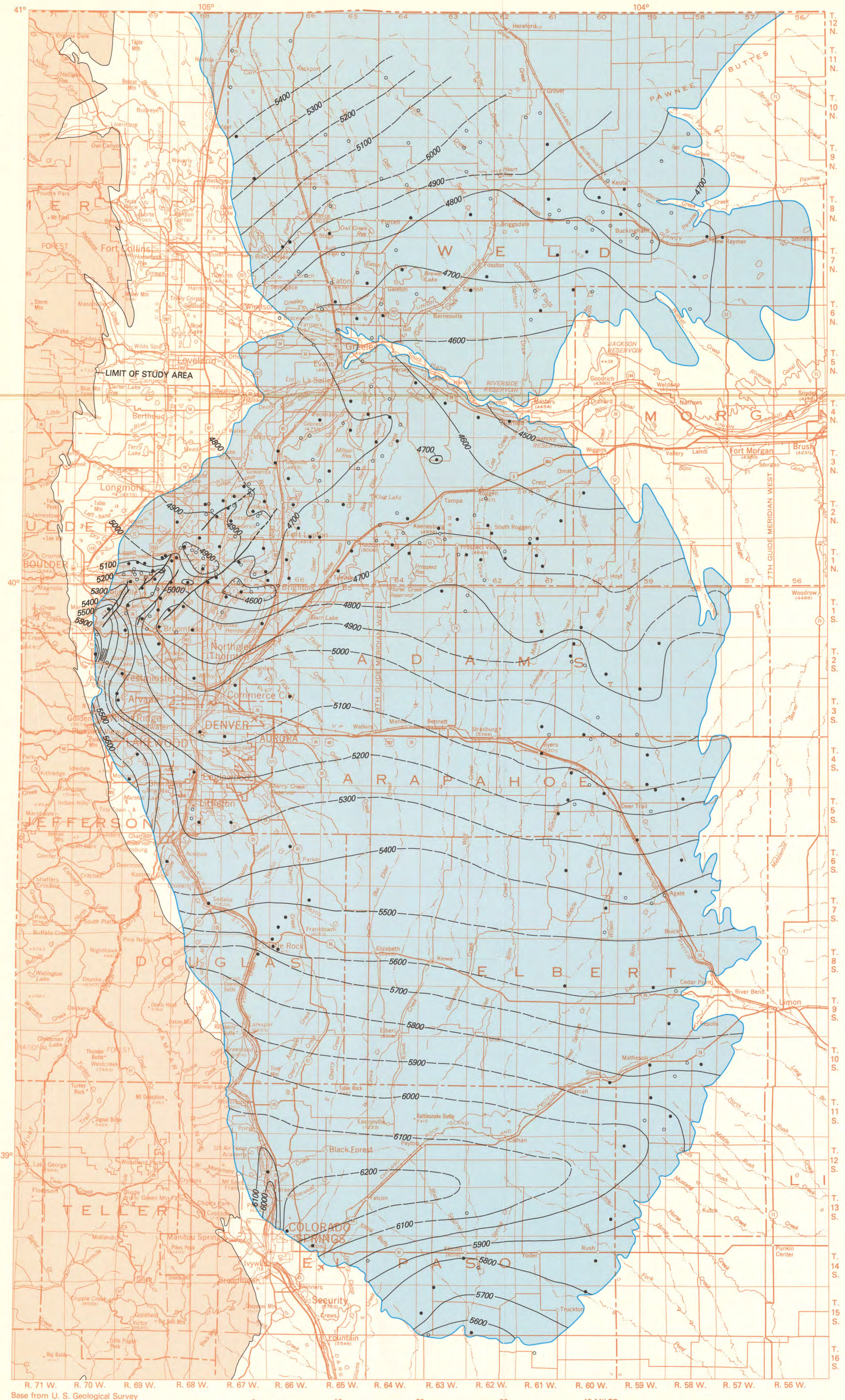


Base from U. S. Geological Survey 1:500,000 Colorado State base map, 1969

EXPLANATION

OUTCROP OF PRECAMBRIAN ROCKS

AREA UNDERLAIN BY THE LARAMIE-FOX HILLS AQUIFER

APPROXIMATE LIMIT OF THE LARAMIE-FOX HILLS AQUIFER

FAULT—Dashed where inferred

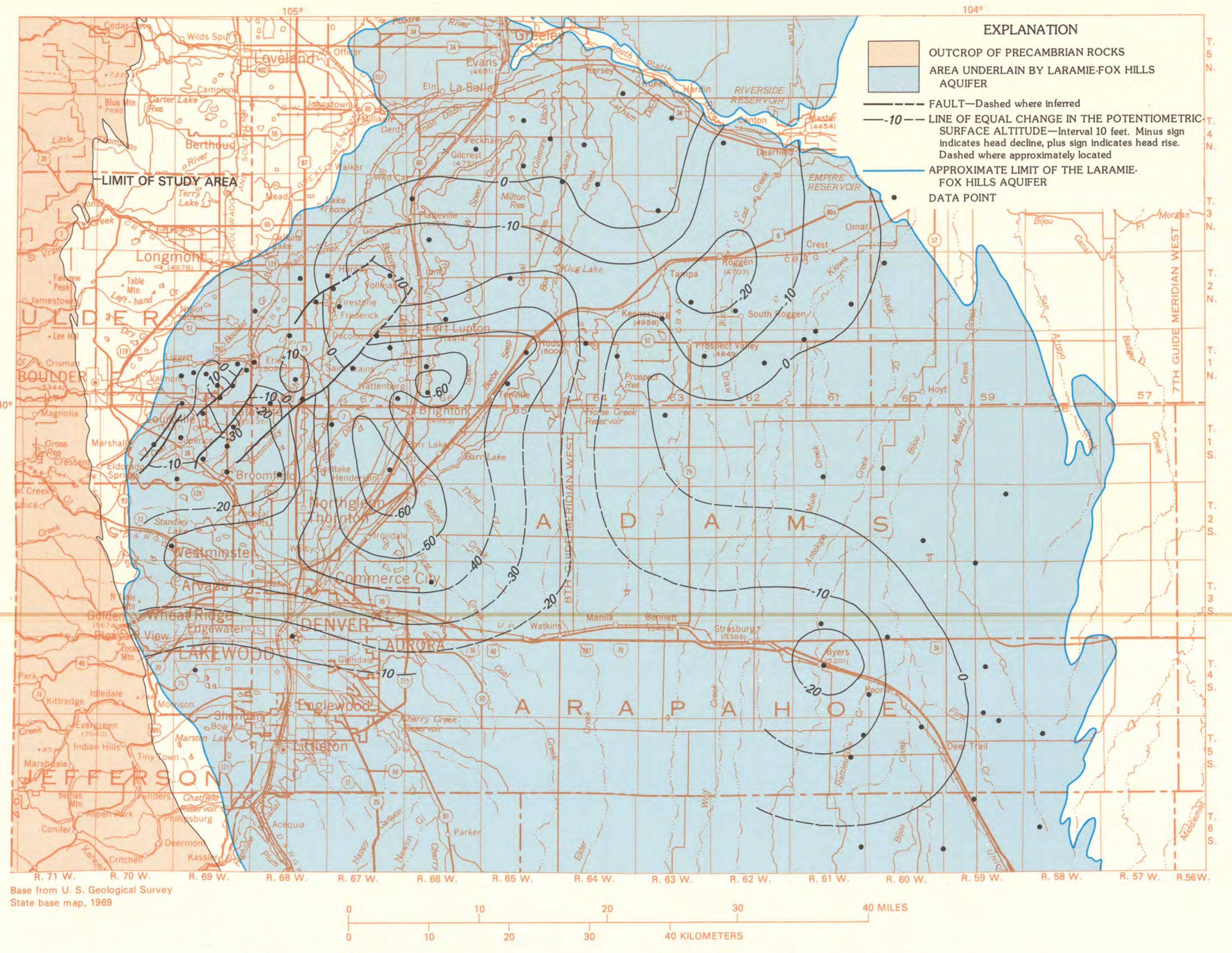
4700 POTENTIOMETRIC CONTOUR—Shows altitude of standing-water level in wells completed in the Laramie-Fox Hills aquifer. Dashed where approximately located. Contour interval 100 feet. Datum is sea level

DATA POINTS

Head measured in 1983

Head estimated from earlier measurement or from partially penetrating well

Figure 10.—1983 potentiometric surface for the Laramie-Fox Hills aquifer in the northern and central Denver Basin.



