in Washington County probably correlates with that of the Ogallala throughout the High Plains area.

*Biorbia* seeds, which are typical of the formation in western Kansas (Elias, 1931, p. 150), were found in a few places along with a few bone fragments, but not enough evidence was available for age determination. According to most authorities, the Ogallala Formation in Washington County is of middle Pliocene age.

## QUATERNARY SYSTEM—PLEISTOCENE AND RECENT SERIES

### PEORIAN LOESS

The loess, which mantles most of the High Plains area of Washington County, is composed of massive, well-sorted eolian silt. It generally is a moderate yellowish brown (10*YR* 5/4) on a fresh surface and weathers to a yellowish gray (5*Y* 7/2). The materials are highly uniform in grain size and form steep slopes. In stream cuts the loess will hold vertical slopes and display a columnar structure in spite of the fact that there is little or no cementing material. Although the loess is considered to be of uniform grain size throughout the section, it is common to find fine to medium sand in thin water-laid stringers within the bottom foot. In some places, a dark-gray soil zone was found in the section.

The formation reaches a maximum thickness of about 120 feet. The areal extent of the loess shown on plate 1 represents only those areas where the loess occurs in an appreciable thickness; however, it covers most of the county with at least a thin mantle. The loess was deposited at about the time of the last glacial period when strong northwesterly winds swept across the South Platte valley and spread silt over many square miles. Some silt was deposited wherever there was vegetation or other obstructions on the surface. The deposits increased in size until there appeared long linear ridges, which trended in the direction of the prevailing wind, about N. 30° NW. The abrupt change in altitude from the flat-lying Ogallala surface to the loess ridges is easily visible on the ground but cannot be detected on aerial photographs. One very prominent ridge is shown on the geologic map (pl. 1) beginning in the center of T. 1 N., R. 53 W., and continuing southeastward in almost a straight line for approximately 40 miles. At a point along Highway 36, in the SW cor. sec. 13, T. 4 S., R. 51 W., this ridge is 120 feet above the adjoining Ogallala plain.

Most of the loess in Washington County probably is equivalent to the Peorian Loess of Wisconsin age in Nebraska, as described by Condra and others (1950, p. 32). In a few areas the soil zone in the upper part of the loess may represent the Brady Soil, and if so, the upper part of the loess would be equivalent to the Bignell Loess (Condra and others, 1950, p. 32). However, no distinction has been made in this report and all the loess is considered to be Peorian.

### ALLUVIUM

The alluvial deposits of Washington County range in age from early Pleistocene to Recent. They are generally composed of pink, brown, or gray clay, silt, sand, and gravel. Although alluvial deposits are found in many places in the county, they are thickest in the Arikaree, Beaver, and South Platte valleys. Many of the materials in the Arikaree and Beaver valleys are of local origin and generally are finer grained than the materials in the South Platte valley. Commonly they are difficult to distinguish from the Ogallala deposits. The alluvium in the county has been mapped as a unit for this study, but it is discussed according to stream valleys.

*Alluvium of South Platte valley.*—The ancestral South Platte River was entrenched into the Cretaceous rocks on numerous occasions during the Pleistocene Epoch. Remnants of the alluvial material deposited after each period of downcutting were later removed or covered in Washington County. The extent of this Pleistocene valley and a detailed discussion of the lithologic and hydrologic characteristics of the alluvium may be found in a report by Bjorklund and Brown (1957, p. 30–31). In general, the deposit is typically stratified alluvium. Its thickness ranges from 0 to about 250 feet, and its width is somewhat greater than the width of the present valley. Information from shothole logs indicates that the alluvium may extend several miles beneath the sandhills to the southeast.

Some smaller tributary channels occur southeast of the South Platte River, but their surface expression has been obliterated by dune sand.

W. D. E. Cardwell (written commun., 1956) reported that Camp Creek (T. 3 N., R. 54 W.) is situated in an older valley that is 3 to 3½ miles wide and is as much as 125 feet deep. The materials were described by Cardwell as having formed by typical fluvial deposition characterized by lensing beds of silt, clay, and sand away from the channel and beds of sand and gravel interbedded with thin beds of clay and silt in the channel proper.

Information collected during the well inventory indicates that smaller channels similar to the one in the Camp Creek area may occur in other parts of the sandhill area.

*Alluvium of Beaver valley.*—The Beaver Creek drainage is a complex system of meandering streams that have cut and refilled their channels periodically throughout most of Pleistocene time. Some of the streams presently occupy their original channels, but others do not. The lower end of the valley was probably a system of braided streams through which a well-defined channel of Beaver Creek was cut during Wisconsin time. Vega and Sand Creeks are in approximately the same channel that was cut and refilled with early and middle Pleistocene sediments. Middlemist and Plum Bush Creeks have migrated away from their original channels and presently contain only a small amount of late Pleistocene or Recent alluvium. Some remnants of the earlier channel deposits have been found on the ridges above the present stream valley, but they are not extensive enough to be mappable. In a roadcut along State Highway 71, in sec. 18, T. 4 S., R. 55 W., an earlier deposit of the Middle Plum Bush Creek is exposed approximately 200 feet above the present streambed.

Loess has prevented the removal of alluvial deposits in some areas. Only the recent erosional channel in the loess is distinguishable in most of the Vega Creek and Sand Creek areas, and all or part of the ancestral channel may still remain beneath the loess.

The alluvial deposits of the Beaver Creek area are generally of local origin. The earlier deposits are finer grained but similar to the Ogallala Formation from which they were derived. The later Pleistocene and Recent deposits contain large amounts of gray clay and limonite derived from the Pierre Shale. A fine-grained quartz sand containing thin layers of limonite and magnetite-stained pebbles, which also is commonly contained in these alluvial deposits, probably was derived from the Fox Hills Sandstone.

The thickness of the alluvium varies considerably throughout the Beaver Creek area. Alluvium in Beaver Creek reaches a maximum thickness of about 60 feet at a point near the Morgan County line. Thicknesses in Middlemist and Plum Bush Creeks are less than 40 feet. The maximum thickness of deposits in Vega and Sand Creeks increases from about 40 feet at the lower end to about 90 feet at the upper end of Vega Creek.

*Alluvium of Arikaree valley.*—The Arikaree valley occupies the site of an older and larger valley that had been eroded and refilled during Pleistocene time. The alluvium in the older valley is a typical fluvial deposit and contains lenses or channels of sand, gravel, silt, and clay. Most of the Pleistocene materials exposed along the present stream channel are composed of beds of sandy clay or fine to medium sand that contains a large amount of clay and caliche. Lenses of loose sand and gravel containing only small amounts of clay or silt were penetrated by test drilling, but no continuous channels were evident. Some of the alluvial deposits along the Arikaree River are overlain by loess. The shape and character of the present channel is probably the result chiefly of recent downcutting and is not directly related to the ancestral channel.

Beds of fine-grained quartzitic sand and limonite and magnetite-stained pebbles, similar to the material in the Beaver Creek valley, are common throughout the valley and probably were derived from the Fox Hills Sandstone during early Pleistocene time. These beds of sand are overlain in several areas by a lens of reworked volcanic ash that is probably equivalent to the Pearlette Ash Member of the Sappa Formation of Kansas.

The range in thickness of alluvial deposits in the Arikaree Valley is not known because many of the well logs in this area do not distinguish alluvium from the underlying Ogallala Formation, which is similar. The greatest known thickness (65 ft) was measured in a test hole in the SE¼SE¼ sec. 34, T. 4 S., R. 49 W.

#### DUNE SAND

The dune sand, which covers more than one-fifth of Washington County, is composed chiefly of loose, poorly sorted, very fine to medium sand and some silt and clay. It generally is a moderate reddish orange (10*R* 6/6). The thickness ranges from a few inches to about 100 feet. The material is composed chiefly of quartz sand containing large amounts of feldspar, which provides the characteristic color.

The dune sand was deposited when winds of even greater velocities than those that spread the loess deposits scoured the South Platte valley and carried the sand many miles to the southeast. Because the dune deposits are in the troughs between the loess deposits, it seems that winds were scouring wide swaths through the loess at the same time the dune sand was being deposited.

