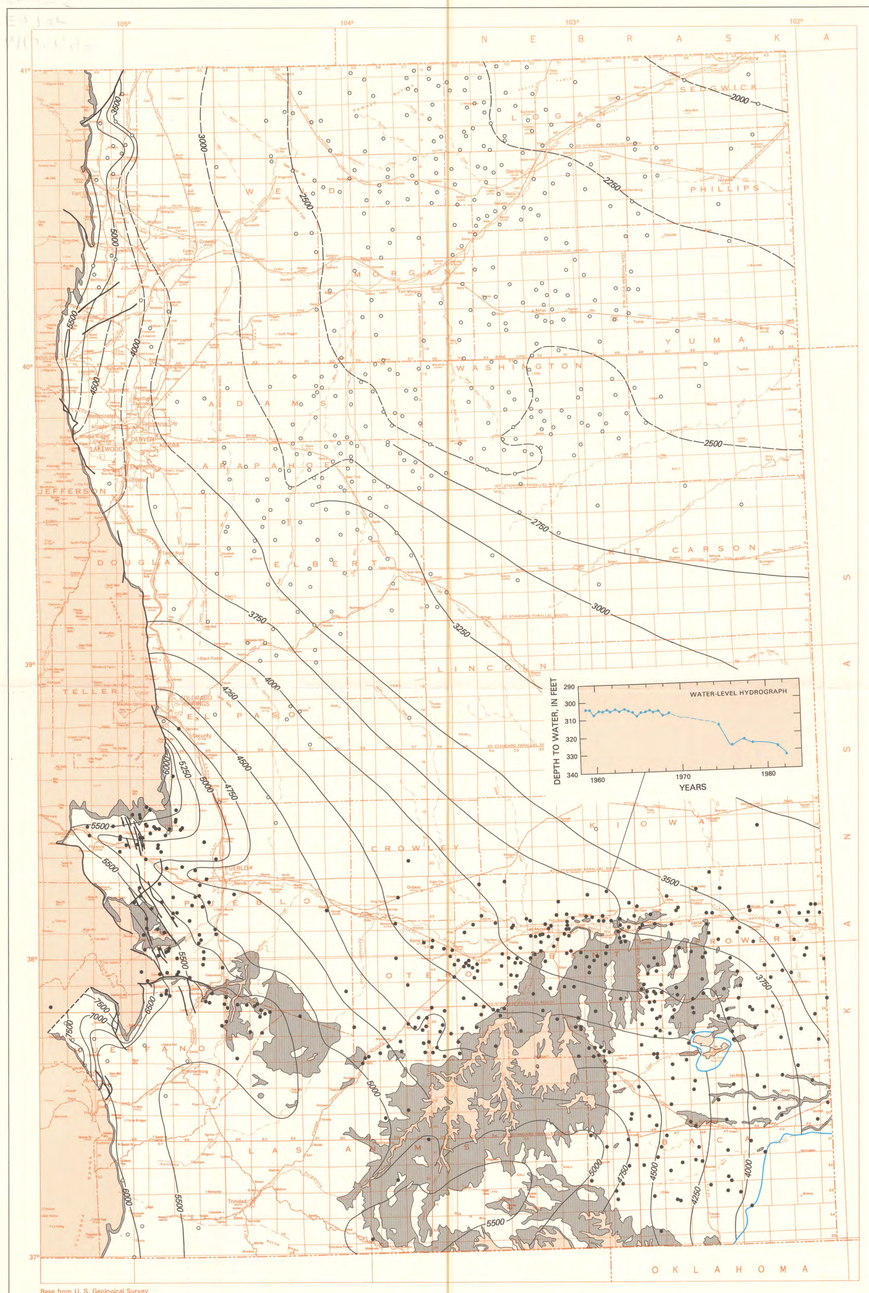

Figure 19.—Predevelopment potentiometric surface for the Dakota-Cheyenne aquifer in eastern Colorado.