Base from U. S. Geological Survey State base map, 1969

EXPLANATION

OUTCROP OF PRECAMBRIAN ROCKS

AREA UNDERLAIN BY LARAMIE-FOX HILLS AQUIFER

FAULT—Dashed where inferred

-10 LINE OF EQUAL CHANGE IN THE POTENTIOMETRIC SURFACE ALTITUDE—Interval 10 feet. Minus sign indicates head decline, plus sign indicates head rise. Dashed where approximately located

APPROXIMATE LIMIT OF THE LARAMIE-FOX HILLS AQUIFER

DATA POINT

Figure 11.—1978-1983 change in the potentiometric surface altitude in the Laramie-Fox Hills aquifer near Denver.

TABLE 1. Mean 1958-78 water budget for the Laramie-Fox Hills aquifer in the central Denver Basin

[Values in cubic foot per second]

| | |
|---|---|
| **RECHARGE** | |
| Precipitation recharge | 5.8 |
| Induced recharge plus captured discharge | 3.1 |
| Decrease in ground-water storage | 1.0 |
| Total | 9.9 |
| **DISCHARGE** | |
| Pumpage | 4.1 |
| Natural discharge to the drainage areas of: | |
| Bijou Creek | 2.1 |
| San Arroyo-Badger Creeks | 1.1 |
| Kiowa Creek | .7 |
| South Platte River | .3 |
| Rush-Steel Fork Creek | .5 |
| Black Squirrel Creek | .2 |
| Monument-Fountain Creeks | .2 |
| Big Sandy Creek | .2 |
| Lost Creek | .2 |
| Box Elder Creek | .1 |
| Total | 9.9 |

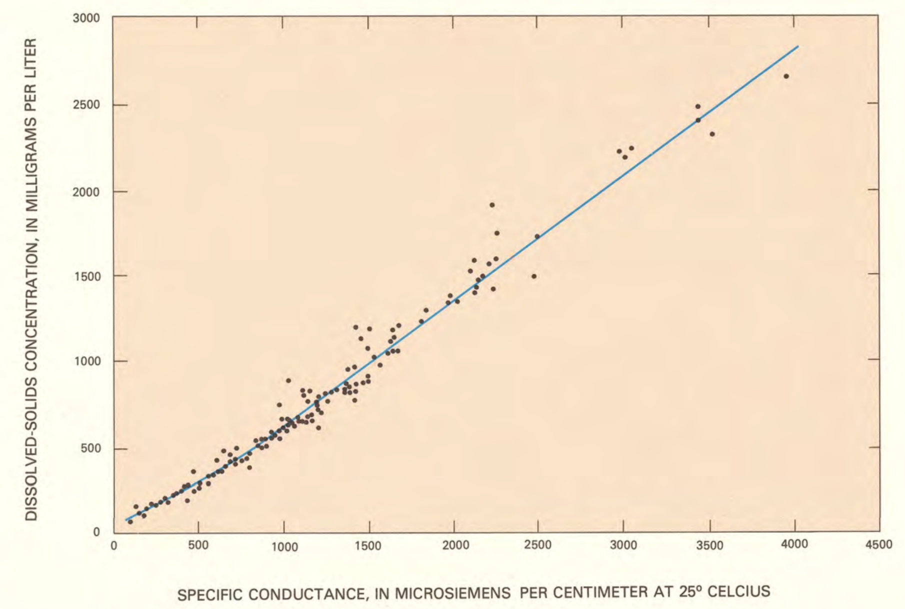



Figure 12.—Relation of dissolved-solids concentration to specific conductance of water from the Laramie-Fox Hills aquifer in the northern and central Denver Basin.