The dune sand along the south side of the South Platte River is about 18 miles wide and covers about 270 square miles in Washington County. The sand was deposited on a northwestward-sloping surface and thickens in that direction too a maximum of about 80 feet. The dune sand in the east-central part of the county covers about 240 square miles and reaches a maximum thickness of about 100 feet. However, it is not uncommon to find the algal limestone of the Ogallala Formation within a few feet of the surface in the interdune valleys.

The age of the dune sand in Washington County seems to be Wisconsin to Recent. It is at least late Wisconsin because dune sand covers deposits in the channel of the South Platte valley. The age of the most recent deposition is not known, but all the dunes appear to be mature or older.

## GROUND WATER

### OCCURRENCE

Most of the potable ground water in Washington County occurs in two distinct ground-water provinces. These provinces correspond to the two principal surface drainage systems. The province in the

South Platte River basin consists chiefly of alluvial deposits of the South Platte River and its tributaries. The province in the Kansas River basin consists chiefly of the Ogallala Formation, which forms the surface of the High Plains, as well as alluvial deposits of the stream valleys that cut across the Ogallala. The boundary between the two provinces in Washington County is shown on most of the figures. For ease of discussion, the westernmost one will be referred to as the South Platte ground-water province and the easternmost as the High Plains ground-water province.

### SOURCE AND MOVEMENT

Ground water in both ground-water provinces is derived chiefly from precipitation in Washington County. The only other appreciable sources are underflow into the county and irrigation losses, both of which are significant only in the small area immediately adjoining the South Platte River.

Only a small part of the precipitation reaches the ground-water reservoir; most of the water is lost by evapotranspiration before it can percolate downward to the water table. Although a large part of the water is absorbed by the soil, most of it is retained near the surface within reach of the roots of plants. The potential evapotranspiration rate exceeds the average precipitation rate; thus, only during very wet periods is the opportunity favorable for appreciable amounts of water to escape downward to the water table.

Most of the soils in the county are permeable enough and the topography is flat enough that a large part of the precipitation is absorbed. The small amount of runoff, in areas where the soils are relatively impermeable or land-surface slopes are great, usually flows only short distances before it reaches and is absorbed by permeable materials in the drainageways. Only during intense storms of long duration does runoff leave the county. Of the two ground-water provinces, conditions conducive to runoff are more extensive in the South Platte than in the High Plains.

In the South Platte ground-water province, water recharged at the surface moves as underflow through the alluvial deposits in the valleys toward the South Platte River. Where the water table is close to the surface, a part of the water is discharged to the atmosphere by evapotranspiration. The remaining water is discharged to the surface as streamflow in the lower reaches of Beaver Creek or in the South Platte River or becomes a part of the underflow in the valley of the South Platte River.

Along the South Platte River, a part of the water diverted for irrigation recharges the ground-water reservoir. It is a significant source of water only in a small part of the county between the irrigation canal and the river. Underflow along the South Platte might be considered as a source of water, but it probably has little or no effect on the availability of water in the county because it is negated by about the same amount of underflow out of the county.

In the High Plains ground-water province, water recharged at the surface moves as underflow eastward out of the county. It does not reappear at the surface, and, because the depth to water throughout most of the area is great, very little is discharged to the atmosphere as evapotranspiration. The nearest points of discharge are in the channels of the North Fork of the Republican River in eastern Yuma County and the South Fork of the Republican River in eastern Kit Carson County, where the streams become perennial. The direction of water movement is perpendicular to the water-table contours shown on plate 2.

The Chadron Formation contains potable water and in places is capable of yielding appreciable amounts to wells. However, by comparison to the other ground-water reservoirs, this aquifer seems to have less potential for development. The aquifer in the Chadron occurs in both ground-water provinces, in places underlies the major aquifers, and is hydraulically connected to them. Present knowledge of the aquifer indicates that the water occurs chiefly in fractures in the clay, but also in lenses or channellike stringers of sand. It is not known whether the water-bearing zones are continuous, or in which direction the water is moving. Answers to these and other questions about the hydraulic nature of this ground-water reservoir will require additional field studies that will include major exploration of the subsurface.

## HYDRAULIC PROPERTIES OF AQUIFERS

### OGALLALA FORMATION AND ALLUVIUM

Numerous investigations in Colorado and adjacent States that have included studies and tests of the hydraulic properties of the Ogallala Formation and alluvial deposits of Tertiary and Recent age have produced the same general conclusions: (1) The permeability of the deposits varies widely, but commonly there is sufficient coarse-grained material to permit the development of wells yielding 500 to 2,000 gpm (gallons per minute), (2) the ability of the deposits to yield water from storage, expressed in terms of the coefficient of storage,[1] commonly ranges from 0.1 to 0.3, and (3) the materials, where exposed, generally absorb moisture readily, but the major part of the absorbed moisture is retained near the surface and subsequently returned to the atmosphere. Although numerous tests of materials

[1] The volume of water an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface is called the coefficient of storage.

were not made during this study, field observations of well yields, materials in outcrops, and samples from test holes suggest that the same general conclusions apply to Ogallala deposits and alluvium in Washington County.

Pumping tests were made wherever quantitative information on aquifer properties seemed obtainable. Owing to the scarcity of favorable sites and the lack of representative coverage of the aquifers in the county, results of tests are of questionable value except locally. Table 2 summarizes the test results.

TABLE 2.—*Summary of data obtained from aquifer tests in Washington County, Colo.*

| Well | Pumping rate (gpm) | Duration of test (hr) | Draw-down at end of test (ft) | Calculated $T$ [a] (gpd per ft) | Calcu-lated $P$ [b] (gpd per sq ft) | Type of material tested |
|---|---|---|---|---|---|---|
| C1-55-7add | 525 | 50 | 17.02 | 160,000 | 5,800 | Sand and gravel. |
| C2-51-31cdc | 505 | 6⅓ | 11.98 | 280,000 | 7,300 | Do. |
| C4-49-34dba | 1,450 | 50 | 15.65 | 115,000 | 3,400 | Do. |
| C5-51-22cca | 595 | 50 | 20.77 | 60,000 | 2,600 | Do. |

[a] *T*, transmissibility=amount of water, in gallons per day per foot at the prevailing temperature, that will flow in 1 day under unit hydraulic gradient through a cross section 1-ft wide extending the full thickness of the aquifer.
[b] *P*, permeability=transmissibility divided by the aquifer thickness.

Tests in adjoining counties gave results that ranged from 200 to 5,000 gpd (gallons per day) per sq ft for permeability.

The coefficient of storage could not be determined from the test data in Washington County.

Partly on the basis of test results in other counties but largely on judgment, the average permeability of the Ogallala deposits in Washington County is estimated to be about 600 gpd per sq ft. The coefficients of storage probably average about 0.15 for the Ogallala and 0.20 for the alluvial deposits.

The logs and samples from wells and test holes (McGovern, 1961) in the county suggest that deposits in the deep buried valleys in the bedrock surface are the most permeable (pl. 3). Coarse-grained material, whose permeability may have been impaired substantially by cementing material or by the infiltration of large amounts of clay and silt particles, was noted at scattered locations, generally in the upper part of the formations.

### CHADRON FORMATION

Unlike the Ogallala and alluvial deposits, whose permeability depends on the size of intergranular pore spaces, the Chadron Formation is permeable owing chiefly to the size, number, and degree of interconnection of the fracture systems. Although the formation contains channellike deposits of sand, the bulk of the formation consists of silt and clay that is dense and nearly impermeable. Extensive fracture systems in the clay and silt are largely responsible for the fairly large yields (see p. 34) from wells tapping the formation. The extent or frequency of occurrence of the fracture systems is unknown, and additional detailed studies are needed to evaluate the hydraulic properties of the Chadron Formation.

## CONFIGURATION OF THE WATER TABLE IN THE HIGH PLAINS GROUND-WATER PROVINCE

The configuration of the water table in the High Plains ground-water province is shown by contours on plate 2. The water table in the South Platte ground-water province was not mapped. Data from scattered localities indicate that it is discontinuous except in the alluvial and surficial deposits, where it generally coincides with the configuration of the land surface.

The mapped surface is continuous throughout most of the Ogallala Formation. In some places it extends into the overlying alluvial and surficial deposits. The data also suggest that the water table may continue into the fractured zones of the Chadron in places. Because of this possibility and because of a shortage of water-level data, mapping of the surface along the west edge of the High Plains was impractical.