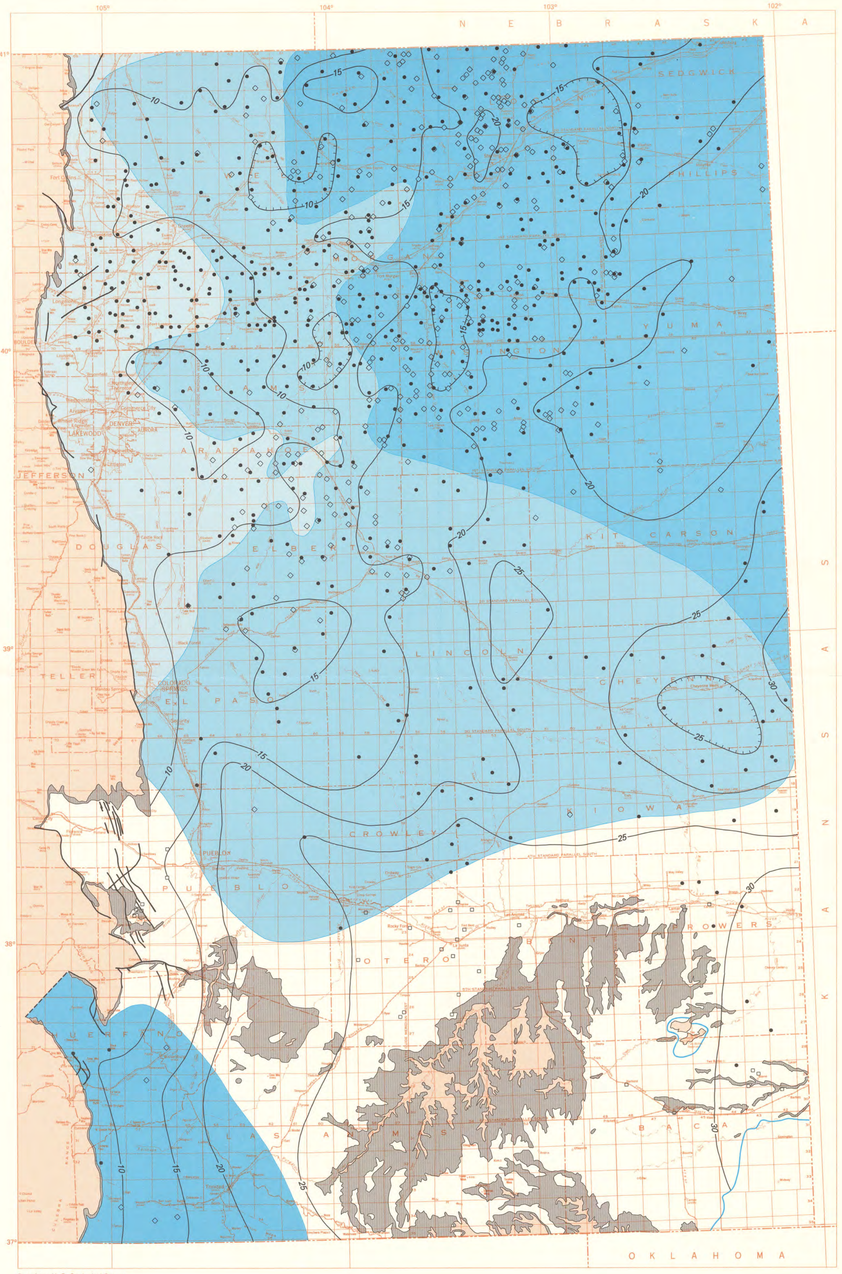

Figure 20.—Average porosity and hydraulic conductivity of the Dakota-Cheyenne aquifer in eastern Colorado.