The slope of the water table in the High Plains ground-water province indicates that the regional underflow is eastward and that most of the water in this province ultimately crosses the east boundary of the county. The slope averages slightly more than 20 feet per mile; locally it ranges from 10 to 100 feet per mile.

Along the west edge of the High Plains a small amount of water moves westward, as indicated by the seeps along the escarpment.

The contours are based on water-level data collected from July 1957 to September 1959. Fluctuations of water levels during the period probably were not great enough to alter appreciably the configuration as depicted from what it might have been if the contours had been based on water levels measured all at one time.

The configuration of the water table as shown on plate 2 probably reflects very closely natural conditions that have prevailed for a long time. Withdrawals of ground water in the area have not been great enough to appreciably change the natural conditions except perhaps in a few local areas along the Arikaree River valley or other small areas where withdrawals have been great. Thus, the map provides a basis for future comparisons that may show how extensive development of ground water will alter the shape of the water table and the pattern of underflow.

The chief factor influencing the shape of the water table is the bedrock surface. (See pl. 3.) The regional eastward slope of the bedrock surface accounts for the regional eastward slope of the water table. A comparison of the bedrock and water-table maps shows that the water-table ridge near the center of the county corresponds with a bedrock high. Careful study reveals that other, less pronounced, bedrock features also affect the configuration of the water table.

Another factor noticeably influencing the contour pattern is the above-average recharge in the Arikaree River valley. Runoff in the drainage shed of the Arikaree concentrates in the valley and infiltrates the permeable alluvial materials, creating a noticeable ridge on the water table near the east edge of the county. Other factors that affect the shape of the water table are not readily distinguishable; they include changes in permeability and thickness of permeable materials.

## DEPTH TO WATER

The depth to water is a major factor affecting the cost of drilling wells and operating pumps. In parts of Washington County, where the depth to water is greater than 100 feet, pumping for irrigation may not be economically feasible owing to the high cost of operation and low yields. Small quantities of water for stock and domestic uses are pumped from considerably greater depths in some areas.

The depth to water in the Ogallala Formation ranges from about 10 feet in the center of the county to about 250 feet along the east edge. In the South Platte valley, the Beaver valley, and the Arikaree valley, the depth to water ranges from a few feet to about 50 feet, depending on the proximity of the well to the flood plain of the stream.

The depth to water in the Pierre Shale and the Chadron Formation is unpredictable because the water-bearing zones may be almost anywhere in the formation or may be completely absent.

## SATURATED THICKNESS

Thickness of the saturated material in the High Plains ground-water province is shown on plate 4. The zone of saturation is generally less than 50 feet thick in the western two-thirds of the area underlain by the Ogallala Formation. The thickness may exceed 50 feet wherever deep valleys have been cut into the bedrock surface and also along the east boundary of the county.

Saturated thickness in the alluvium of Beaver valley is less than 50 feet and in the alluvium of South Platte valley ranges from a few feet to about 220 feet, according to Bjorklund and Brown (1957, pl. 4, sheet 2).

The thickness of saturation of a formation and its permeability are major factors determining the potential yield of a well. Adequate supplies for stock or domestic uses may be obtained from a few feet of saturated material that is sufficiently permeable. Quantities sufficient for irrigation ordinarily can be obtained from the Ogallala Formation wherever the thickness of saturation exceeds 100 feet. In areas where the permeability of the alluvium or Ogallala Formation is high, yields of 500 to 1,000 gpm can be obtained from a saturated thickness of only 30 to 40 feet. Smaller supplies from thinner deposits may be feasible to develop for irrigation if the water table is close to the surface.

The total quantity of water in storage in the High Plains ground-water province of Washington County (see table 3) was calculated from the volume of saturated material and an assumed average storage coefficient of 0.15 (p. 23).

TABLE 3.—*Ground water in storage in the High Plains ground-water province of Washington County, Colo.*

[Calculated from pl. 4]

| Range in thickness (ft) | Average saturated thickness (ft) | Area (1,000 acres) | Volume of saturated material (acre-ft×10⁶) | Water in storage (acre-ft×10⁶) |
|---|---|---|---|---|
| 50 | 20 | 719.0 | 14.4 | 2.16 |
| 50–100 | 75 | 259.0 | 19.4 | 2.91 |
| 100–150 | 125 | 53.8 | 6.7 | 1.00 |
| 150–200 | 175 | 13.4 | 2.4 | .36 |
| 200 | 200 | .6 | .1 | .02 |
| Total | ---------- | 1,045.8 | 43.0 | 6.45 |

The total storage figure, however, does not represent the amount of recoverable ground water in storage available for irrigation because: (1) It would be physically impossible to dewater the entire formation, (2) large quantities of ground water are located in areas where the soils would be unsuitable for large-scale irrigation, and (3) the density of pumps required to obtain adequate amounts of water would make withdrawal of the lower several feet of water from the formation financially infeasible. The amount of recoverable ground water is discussed in the section "Potential ground-water development."

## NATURAL RECHARGE AND DISCHARGE

The quantity of water that moves downward from the soil zone to recharge the ground-water reservoir and the rate at which it moves laterally through the zone of saturation are largely dependent on the character of the rocks underlying the surface. The almost impermeable clay of the Pierre Shale absorbs only small quantities of water and restricts downward movement of water. Although the silt of the Chadron Formation is equally impermeable, intense fracturing permits water to move downward into some parts of the formation. However, a substantial reduction of yields after continued pumping from the fracture zone indicates either restricted lateral movement of water or a small areal extent of the fracture zone. The permeability of gravel, sand, and clay of the alluvial deposits or the Ogallala Formation varies widely but is generally sufficient to allow absorption of most of the available moisture.

Only part of the total discharge in the South Platte ground-water province is measurable from data collected during this investigation. A substantial part of the water recharged is discharged along the stream courses by effluent seepage and by evapotranspiration; no estimates of discharge by evapotranspiration were made; only that part of the effluent seepage along the South Platte River was estimated. Although the recharge to this province was not measured, it probably averages somewhat less than the recharge in the High Plains as indicated by a better established drainage system and a faster rate of runoff.

Alluvial deposits of the South Platte valley are recharged by irrigation losses and precipitation in the area and by underflow from outside the area. The Beaver valley in Washington County receives all its recharge from precipitation on the valley and adjacent aeolian deposits.

Ground water is discharged from both valleys by evapotranspiration, pumping, and subsurface outflow. Bjorklund and Brown (1957, p. 58) determined the ground-water inflow of the South Platte River at Hardin, Colo. (about 50 miles west of Washington County), to be 10 cfs (cubic feet per second), and they stated that the outflow at the Nebraska line is equal to the inflow. Therefore, the underflow through the South Platte valley in Washington County should be nearly the same. Bjorklund and Brown (1957, p. 58) also determined that 11.9 cfs was contributed to the South Platte valley by the underflow of Beaver Creek. About 8 cfs of this amount is derived from Washington County.

All the recharge to the High Plains ground-water province is derived from precipitation on the High Plains surface. The rate of recharge is approximately equal to the rate of underflow from the county because there is no other signficant means of natural discharge and pumpage is largely from storage.

Underflow into Yuma County can be computed by means of Darcy's law, which may be stated as follows:

$$Q=PIA$$

where

$Q$=the quantity of water in gallons per day

$P$=the average coefficient of permeability, estimated to be 600 gpd per sq ft

$I$=the hydraulic gradient; it averages about 20 ft per mi or 0.004 ft per ft

$A$=the cross-sectional area of the saturated material, determined to be 31 million sq ft.

Thus, the average estimated underflow into Yuma County is 74 mgd (million gallons per day), or about 83,000 acre-ft per year. Because recharge is approximately equal to discharge by underflow, the annual estimated rate of recharge from precipitation on 1,046,000 acres (area underlain by the Ogallala Formation) is 0.95 inch.

## WATER-LEVEL FLUCTUATIONS

Fluctuation of water levels in wells reflects local changes in ground-water storage and is useful in detecting changes in the relation of recharge to discharge.

From the few years of water-level records tabulated in a report by McGovern (1961), no long-term regional trends of storage change are apparent, although the data suggest that the water table in many areas fluctuates in response to changes in climate. Locally pumping has caused declines, and irrigation by surface water has caused rises that mask natural fluctuations.

The response of water levels to climatic changes generally is more pronounced and abrupt where the water table is close to the land surface. As the depth to the water table increases, downward percolating water recharges the aquifer more uniformly and fluctuations are less pronounced. In Washington County, the effects of recharge from the surface where the depth is greater than 100 feet generally cannot be detected.

Figure 5 illustrates the effects of recharge and discharge or water-level fluctuations in different aquifers and in different parts of the county. Well C1–55–21bd, in the Beaver Creek valley, and wells C4–49–25ba and C5–51–23–cb, in the Arikaree River valley, obtain water from alluvial deposits at shallow depths. Well B3–49–16ddd, 6 miles north of Otis, obtains water from the Ogallala Formation at a depth of more than 200 feet.

Withdrawal of water from storage results in an immediate decline of water levels in the vicinity of the pumped well. The cone of depression (dewatered zone surrounding a pumping well) enlarges continuously until pumping ceases. After withdrawal ends, water continues to move toward the well until the water table returns to a near normal state. The net result is a loss in storage, although

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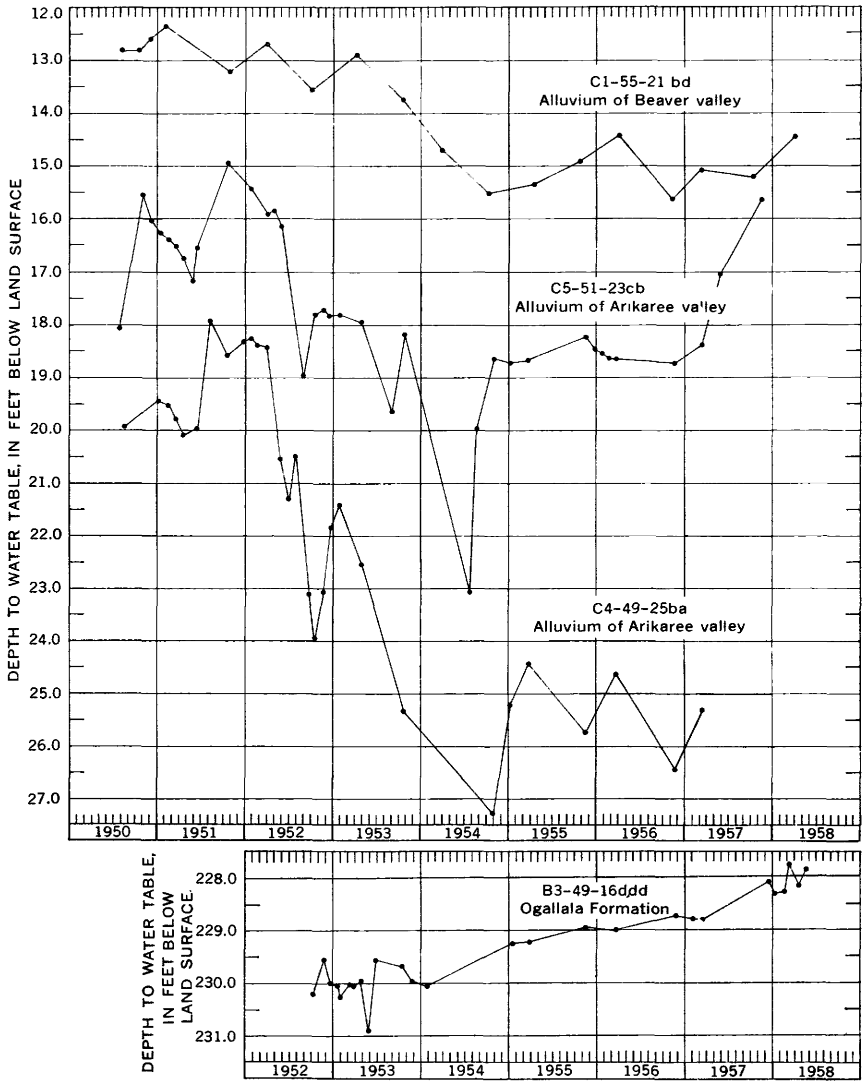


FIGURE 5.—Water-level fluctuations in wells C1-55-21bd, C4-49-25ba, C5-51-23cb, and B3-49-16ddd in Washington County, Colo.

the water-table decline in relation to a large area may not be measurable after short periods of pumping.

Evaluation of water-level fluctuations in the shallow alluvial deposits is further complicated by several factors that may be acting simultaneously. For example, flood water in the Arikaree valley percolates downward and creates a ground-water mound beneath the streambed. As the mound slowly dissipates, water levels in the valley may decline at the same time nearby water levels are rising. Thus, a fluctuation of water level might reflect several different modes of ground-water discharge or even a combination of recharge and discharge.

Water-level measurements made during the investigation of Washington County are not especially diagnostic. However, they indicate the magnitude of seasonal fluctuation that might be expected in areas of intensive development, as compared with areas of little or no development, and suggest that the aquifers are not being depleted rapidly. The short length of record and the variable rate of development make it impossible to predict the effects of future irrigation demands on a long-term basis. A continued program of water-level measurements is needed in all areas of the county where ground water has already been developed for irrigation or where such development may take place. These records would be of great value in forecasting both local depletion and trends in regional ground-water conditions.

## UTILIZATION OF WATER

All ground water withdrawn for use in Washington County is not consumed; the unconsumed part returns to the aquifers generally within a short distance of its point of withdrawal. Thus, the rate of depletion of the aquifer is somewhat less than the withdrawal rate. The quantities estimated in this section of the report represent withdrawals; a regional study planned in the future, which will include Washington County, will attempt to determine the amount used consumptively.

About 18,000 acre-ft of ground water was withdrawn in 1959 for use in Washington County; about 55 percent was from the High Plains ground-water province. The largest use is for irrigation—estimated to be about 15,000 acre-ft per year. Public supplies account for 2 or 3 percent of the total; industrial supplies, about 10 percent; domestic and stock supplies, about 5 percent.

The total use of ground water in the county has increased rapidly in the past 10 years and probably will increase more rapidly in the future, largely owing to an expected increase in irrigation.

### DOMESTIC AND STOCK SUPPLIES

Almost all water used for domestic and stock supplies in Washington County is obtained from ground-water sources. Nearly all the stock water and many of the domestic water supplies are obtained from small-diameter wells equipped with cylinder pumps powered by windmills. The more modern rural homes have a variety of electrical pumps. Most of the water obtained from ground-water sources is of adequate quality for domestic use if the wells are properly constructed and maintained. From 800 to 1,000 acre-ft of water per year is used for stock and domestic purposes.

### MUNICIPAL SUPPLIES

Only the towns of Akron and Otis are supplied by municipal systems. All other communities in Washington County are dependent on individual wells to meet their requirements.

Akron's water supply is obtained from eight wells tapping the Ogallala Formation in secs. 17 and 18, T. 2 N., R. 52 W., approximately 1½ miles south of town (McGovern, 1961, p. 6). The wells range in depth from 40 to 70 feet, and their yields range from 35 to 250 gpm. Water from the well field is delivered by a 6-inch main to the town system and by a 12-inch line to a million-gallon storage reservoir. Water is delivered from the reservoir to the system by two centrifugal pumps having a combined capacity of about 900 gpm. Treatment of the water as of 1959 was restricted to chlorination. Two additional wells within the town limits have smaller yields and are used only occasionally. Water pumpage in Akron is not metered; the average daily withdrawal in 1959 was estimated to be 370,000 gpd (400 acre-ft per yr).

Otis is supplied by one well drilled into the Ogallala Formation to a depth of 220 feet. Water is pumped from the well by two 8-inch turbine pumps, at 600 gpm, into a 105,000-gallon elevated storage tank. An average of 70,000 gpd (80 acre-ft per yr) was delivered to the system in 1959. The water is not treated.

### INDUSTRIAL SUPPLIES

The only known industrial use of ground water in Washington County has been for oil field flooding. In 1959, three wells in the alluvium of Camp Creek, secs. 18 and 20, T. 3 N., R. 54 W., pumped about 2 million gpd (about 2,200 acre-ft) to the oil fields southwest of Woodrow. The wells, which are pumped alternately, are reported to be capable of yielding 1,500 gpm each.