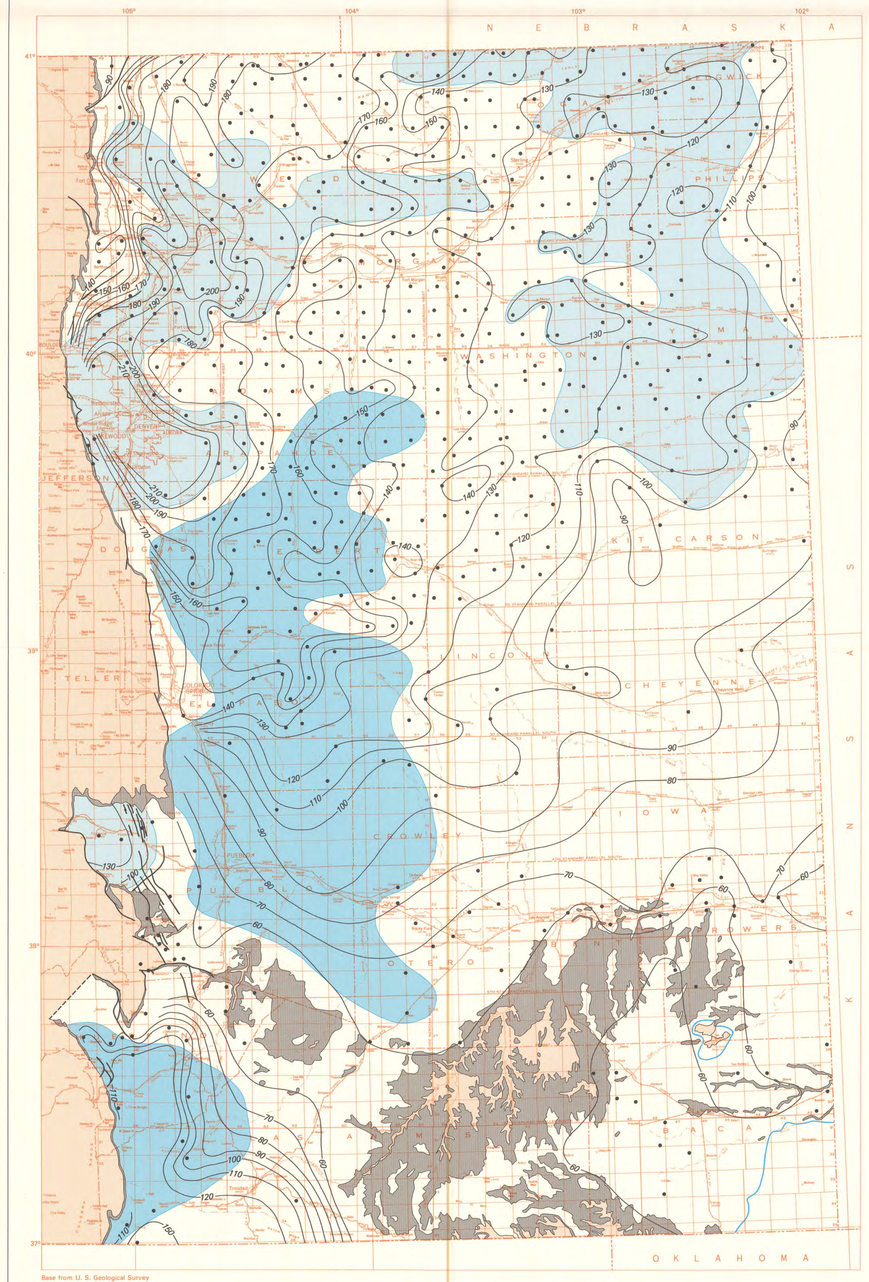

Figure 22.—Temperature and thermal zones in the Dakota-Cheyenne aquifer in eastern Colorado.

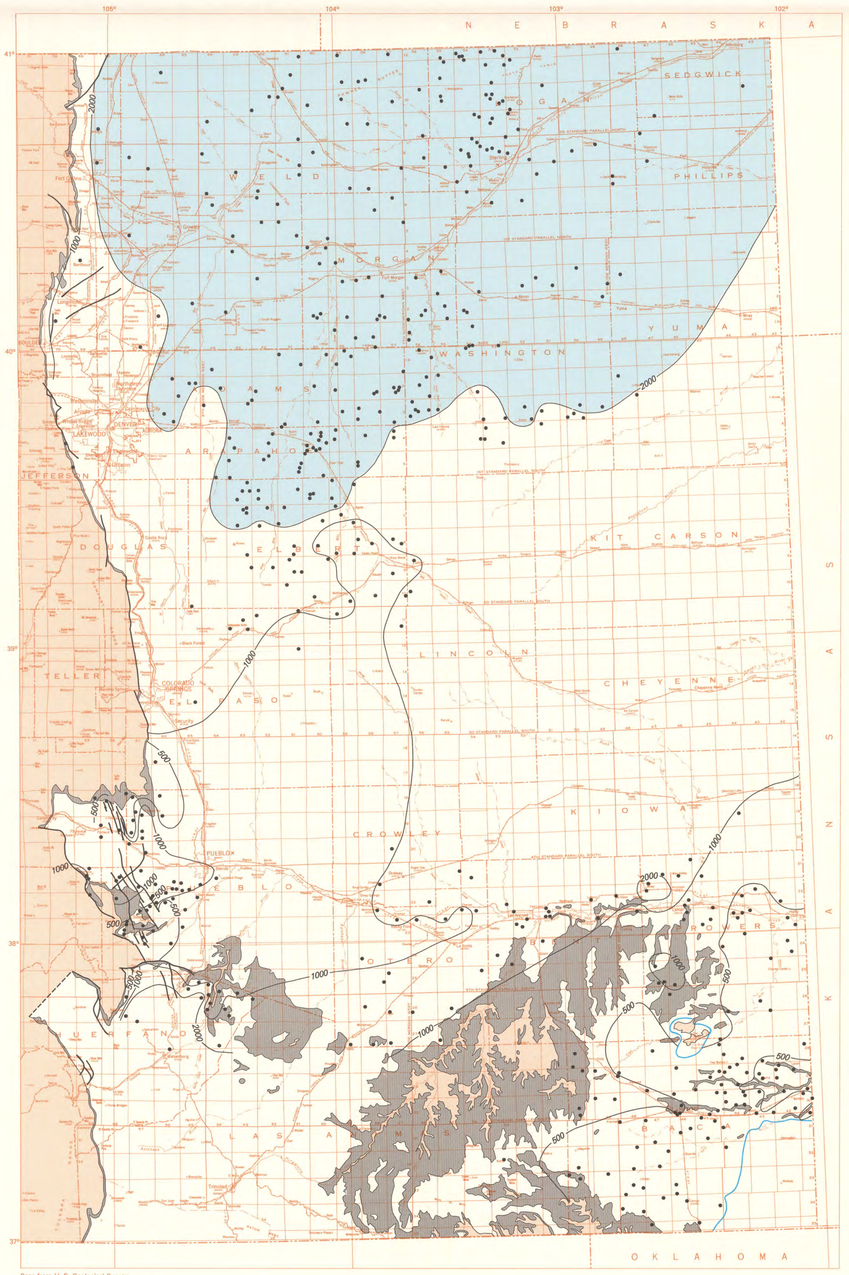

Figure 24.—Dissolved-solids concentration of water from the Dakota-Cheyenne aquifer in eastern Colorado.