### IRRIGATION SUPPLIES

Irrigation by ground water was first attempted in Washington County in 1920. Although the attempt was successful, development progressed slowly and was confined to the South Platte valley until about 1940, when the rate of development increased there and in other parts of the county. By the end of 1959, there were 134 irrigation wells in the county. However, a large part of the county is still virtually undeveloped.

In 1959, there were 33 irrigation wells in the small part of the South Platte valley in Washington County. This heavy concentration of wells is representative of the valley both upstream and downstream. The wells yield 200–3,000 gpm; the average is about 1,000 gpm. Because this area was discussed in detail by a report on the lower South Platte River valley (Bjorklund and Brown, 1957), no attempt was made in this report to collect further information or to compute pumpage.

In the Beaver Creek valley which includes the heavily pumped areas along Sand and Vega Creeks, there were 48 irrigation wells in 1959 that yielded 50–1,000 gpm. In the Arikaree valley, there were 48 irrigation wells that yielded 40–1,500 gpm. Five other irrigation wells were scattered elsewhere throughout the county.

Estimates of pumpage for irrigation during the period of study, based chiefly on correlations with electric power records for all areas except the South Platte valley, are shown in table 4.

TABLE 4.—*Summary of ground water pumped for irrigation in Washington County, Colo.*

| Area | Pumpage (1,000 acre-ft) | | |
|---|---|---|---|
| | 1957 | 1958 | 1959 |
| Beaver Creek valley | 2.1 | 3.0 | 3.5 |
| Arikaree River valley | 1.6 | 1.1 | 2.9 |
| High Plains ground-water province | .4 | .4 | .4 |
| Others | .1 | | .1 |
| Total | 4.2 | 4.5 | 6.9 |

The amount pumped from the South Platte valley in 1959 was estimated to be roughly 8,000 acre-ft.

Irrigation wells in the county, with a few exceptions, are equipped with electrically driven turbine pumps. The casings, which generally are galvanized iron, range from 18 to 36 inches in diameter and are either perforated or torch cut opposite the water-bearing beds. Only a few of the more recently installed wells have been gravel packed, reportedly to increase yields. Most of the methods of installation presently in use appear to give satisfactory results.

## WATER-BEARING PROPERTIES OF GEOLOGIC FORMATIONS

The water-bearing properties of geologic formations in Washington County differ widely. The principal sources of water are the alluvial deposits, the Ogallala Formation, and parts of the Chadron Formation. The remaining geologic formations that crop out in Washington County yield little or no water to wells. (See table 1.) The following summary is included chiefly to assist future prospecting in undeveloped areas.

733–829—64——4

## PIERRE SHALE

The Pierre Shale is of hydrologic importance in this area chiefly because its impermeable layers prevents or retard the downward movement of ground water. Its upper surface generally is the lower limit for the occurrence of fresh water.

The Pierre, which is composed chiefly of indurated clay and sandy clay and intercalated lenses of dense limestone, is generally of very low permeability. In a few places, small quantities of water can be obtained from sandstone, partings along bedding planes, or fracture zones. Occurrences of these water-bearing zones in unexplored areas probably are spotty and remain unpredictable. Small quantities of water for domestic or stock uses generally can be obtained only by drilling through a considerable thickness of weathered material. Water obtained from the Pierre Shale is generally of poor quality for most uses.

## CHADRON FORMATION

Although the Chadron Formation underlies less than half the county and its yield to wells is generally small, it is an important source of ground water in parts of Washington County. In several areas where the younger deposits are drained or have been removed, the Chadron yields sufficient water for stock and domestic supplies; and, reportedly in a few areas, it yields moderately large quantities of water. Water may occur in either the sand or the siltstone of the formation and may be under either artesian or water-table conditions. Yields of wells vary considerably within short distances.

The siltstone of the Chadron Formation is relatively impermeable except in some areas where the material is intensely fractured. An irrigation well in sec. 21, T. 2 N., R. 52 W., reportedly yielded about 350 gpm from 60 feet of "yellow clay" (presumed to be siltstone) when first installed in 1954. A reduction in yield to about 50 gpm by 1958 probably was due to the lack of storage.

The scattered sandstone lenses of the Chadron Formation yield adequate quantities of water to numerous domestic and stock wells. The sand ranges from uniform fine-grained loose sand to cemented conglomeratic sandstone. The cemented sandstone seems to be relatively impermeable, but drillers have reported loose water-bearing sand immediately underlying it. Water in the sand is generally under artesian pressure and will rise above the level at which it is first tapped. The pressure in this area, however, is insufficient to cause wells to flow.

Because its character is erratic, many dry holes have been drilled into the Chadron Formation. The quality of water obtained from the formation is fair to poor for domestic use.

## OGALLALA FORMATION

The Ogallala Formation is the most extensive source of large ground-water supplies in Washington County. Owing to the heterogeneous lithology of the formation, permeability differs greatly over short distances, both vertically and laterally. Yields from the formation range from a few gallons per minute to more than 1,500 gpm depending on the thickness and the permeability of the saturated material. The depth to water ranges from 0 to about 200 feet, and the thickness of saturated material ranges from 0 to about 250 feet.

The permeability of sand and gravel of the formation depends mostly on the amount of contained clay and silt and the presence of calcareous cement. Although the formation is well stratified throughout, the sand and gravel become generally less cemented and better sorted downward. Wells in the deep bedrock channels can be expected to yield greater quantities of water because they generally penetrate more permeable strata and a greater thickness of saturated material.

The silt and clay of the formation are relatively impermeable. The presence of calcium carbonate cement further reduces the permeability. The limestone in the formation also is relatively impermeable. Dissolution and collapse of the limestone probably caused many of the small depressions on the Ogallala surface, which pond runoff and allow it to percolate down to the water table.

## PEORIAN LOESS

The loess, which is composed of uniform fine-grained material, has a low permeability and generally is above the water table. In areas where the loess is thick, recharge to the underlying gravel is slight. However, the loess is highly porous and is capable of storing large quantities of water. In many areas, several thin sand lenses were found at the base of the loess, but it is doubtful that they are capable of yielding enough water for stock or domestic use.

## ALLUVIUM

Although thick alluvial deposits cover only a relatively small part of Washington County, they produce greater quantities of water than any other source. Yields from the alluvium range from a few gallons per minute to about 3,000 gpm, and the thickness of saturated material ranges from 0 to 220 feet. Irrigation supplies are obtained at shallow depths from the alluvium of the South Platte River, the Arikaree River, and Beaver Creek and its tributaries.

*Alluvium of the South Platte valley.*—Although the area in Washington County that is underlain by the alluvium of the South Platte valley is less than 15 square miles, in 1959 it contained one-fourth of the irrigation wells and accounted for more than half the water withdrawn. The thickness of the alluvium ranges from 0 to 250 feet, and in 1959 the depth to water generally was less than 20 feet. The thickness of saturated material ranged from 0 to 220 feet. The maximum yield reported was 3,200 gpm with 33 feet drawdown from a well in sec. 16, T. 5 N., R. 54 W., where the thickness of saturated material was 125 feet. Quantities of water sufficient for irrigation are available in most of the area, and quantities of water sufficient for stock or domestic supply probably are available throughout all this area.

Alluvial deposits in former channels that entered the South Platte valley from the south are entirely or partly covered by sandhills, some of which are a potential source of water. Cardwell (written commun. 1956) reported a well in the dune-sand area of Camp Creek that yielded about 1,300 gpm. Two irrigation wells that yield about 200 gpm each tap another buried channel in secs. 3 and 4, T. 5 N., R. 52 W., near the Logan County line. Similar channels may extend through other parts of the area, but they may be difficult to locate owing to the lack of surface expression.

*Alluvium of the Arikaree valley.*—The alluvium of the Arikaree valley overlies the Ogallala Formation in most places. The two constitute a single aquifer owing to similarity of their physical characteristics and water-bearing properties. Probably many wells in the Arikaree valley penetrate both Ogallala and Pleistocene deposits.

Irrigation wells in this area are located either on the flood plain or along the outer edge of the valley, and their depths range from 30 to 90 feet. Depths to water in these wells range from 10 to 40 feet, depending on their proximity to the stream channel. Yields range from 40 to 1,500 gpm.

*Alluvium of Beaver valley.*—The alluvium of Beaver Creek and its larger tributaries generally yields moderate to large quantities of water to wells. The areas where large supplies of ground water are available in Beaver valley alluvium are smaller and less uniformly distributed than are such areas in the alluvium of the Arikaree or South Platte valleys.

The principal known areas where sufficient amounts are available for major irrigation supplies are lower Beaver Creek and upper Vega Creek valleys. Alluvium in the lower end of Beaver Creek attains a thickness of 60 feet and a 35-foot thickness is saturated. Yields range from 40 to 800 gpm. Alluvium in the upper end of Vega Creek attains a thickness of 90 feet, of which 45 feet is saturated. Yields in this area reportedly range from 200 to 1,000 gpm.

Other areas that have thinner saturated deposits and only minor supplies of water are Middlemist, Plum Bush, and Sand Creeks, the lower end of Vega Creek, and the upper end of Beaver Creek. Alluvium in these areas is less than 50 feet thick and 30 feet or less is saturated. Wells in these areas yield 50–550 gpm.

#### DUNE SAND

The dune sand, like the loess, has a high porosity. The sandhills area provides an ideal catchment for precipitation; the permeability is high enough to allow much of the water to move downward into the underlying formations. The dune sand is not known to yield water to wells in Washington County, partly because most of it lies above the water table.

### CHEMICAL QUALITY OF GROUND WATER

The chemical quality of ground water is largely the result of the geologic and hydrologic environment. Precipitation absorbs carbon dioxide from the atmosphere and decayed organic matter in the soil, becomes acidic, and is then better able to dissolve the minerals with which it comes in contact as it percolates through the rocks. The concentration of minerals in solution depends on the solubility of the minerals in the formation and the length of time the water remains in contact with them.

Variations in mineral content of water in Washington County are shown on the isoconductance map (fig. 6). Conductivities shown on the map were those measured during the well inventory and do not necessarily agree with laboratory values.

The mineralization of ground water in the Ogallala Formation is dependent on thickness of saturated material, amount of recharge, and solubility of minerals in the underlying bedrock. In areas where the thickness of saturated material is relatively great, the mineral content of the water generally is low, as indicated by the low conductivities (250–450 micromhos at 25°C). Areas in which the conductivity exceeded 450 generally correspond with a bedrock high and a thin zone of saturation. Other conditions being equal, water in contact with the Chadron Formation generally is less mineralized than that in contact with the Pierre Shale. The conductivity of the water in the Chadron ranged from about 400 in the sandstone to a maximum of about 2,000 in the fractured siltstone. The conductivity of water in the alluvium overlying the Pierre Shale varied widely and at maximum was about 4,000. In a few areas where the recharge rate is high, such as the Arikaree valley, the concentration of dissolved solids was low.

Samples of water from 12 selected wells, representing each of the water-bearing formations and a variety of hydrologic environments, were analyzed to determine the concentration of several chemical constituents. The results of these analyses are shown in table 5.

TABLE 5.—*Chemical analyses of water from*

[Concentration of dissolved constituents, dissolved solids, and hardness given in parts per

| Well | Geologic source | Depth (ft) | Date of collection | Temperature (°F) | Silica ($SiO_2$) | Calcium (Ca) | Magnesium (Mg) | Sodium (Na) | Potassium (K) |
|---|---|---|---|---|---|---|---|---|---|
| B2-50-9ddc | To | 220 | 5-23-58 | 58 | 56 | 35 | 11 | 9.6 | 7.8 |
| B2-52-17ccb | Qal-To | 54 | 5-23-58 | 53 | 61 | 61 | 15 | 26 | 11 |
| B3-49-16ddd | To | 245 | 10-12-59 | 58 | -------- | 37 | 11 | 14 | 7.4 |
| B3-52-4cdd | Tc | 106 | 10- 9-59 | 56 | -------- | 48 | 18 | 54 | 16 |
| B3-54-20aad | Qal | 29 | 10- 9-59 | 55 | -------- | 115 | 40 | 153 | 53 |
| C1-52-4ddd | To | -------- | 10-13-59 | 53 | -------- | 82 | 30 | 53 | 11 |
| C2-50-34dcc | To | 164 | 10-12-59 | 56 | -------- | 34 | 13 | 20 | 7.4 |
| C2-54-21bac | Qal | 40 | 10-13-59 | 55 | -------- | 87 | 18 | 27 | 5.8 |
| C2-56-26bdb | Qal | -------- | 10-13-59 | 54 | -------- | 504 | 195 | 350 | 14 |
| C4-49-32bcc | Qal-To | 31 | 5-23-58 | 59 | 49 | 51 | 12 | 26 | 7.8 |
| C4-51-5baa | To | 102 | 10-12-59 | 56 | -------- | 78 | 34 | 64 | 9.6 |
| C4-55-35cdd | Qal | 36 | 10-12-59 | 53 | -------- | 64 | 9.7 | 11 | 3.0 |

## SUITABILITY FOR DOMESTIC AND MUNICIPAL SUPPLIES

Water intended for domestic use should have less than 500 ppm (parts per million) of dissolved solids and should not contain excessive amounts of certain chemical constituents. The U.S. Public Health Service (1946) set standards for drinking water on interstate carriers that have been adopted as criteria for many public supplies. Those standards that pertain to chemical constituents in water are as follows:

| *Constituents* | *Limiting concentrations (ppm)* |
|---|---|
| Magnesium | 125 |
| Sulfate | 250 |
| Chloride | 250 |
| Fluoride | 1.5 |
| Dissolved solids (recommended) | 500 |
| (permissible) | 1,000 |

Water containing greater concentrations than those listed is used in some areas, and some undesirable effects are noted frequently by nonresidents. Chloride in excess of the recommended limit imparts a salty taste to the water. High magnesium in combination with sulfate has cathartic effects. Nitrate concentrations in excess of 45 ppm may cause cyanosis in infants (Comly, 1945). Dean (1936) stated that concentrations of fluoride greater than 1.5 ppm will cause dental defects in the formation of permanent teeth and that a concentration of at least 1.0 ppm is desirable to inhibit dental caries. Revised standards for fluoride concentrations have been proposed by the U.S. Public Health Service, Drinking Water Standards (1962).

*selected wells in Washington County, Colo.*

million. Geologic source: To, Ogallala Formation; Tc, Chadron Formation: Qal, alluvium]

| Bicarbonate ($HCO_3$) | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids | Hardness as $CaCO_3$ | Noncarbonate hardness as $CaCO_3$ | Percent sodium (Na) | SAR (Sodium-adsorption-ratio) | Specific conductance (micromhos per cm at 25° C) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 163 | 13 | 4.0 | 0.7 | 8.0 | 225 | 133 | 0 | 13 | 0.4 | 306 | 7.9 |
| 206 | 50 | 24 | .6 | 27 | 377 | 214 | 44 | 20 | .8 | 558 | 7.9 |
| 172 | 15 | 7.0 | .7 | 7.2 | 184 | 138 | 0 | 17 | .5 | 341 | 7.8 |
| 274 | 33 | 20 | .9 | 50 | 375 | 194 | 0 | 35 | 1.6 | 645 | 8.0 |
| 490 | 310 | 74 | 1.1 | 22 | 1,010 | 452 | 50 | 39 | 3.1 | 1,570 | 7.8 |
| 168 | 83 | 104 | 1.0 | 104 | 551 | 328 | 190 | 25 | 1.3 | 951 | 7.7 |
| 184 | 21 | 7.0 | .8 | 7.4 | 201 | 138 | 0 | 23 | .7 | 361 | 7.7 |
| 300 | 69 | 18 | .2 | 6.9 | 380 | 291 | 45 | 16 | .7 | 655 | 7.9 |
| 228 | 2,480 | 66 | .3 | 11 | 3,730 | 2,060 | 1,870 | 27 | 3.4 | 4,080 | 7.7 |
| 222 | 23 | 19 | .5 | 15 | 312 | 177 | 0 | 23 | .9 | 446 | 8.0 |
| 186 | 211 | 54 | 1.1 | 42 | 585 | 334 | 182 | 29 | 1.5 | 985 | 8.0 |
| 204 | 33 | 4.0 | .2 | 20 | 245 | 200 | 32 | 11 | .3 | 435 | 7.8 |

These standards would reduce the recommended upper and lower limits of water in the Washington County area to 1.2 and 0.7 ppm, respectively.