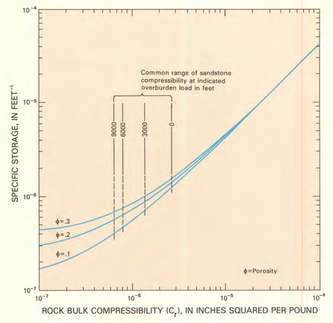

Figure 21.—Relation of specific storage to rock compressibility and porosity.

DAKOTA-CHEYENNE AQUIFER

Hydrology

The potentiometric surface for the Dakota-Cheyenne aquifer, shown in figure 19, represents the pristine head configuration as it is estimated to have existed prior to pumpage of water and petroleum. The surface was defined by water-level measurements in water wells in the southern part of the area and by drill-stem tests from petroleum-exploration holes in the northern part of the area. Pressures from drill-stem tests are expressed in terms of equivalent head of a column of fresh water. The water-level measurements are generally accurate to within a few feet and define a consistent pattern of hydraulic gradient in the aquifer; this is not always the case with the drill-stem test results.

About 13,000 drill-stem tests were reviewed in an effort to find valid tests that accurately define the predevelopment heads in the northern part of the aquifer. The majority of the tests were found to be unsuitable for this purpose because of inappropriate test intervals or inaccurate and incomplete testing procedures. However, even the apparently valid tests often yielded highly inconsistent equivalent freshwater head information; these tests show several hundred, to as much as two thousand, feet of head difference between some adjacent wells completed in the Dakota Sandstone. Although some inconsistencies are undoubtedly due to unidentified petroleum production in nearby areas, effects of gas or mud in drill-stem test recovery fluids, effects of osmosis, or erroneous test results, such errors cannot explain the large mass of inconsistent data. Most of these test results are thought by the authors to be an accurate indication of the variability of head that can occur in adjacent parts of the aquifer. Work by Land and Weimer (1978), Mossel (1978), and Peterson and Janes (1978) indicates that the Dakota Sandstone consists of complexly interbedded channel and delta deposits. These deposits sometimes are associated with hydraulic discontinuities produced by lack of hydraulic connection between adjacent parts of the formation.

Thus, it is difficult to determine if the head and hydraulic conductivity data obtained from a drill-stem test represent: (1) Conditions within the general ground-water flow field of the aquifer, or (2) conditions within an isolated segment of the aquifer that is not in good hydraulic connection with other parts of the formation. Drill-stem tests are performed as part of the exploration for hydrocarbon traps, and these data may be biased by more frequently representing conditions in isolated segments of the formation. For this reason, only those drill-stem test results that showed head relations consistent with nearby head data were used for contouring in figure 19. Possible bias of the drill-stem test data and the introduction of other biases through data selection preclude accurate definition of the potentiometric surface in the area indicated by dashed potentiometric contours. Although contouring in figure 19 indicates a regional hydraulic gradient in the area northeast of Denver, this gradient is poorly defined by data, and parts of the aquifer in this area may not be hydraulically connected to the regional flow system. Water-chemistry data discussed later and resistivity data in Russell (1963) support this interpretation.

The potentiometric surface indicates ground-water movement in an easterly or northeasterly direction away from recharge areas along the Apishapa Arch and the western margin of the aquifer. The potentiometric surface ranges in altitude from less than 2,000 ft above sea level in northeastern Colorado to more than 5,000 ft above sea level north of Golden, in the area between Colorado Springs and Trinidad, and on the Apishapa Arch east of Trinidad. Hydraulic gradients are apparently relatively flat (less than 5 ft/mi) northeast of Denver and steepen westward to 400 ft/mi in some areas. This change in gradient is likely due to a marked westward reduction in aquifer transmissivity caused by thinning and decreasing hydraulic conductivity. Faults also may affect heads in the area north of Golden, but data are inadequate to define local head configurations. Estimates of recharge along the 90-mi-long basin margin north of Golden range from 0.03 to 0.3 ft³/s depending on the values of hydraulic conductivity used. The potentiometric surface between Golden and Colorado Springs is poorly defined but indicates that minimal recharge likely occurs in this reach. Faults and associated structural features (Berg, 1962; Bieber, 1983; Jacob, 1983) likely affect the hydrology of the aquifer in this reach by truncating the formations (fig. 15A) or offsetting the formations (fig. 15B). Both processes may effectively eliminate recharge to the aquifer along this segment of the western margin of the basin.

The basin margin from about 10 mi south of Colorado Springs to about 20 mi south of Pueblo is the principal recharge area for the Dakota-Cheyenne aquifer. In this reach the Dakota and Cheyenne sandstones crop out or are at shallow depth over a 200-mi² area, and they are readily recharged by infiltration of precipitation or by seepage from ephemeral streams. Of the estimated 5.5 ft³/s of recharge in this area, most discharges to the Arkansas River between Canon City and Fowler. Underflow from this segment of the basin margin into the deeper parts of the basin northeast of Pueblo is estimated to be less than 0.5 ft³/s.

The configuration of the potentiometric surface near the Apishapa, Sierra Grande, and Las Animas Arches is complex because of the irregular outcrop of the formations, deeply eroded topography, and because of faults that may form local barriers to water movement if the sandstone units are offset against impermeable shale, or if relatively impermeable fault gouge has developed. Ground water generally moves from the Apishapa and Sierra Grande Arches into Kansas to the east or into the Arkansas River or the Denver Basin to the north. Within the outcrop area local flow systems result from water moving to discharge areas located along deeply eroded valleys such as those of the Purgatoire River and its tributaries. In the Raton Basin, recharge appears to occur along the western margin outcrops and at the southern end of the Wet Mountain Valley; however, few data are available to define the potentiometric surface.

The potentiometric surface, the estimated structure along the western margin of the basin, and hydraulic conductivity, temperature, and porosity data all are consistent in defining a system of eastward increasing hydraulic connection within the aquifer, with minimal recharge along the Denver Basin margin north of Colorado Springs. Where recharge occurs north of Colorado Springs, the low transmissivity of the aquifer produces steep easterly hydraulic gradients near the basin margin. The west-to-east thickening of the aquifer combined with an easterly increase in hydraulic conductivity creates much larger transmissivity to the east. This causes the potentiometric surface in the east-central part of the Denver Basin to be relatively flat and to be affected more by lower heads in western Kansas and Nebraska than by higher heads along the Front Range outcrop. The unusually low heads found in the Dakota-Cheyenne aquifer are the likely result of this condition. In some areas, the equivalent freshwater head is more than 2,000 ft below land surface; heads in overlying shallow bedrock or alluvial aquifers generally are less than 100 ft below land surface. Ground-water flow modeling of the Dakota aquifer by P.C.D. Milly (U.S. Geological Survey, written commun., 1978) indicated that the measured head configuration in the aquifer could be reasonably simulated by a model based on hydrologic conditions similar to those presented here.

Fluid withdrawal, secondary hydrocarbon recovery practices, and changes in precipitation runoff have produced transient head changes in the Dakota-Cheyenne aquifer. These changes may range from a thousand feet or more of head decline in producing oil fields to an equal magnitude of head rise in response to water-flood secondary recovery. Data necessary to define the magnitude and extent of such local head changes generally are not available. In the southeastern part of the study area, extensive local withdrawal of ground water and variation in precipitation and flow in the Arkansas River have caused varying rates of water-level decline in different areas and at different depths in the aquifer. Water levels in this area (hydrograph in fig. 19) generally have remained constant or declined 20 to 70 ft between the mid-1960's and early 1980's. Declines from pristine conditions may have exceeded 100 ft in some areas. West of Pueblo, water levels have risen 10 to 40 ft in many wells and declined about 20 ft in other wells between about 1973 and 1984. Heads in much of this area apparently are still near the pristine conditions indicated in figure 19.

Hydraulic conductivity of the water-yielding rocks in the Dakota-Cheyenne aquifer is minimal in local areas where the sandstone is poorly sorted and clayey or is well consolidated. The conductivity is more than 20 ft/d in zones of well-sorted, coarse-grained sandstone. In the northern part of the area, hydraulic-conductivity values derived from drill-stem tests in adjacent wells sometimes differ by one or two orders of magnitude due to the discontinuous nature of the sedimentary structures in the intervals being tested. Water wells usually are completed through sections thicker than the intervals typically tested by drill-stem tests. As a result, hydraulic-conductivity values based on aquifer tests in water wells generally are less variable. In both cases, the large variance of the data precluded contouring and required estimation of means for large areas having generally similar values of hydraulic conductivity. The geometric means of the hydraulic-conductivity data are shown in figure 20 to range from 0.001 to 2.0 ft/d; the smallest value is associated with the zone along the western margin of the Denver Basin; the largest value is associated with a zone of relatively shallow aquifer depth near the Arkansas River and Apishapa Arch.