The quality of ground water in Washington County is generally within the recommended limits for domestic use, although locally the water may contain objectionable amounts of some constituents. A water sample from the alluvium of Beaver valley was considerably higher in calcium, magnesium, and sodium sulfates than all other samples. This sample probably represents the poorest quality of water to be found in the county. All water from the Ogallala Formation and most water from the Chadron Formation is within the permissible limits for dissolved solids. All water sampled within the county is rated as either hard or very hard; the hardness of samples ranges from 133 to 2,060 ppm.

Two samples contained more than 45 ppm of nitrate; they probably represent local contamination due to nitrogenous materials entering a poorly sealed well from cesspools or barnyards.

## SUITABILITY FOR IRRIGATION

The chemical factors that determine the suitability of water for irrigation are the total salt content, the concentration of certain constituents, and the relative proportion among certain ions. However, the effects of the chemical factors can be altered by such physical factors as soil type, crop type, drainage, climate, and quantity of water applied.

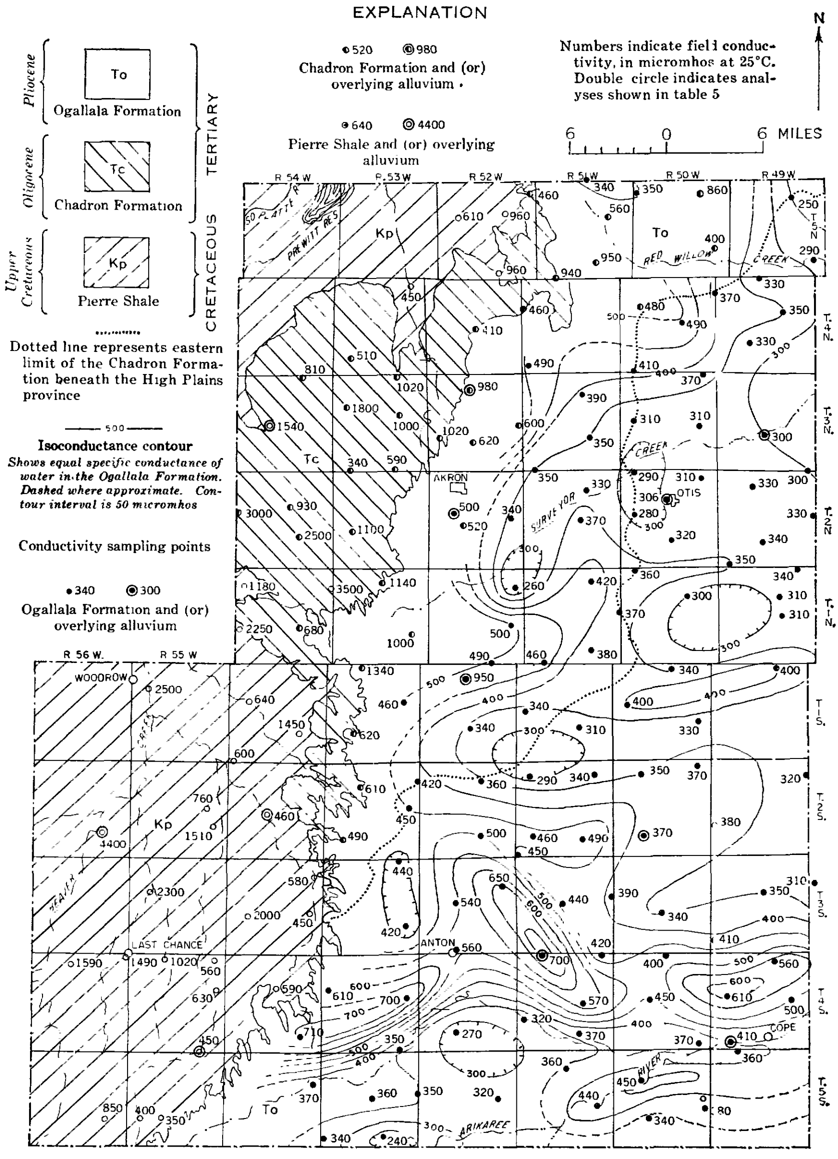


FIGURE 6.—Map showing variations in conductivity of ground water in Washington County, Colo.

A system of classifying irrigation water on the basis of salinity and sodium hazards—measured, respectively, by specific conductivity and by SAR (sodium-adsorption-ratio)—has been developed by the U.S. Salinity Laboratory Staff (1954). Boron hazard, as classified in their report, is not a factor in this area because boron concentrations are all low. Water that contains a high concentration of salts tends to be taken up by plants at a decreasing rate. Water that contains a high ratio of sodium to calcium and magnesium affects the soil texture and may cause it to become relatively impermeable. Wilcox (1955) indicated that, in general, water may be safely used for supplemental irrigation if its conductivity is less than 2,250 micromhos per centimeter at 25°C and its SAR is less than 14. All the samples analyzed from Washington County had a SAR value of less than four and the specific conductance of only one sample exceeded 2,250 micromhos per centimeter at 25°C (table 5). Therefore, any water obtained from the Ogallala Formation is probably suitable for irrigation, but the suitability of water obtained from the older formations or the alluvium overlying the older formations is variable and such water should be analyzed before considering its use for irrigation.

## POTENTIAL GROUND-WATER DEVELOPMENT

Most of the large-scale development of ground water in Washington County has been concentrated in the South Platte, Beaver, and Arikaree valleys. As a result of heavy pumping, water levels and yields have declined in these areas. Where wells are scattered, additional supplies can be developed in the Beaver and Arikaree valleys without rapidly depleting the supply. Large quantities of ground water can be developed from the High Plains ground-water province of the county, although withdrawals would be largely from storage.

Some people consider that the ground-water resources of an area are best utilized by pumping at a rate that does not exceed the rate of recharge. However, large amounts of water can be withdrawn for long periods of time in areas where the recharge rate is low and the amount of stored water is great. The magnitude of the resultant water-level decline will vary in relation to the thickness of saturated material and the rate of withdrawal. For example, an annual 1-foot decline of the water table may have an insignificant effect in parts of the High Plains where depth of saturation exceeds 100 feet, whereas a decline of this magnitude in the smaller tributary valleys would deplete the aquifer rapidly.

By 1960, ground water in the South Platte valley had been developed to the extent that water levels were steadily declining. Although additional development probably will continue in Washington County and in the adjacent parts of the valley, it can only aggravate a situation that is already considered critical.

The number of irrigation wells in the lower end of the Beaver valley in Morgan County far exceeds the number in Washington County. Bjorklund and Brown (1957, p. 50) described the decline of water levels in the area of Gary, Colo. (5 miles north of the Washington County line), as presenting the most critical ground-water condition in the lower South Platte valley. Any additional development in the Woodrow area (fig. 1) of Washington County would only intensify the problem. However, it is reasonable to assume that in the tributary valleys, such as Vega and Sand Creeks, some of the ground water presently being lost through evaporation and transpiration can be salvaged. Part of this water being consumed nonbeneficially might be salvaged without appreciably affecting the availability of water in the lower part of the valley. Evapotranspiration can be reduced by lowering the water table below the root zone of plants.

Substantial declines in water levels have been reported from several areas in the Arikaree valley. Records of water levels for the period 1950–58 indicate that the declines are only local depressions caused by excessive pumping in an area where saturated material is relatively thin. Water levels in other parts of the valley showed little or no decline during the same period. A small amount of additional water can be developed in the valley outside the area of heavy withdrawals without depleting the aquifer rapidly. If the alluvium can be recharged artificially, as the farmers in the area have proposed, water levels could be raised or the rate of decline reduced in parts of the valley. Water is available for recharge from the occasional flood runoff in the Arikaree River.

The potential development of ground water for irrigation in the High Plains ground-water province of Washington County probably will be limited to irrigable-land areas that overlie adequate thicknesses of saturated materials. A large part of the county, however, either consists of nonirrigable lands or has little ground water available.

If it is assumed that all ground-water storage above 30 feet from the base of the Ogallala Formation is capable of yielding quantities adequate for irrigation (approximately 500 gpm) and that 10 percent of the water is usable where the thickness of saturated material averages 20 feet, then less than half the 6 million acre-ft of stored water can be recovered. Unfortunately, a large part of the area underlain by the highly productive part of the aquifer is land unsuited for irrigation, and other large uses of ground water are not anticipated in the foreseeable future. Thus, it may be feasible to utilize only about 1 million acre-ft of the ground water in storage for agriculture. The remaining water would stand as a reserve that ultimately could be transported to irrigable land or used for purposes other than irrigation.