The zone of small hydraulic conductivity may be due to poor sorting, greater clay content, or diagenetic reduction in porosity of the sandstone. This change of facies may be associated with northeasterly prograding deltas postulated by Haun (1963), Weimer (1970), and MacKenzie (1971) to have been formed by the deposition of detritus transported from westerly source areas as opposed to the easterly source areas commonly identified in the Dakota Sandstone in other parts of the basin. The large hydraulic conductivity in the southern part of the area may result from greater porosity produced by lesser overburden load, dissolution of the rock matrix by recharged water not yet in equilibrium with the rock, and fracturing produced by surficial processes or unloading of overburden. A general eastward increase in hydraulic conductivity across the Denver Basin is indicated and is consistent with results of flow modeling (P.C.D. Milly, U.S. Geological Survey, written commun., 1978) which demonstrated that an increase is required to account properly for the change in gradient of the potentiometric surface across the basin.

The aquifer is confined by the underlying Morrison Formation and the overlying Graneros Shale. The vertical hydraulic conductivities of these formations generally are not defined by observational data; however, results of flow modeling (P.C.D. Milly, U.S. Geological Survey, written commun., 1978) indicate that negligible vertical leakage likely occurs across the confining layers. A vertical hydraulic conductivity of the confining layers ranging from 4×10^{-7} to 9×10^{-8} ft/d was shown by P.C.D. Milly (U.S. Geological Survey, written commun., 1978) to be compatible with the lateral hydraulic conductivity and potentiometric surface.

The effectiveness of the underlying Morrison Formation as a confining layer is indicated by Banta (1983) who reports that in T. 21 S., R. 67 W., 31 sandstone beds under the Morrison (probably Lyons Sandstone) have static heads about 200 ft above the top of the Morrison; yet, the sandstone beds overlying the Morrison are unsaturated. The effectiveness of the Morrison as a confining layer likely varies throughout eastern Colorado in response to varying lithology. In areas where the Kiowa Shale Member consists of thick shale beds having few joints, it likely forms an effective confining layer between the Dakota Sandstone and the Cheyenne Sandstone Member. In other areas the Kiowa, because of its lesser shale content, forms a leaky confining layer, and the two sandstone units are in hydraulic connection.

Porosity of the water-yielding material of the Dakota-Cheyenne aquifer is shown (fig. 20) to range from less than 10 percent along the western margin of the aquifer to more than 30 percent in the southeastern part of the area. Geophysical logs used to define the porosity distribution are not commonly run on water wells; as a result, few data are available to define porosity in the southern part of the area. However, the sparse data indicate that larger porosity generally occurs in the less deeply buried parts of the aquifer near the Arkansas River and the Apishapa Arch, probably because of the development of secondary porosity near areas of outcrop or subcrop.

In a confined aquifer, the specific storage is related to the porosity and compressibility of the rock and the compressibility of water by the equation:

$$S_s = \frac{S}{b} = \gamma(C_r + \phi C_w) \qquad (1)$$

where:

S_s = specific storage,
S = storage coefficient,
b = aggregate thickness of water-yielding material,
γ = specific weight of water,
C_r = compressibility of rock,
ϕ = porosity, and
C_w = compressibility of water (assumed constant).

A plot of a family of curves that satisfies equation (1) (fig. 21) indicates that for large values of C_r, specific storage primarily is a function of C_r and is relatively independent of ϕC_w. For small values of C_r, specific storage primarily is a function of ϕC_w. The common range of compressibility of sandstone under various overburden loads (Fatt, 1958) is such that specific storage for these rocks lies in the transition zone between the above two extremes. A compressible sandstone located at shallow depth will have a specific storage of about 1.5×10^{-4} ft^{-1} without regard for porosity. Sandstone at a depth of 9,000 ft will have smaller compressibility, and specific storage will be porosity dependent, ranging from about 4×10^{-7} to 7×10^{-7} ft^{-1} for porosity between 10 and 30 percent.

The storage coefficient of the Dakota-Cheyenne aquifer may be estimated (equation 1) as the product of the aggregate sandstone thickness (figs. 17 and 18) and the specific storage (fig. 21), where porosity (fig. 20) is used in the determination of specific storage in areas where the aquifer is deeply buried (fig. 16). These computations indicate that the storage coefficient ranges from about 1.5×10^{-4} to 4.5×10^{-4} where sandstone thickness ranges from 100 to 200 ft in the area of relatively shallow aquifer depth near the Arkansas River and the Apishapa Arch. Storage coefficients based on eight aquifer tests in this area (McLaughlin, 1954; Weist, 1965; Wilson, 1965) were about 1×10^{-4} in six tests and about 1×10^{-3} in two tests, thus bracketing the range of values calculated from specific storage. One value of 4×10^{-5} by McLaughlin (1954) is thought to be invalid. On the axis of the Denver Basin near Denver, the storage coefficient of the thin, low porosity, deeply buried sandstone is about 8×10^{-5}.

The specific yield of the sandstone units is poorly documented in published literature. Aquifer tests on wells completed in unconfined parts of the aquifer generally indicate specific yield to be about 10 percent. Specific yields for Cretaceous sandstone beds located above the Pierre Shale are shown by Robson (1983) to range from about 14 to 20 percent.

Wells completed in the Dakota-Cheyenne aquifer generally have larger yields in the southern part of the aquifer where the transmissivity and storage coefficients are large and the aquifer is at a relatively shallow depth. Well yields of 5 to 50 gal/min are common for domestic and stock wells; some irrigation wells in Baca County are reported to yield more than 1,000 gal/min (McLaughlin, 1954).

Chemical and physical characteristics of the water in the Dakota-Cheyenne aquifer significantly affect potential uses of the aquifer. Large dissolved-solids concentrations, for example, may preclude surface use of the water but may be compatible with subsurface waste disposal by deep-well injection; high water temperatures may be conducive to geothermal applications; cool, low-salinity water may be suitable for municipal or industrial use.

Fluid temperature in the aquifer ranges from less than 60°F in the shallow parts of the aquifer to more than 200°F on the axis of the Denver Basin near Denver and Greeley (fig. 22). Geothermal gradients in the unpatterned area are consistent with the earth's average gradient of about 1.5°F per 100 ft of depth. In the northwestern and northeastern parts of the area and near Canon City, the observed geothermal gradient is greater than the average, and the temperature of the aquifer is 2° to 25°F greater than would be expected on the basis of the average gradient and the depth of the aquifer. The thermal areas near Canon City and Denver are located at depths of about 5,000 and 9,000 ft and may be the result of increased thermal conductivity of the rocks at these depths or of increased thermal gradients produced by residual heat sources associated with uplift of the Front Range. The thermal area in the northeast is consistent with updip eastward movement of water heated in transit through the deeper and hotter parts of the basin to the west. Two areas having aquifer temperatures less than those indicated by the average thermal gradient are located near Pueblo and Walsenburg. Downdip movement of relatively cool water recharged in the outcrop and subcrop along the western margin of the aquifer likely occurs in these areas. The distribution of relatively cool water in both areas is consistent with the direction of water movement indicated by the potentiometric surface, although the temperature distribution in the Raton Basin is poorly defined.

The dissolved-solids concentration of water in the Dakota-Cheyenne aquifer usually ranges from 200 to 25,000 mg/L and is correlated with specific conductance (fig. 23). Water from the aquifer in the recharge areas northwest and southwest of Pueblo ranges in dissolved-solids concentration from 200 to 500 mg/L (fig. 24); generally it is low in chloride and of a calcium bicarbonate type. Faults west of Pueblo appear to affect the local direction of water movement and allow water of differing quality to occur on opposite sides of some faults. Sparse data indicate that dissolved-solids concentrations of water in the aquifer are between 500 to 1,000 mg/L in the recharge area on the Apishapa Arch in eastern Las Animas County. As this water moves eastward, subsequent recharge of better quality water occurs through the veneer of unconsolidated sediments in Baca County. The resulting mixing produces the water containing 250 to 500 mg/L of dissolved solids found in much of Baca and southeastern Prowers Counties (figs. 19 and 24).

In the Denver Basin, the complex stratigraphy of the aquifer affects the water chemistry in a manner consistent with the anomalies observed in the potentiometric surface and the hydraulic conductivity. In some cases, dissolved-solids concentrations observed in water from nearby wells or from different sampling intervals of the same well differ by as much as 20,000 mg/L. Areas where most data indicate large dissolved-solids concentrations commonly have a few embedded data indicating small concentrations; contouring in such areas is subjective and may not represent conditions in the regional flow system (fig. 24). Some of the small-concentration samples were obtained from oil-field production water; this indicates that the small-concentration data are not anomalies produced by drilling mud or other transient-fluid contamination of drill-stem test samples. The water-quality data for the Denver Basin are based on analyses of samples of oil-field production water or drill-stem recovery fluids, and they may be more indicative of water from potential hydrocarbon traps rather than from the aquifer as a whole. The large dissolved-solids concentrations observed in the oil-producing northern part of the basin may be representative of conditions in these stratigraphic traps. The fewer data showing small dissolved-solids concentrations may be indicative of the quality of water in the interconnected regional flow system.

Water in individual zones of the aquifer differs in quality in response to the degree of mixing that has occurred between the transient meteoric water and the connate water. If a zone is hydraulically isolated, the entrapped water may be connate, and its composition may be indicative of the chemical composition of the depositional or diagenetic environment. At the other extreme, if a zone is an interconnected part of the aquifer, flushing should have removed most connate fluids, and the chemical composition of the formation water should be more similar to that found in recharge areas.