## POSSIBILITIES OF ARTIFICIAL RECHARGE

Appreciable quantities of water could be made available for recharge by salvaging water that is presently consumed nonbeneficially. However, the conditions under which this could be accomplished, and the practicality of doing so, differ throughout the county and are favorable only in a small part of the county.

There is no unappropriated surface water in the South Platte valley or Beaver Creek area. In the High Plains ground-water province, water now consumed largely by evaporation could be salvaged by recharging the precipitation that collects in the lakes and ponds or the flood runoff of the Arikaree River.

Artificial recharge has been considered by well owners in the Arikaree valley as a remedy for reduced yields and declining water levels. Current reductions in yield reportedly have discouraged further development and caused abandonment of some irrigation wells in the intensively developed areas. A study of the area revealed that (1) the seasonal demand for water per unit area of the aquifer probably exceeds the seasonal capability of the aquifer to yield water, (2) the aquifer is not being rapidly depleted on a long-term basis, (3) some of the storm runoff that presently leaves the area could be captured and subsequently used to recharge the aquifer, and (4) quantitative records of streamflow and sediment load must be initiated to properly design the detention and silt-removal structures necessary for a successful recharge project.

Records collected during this study (McGovern, 1961) show that when demand was great, water levels in one reach of the Arikaree valley declined as much as 10 feet per year and yields declined accordingly. Pumpage figures also indicate that the demand has been erratic. The most critical decline was during the 1959 season, when a group of six wells within a 1-mile reach pumped 600 acre-ft of water. On the basis of the assumption that the saturated material averages 40 feet in thickness and half a mile in width, the ground-water storage in the Arikaree valley is estimated to be 2,000 acre-ft per mile. Obviously such heavy withdrawals will cause a substantial decline in yield, but the performance of wells should also be checked to determine whether well clogging may be responsible for part of the noted loss.

Mounding of the water table beneath the Arikaree, as shown by the contour map of the water table (pl. 2), indicates that a substantial amount of water is recharged into the aquifer at the present time. Long-term records indicate that the net decline for the period 1950–59 was only 2 feet, and, therefore, the aquifer is not being rapidly depleted.

Storm runoff in the Arikaree River is available for supplementing ground-water supplies, but only if storage can be provided for detention. Storms in this area are generally localized and vary greatly in intensity. Local residents report that the Arikaree River at Cope carries floodwater an average of twice a year and for a duration of not more than 2 days. During the remainder of the year the channel is dry. It may be feasible to capture a part of the water that leaves the area by surface flow and subsequently use it in the county.

The water could be stored in surface- or ground-water reservoirs. If water were stored in an upstream reservoir, it could be delivered subsequently to the land for irrigation, or released at a rate that would allow all the water to be absorbed in the channel. However, the rate of sediment accumulation and loss from evaporation might make a surface-water reservoir infeasible. Although records are not available to determine the rate of sedimentation in the Arikaree River channel, the magnitude of accumulation was apparent after the storm of March 1960. A gravel pit, which had been excavated by the Washington County Highway Department to a depth of about 15 feet and a length of several hundred feet, was completely filled with sediment after the storm.

Water could be stored underground by spreading floodwater on land of low productivity or by using injection wells. Land used for spreading generally requires periodic scarifying or other land treatment to maintain high infiltration rates. Both methods would require some type of diversion structure, preferably one of low cost that could be replaced easily, owing to the problem of siltation. If water is to be injected through wells, temporary storage and treatment for silt removal will be needed.

Figure 7 is an idealized cross section of the Arikaree valley showing the relation of the stream channel to the water table and the underlying geologic formations. The letters A through F indicate the sites where samples of streambed material were collected for laboratory analysis. Samples A and C represent the soil zone in the flood plain at depths of 0–2 inches and 0–1 foot, respectively. Sample B represents the material in an abandoned channel at a depth of 0–2 inches. Sample D represents the material in the present stream channel at a depth of 0–1 foot. Samples F and E were collected from a gravel pit in the stream channel and represent the deposits at depth intervals of 1–5, and 5–7 feet, respectively. The values shown at each site indicate the permeability of the sampled material, as determined by the U.S. Geological Survey Hydrologic Laboratory, Denver, Colo. The letter G designates an irrigation-well site where the permeability was determined by an aquifer test. The determinations show that permeability of the stream deposits varies widely and that, consequently, infiltration rates would also vary.

The prospects of utilizing any of these methods or combination of methods of artificial recharge in the Arikaree valley appear physically possible. However, studies should be made to determine the availability of water and extent of the sedimentation problem to form the basis for a cost-benefit-ratio analysis, which would determine whether such a project is economically feasible.

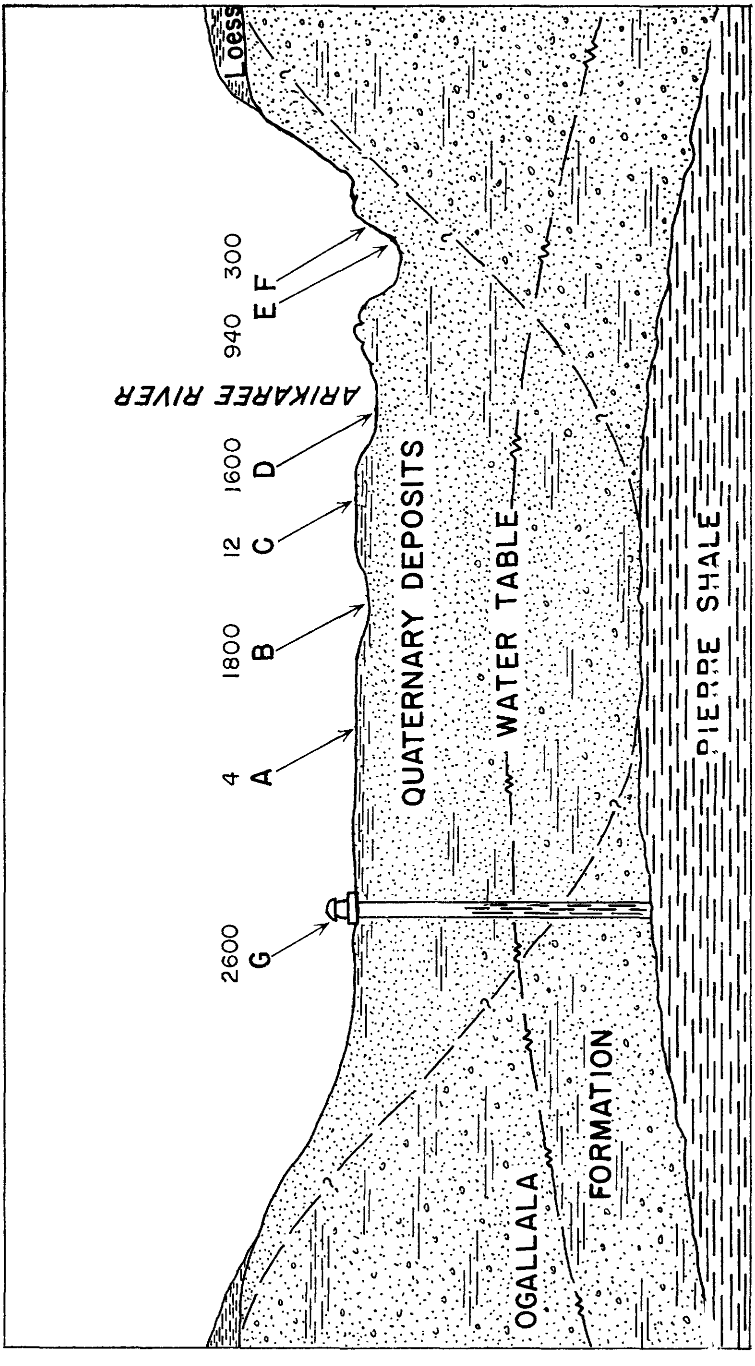


FIGURE 7.—Idealized cross section of the Arikaree valley showing the permeability in gallons per day per square foot, at sampling sites.

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