The 10 largest dissolved-solids concentrations measured in samples from the aquifer ranged from 20,200 to 31,900 mg/L. This water has an average chemical composition similar to that of slightly diluted, present-day sea water, as shown in table 2; sea water has a dissolved-solids concentration of about 34,000 mg/L. If the Cretaceous sea had a chemical composition similar to that of present sea water, then the dissolved-solids concentration and chemical composition of these samples are consistent with the marine deltaic depositional environment in which much of the Dakota Sandstone was deposited. It is possible that the presence of saline water results from upward migration of brines from the underlying Lyons Sandstone. However, this is not probable because of poor hydraulic connection through the 500 to 1,000 ft of shaley material separating the two units and because the Lyons aquifer contains relatively large concentrations of sulfate (6,000 to 15,000 mg/L), whereas the sulfate concentrations in the Dakota-Cheyenne aquifer are relatively small (60 to 2,600 mg/L) even in the most saline zones.

Table 2 indicates that the concentrations of dissolved constituents in large dissolved-solids-content water from the Dakota-Cheyenne aquifer are about one-fourth to 1½ times those of present-day sea water; sulfate concentrations are small, about one-fourth that of sea water. A similar rational comparison between large and small dissolved-solids-content water from the Dakota-Cheyenne aquifer also indicates that sulfate ratios are small (about 2) compared to ratios for other constituents which range from about 0.5 to 100. Ratios for dissolved constituents of water in underlying formations (the Lyons Sandstone is the first deeper unit for which water-quality data are available) to the large dissolved-solids-content water of the Dakota-Cheyenne indicate very large sulfate ratios—about 17, as compared to about 0.5 to 3 for the other constituents. The marked difference in sulfate composition of these two waters indicates that simple mixing of upward-moving saline water could not account for the present chemical composition of the large dissolved-solids-content water in the Dakota-Cheyenne aquifer. Although sulfate reduction or other reactions may alter the composition of the large dissolved-solids-content water, the fate of the sulfur produced by the reactions is unknown because hydrocarbons produced from the Dakota Sandstone commonly contain negligible (0.0–0.2%) sulfur.

In the recharge area along the western margin of the Denver Basin, the water in the aquifer ranges in dissolved-solids concentration from about 200 to 1,000 mg/L and is primarily of a calcium bicarbonate type. The water increases in concentration to about 1,000 to 2,000 mg/L and becomes a sodium bicarbonate type as it moves eastward into the basin. Dissolution, mixing, and geochemical reactions produce the more mineralized sodium bicarbonate water that generally is found within 10 to 50 mi of principal recharge areas. Samples of this water are referred to as "modified recharge water" in table 2. Ten samples of water obtained from the petroleum-producing northern part of the basin and having dissolved-solids concentrations less than 2,000 mg/L also are of a sodium bicarbonate type and are chemically similar to the modified recharge water (table 2). Thus, the relatively fresh water found in this part of the basin likely is derived from surface recharge near the outcrops, and the saline water in this area likely is the remnant of the connate fluid. The complex stratigraphy of this part of the basin probably is responsible for: (1) Highly variable head data observed in drill-stem test results; (2) marked differences in hydraulic conductivity observed over short distances; and (3) nonuniform water chemistry found in the aquifer.

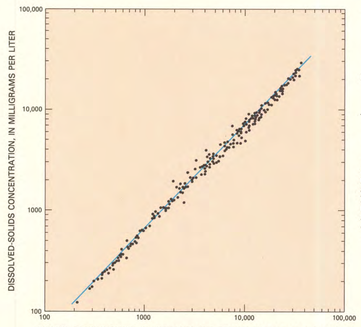

Figure 23.—Relation of dissolved-solids concentration to specific conductance of water from the Dakota-Cheyenne aquifer in eastern Colorado.

TABLE 2.—Ratios of dissolved constituents in selected water

[Dh, water of large dissolved-solids concentration in Dakota-Cheyenne aquifer; Sw, sea water; Dl, water of small dissolved-solids concentration in Dakota-Cheyenne aquifer; Lw, water in Lyons aquifer; Dm, modified recharge water in Dakota-Cheyenne aquifer]

Chemical constituent	Ratio of dissolved constituents			
	Dh/Sw	Dh/Dl	Lw/Dh	Dm/Dl
Calcium	1.5	43	0.58	0.53
Magnesium	.24	45	---	.53
Sodium	.71	11	2.7	.62
Potassium	1.51	107	---	.60
Bicarbonate	3.6	.45	1.6	.70
Sulfate	.24	2.2	17	.96
Chloride	.71	54	1.9	.32

GEOLOGY AND HYDROLOGY OF THE DEEP BEDROCK AQUIFERS IN EASTERN COLORADO

By
S. G. Robson and E. R. Banta

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