## LARAMIE-FOX HILLS AQUIFER

### Hydrology

In the central part of the Denver Basin, the 1983 potentiometric surface in the Laramie-Fox Hills aquifer ranges in altitude from more than 6,200 ft above sea level at the ground-water divide near Colorado Springs to less than 4,500 ft near the South Platte River east of Greeley (fig. 10). Horizontal hydraulic gradients are commonly 20 ft/mi, but they steepen along the western margin and are profoundly affected by faults and abandoned coal mines in the local area near Boulder. Ground water moves in a predominantly northerly direction, but easterly, southeasterly, or southerly movement occurs near the western and southern basin margins. A trough in the potentiometric surface extends from T. 2 N., R. 64 W. to Brighton and south to Littleton; it is the result of ground-water discharge to low-lying alluvial aquifers along the South Platte River and its tributaries. This trough has been deepened and expanded by extensive pumpage in the northern Denver metropolitan area. Water-level declines between 1958 and 1978 from Brighton to Northglenn are shown by Robson and others (1981) to have exceeded 200 ft, averaging 10 ft/yr; declines between 1978 and 1983 are shown in this report (fig. 11) to exceed 60 ft, averaging 12 ft/yr.

In the northern part of the Denver Basin, the potentiometric surface ranges in altitude from more than 5,400 ft near the Colorado-Wyoming border to less than 4,600 ft near the South Platte River (fig. 10). A southeasterly direction of ground-water movement is indicated; the average horizontal hydraulic gradient is about 20 ft/mi. Historical water-level data indicate that no significant water-level declines have occurred in this largely undeveloped part of the basin.

In most of the Raton Basin, data are inadequate to define the potentiometric surface; however, the larger vertical hydraulic conductivity of the rocks overlying the aquifer in this basin likely allows topography to more readily affect the shape of the potentiometric surface. This is substantiated by the shape and gradient of part of the potentiometric surface in the area west of Trinidad as constructed by Geldon (1984). His local results indicate that the potentiometric surface conforms to the generalized shape of the land surface and that both slope at gradients of about 100 ft/mi. Perennial flow in the lower reaches of the Huerfano, Cucharas, Apishapa, and Purgatoire Rivers is sustained primarily by discharge from the bedrock aquifers, and heads in the near-stream bedrock outcrops or subcrops are at approximately the same altitude as those in the alluvium.

Recharge to the Laramie-Fox Hills aquifer results from infiltration of precipitation in the highland outcrops or as percolation of water from overlying alluvial aquifers in subcrop areas where the head in the alluvial aquifer is higher than that in the Laramie-Fox Hills aquifer. Infiltration in the highland areas between stream channels supplies water to both local and regional ground-water flow systems. In the local system, water moves through the aquifer from the upland recharge areas to discharge areas in nearby stream valleys and does not contribute significantly to the large-scale movement of water in the aquifer. In the regional system, however, water moves from recharge areas to greater depth in the aquifer and is discharged only after moving to more remote discharge areas (Robson and Romero, 1981a). The small surface exposure of the steeply dipping beds along the western margin of the Denver Basin and on both the east and west margins of the Raton Basin restricts recharge in these areas. Work by Robson (1984) indicates that about 0.7 ft³/s of recharge occurs in the steeply dipping outcrops along the western margin of the central Denver Basin compared to 5.1 ft³/s of recharge in the other, more extensive, relatively flat-lying outcrops to the east. Data are inadequate to estimate the rate of recharge to the aquifer in the Raton Basin, although the preponderance of coarse clastic materials in the rocks overlying the aquifer in most of the basin likely would allow vertical leakage from overlying units to be an important component of total recharge.

Discharge from the Laramie-Fox Hills aquifer occurs through natural processes such as evaporation, transpiration, spring discharge, and upward leakage to overlying alluvial aquifers or through artificial processes such as pumpage from wells. Valley bottoms are the principal natural discharge areas for the bedrock aquifer. In the valleys, bedrock springs and upward leakage from the aquifer supply water to the streams or the associated alluvial aquifers where evaporation and phreatophyte transpiration remove water from the system. Under pristine conditions, these processes were paramount, and they likely remain the principal discharge mechanisms in the undeveloped parts of the three basins. Development of bedrock water resources began in Denver in 1883, and pumpage from the Laramie-Fox Hills aquifer increased to about 3.0 ft³/s in 1970 and 5.4 ft³/s in 1977. Most of this pumpage occurs near Denver, and discharge greatly exceeds recharge in the metropolitan area (Robson, 1984). In areas where pumpage has caused significant decline of the potentiometric surface, natural discharge may no longer occur, and pumpage may be the principal discharge process.

The mean 1958-1978 water budget for the Laramie-Fox Hills aquifer in the central Denver Basin (table 1) indicates that precipitation supplies about 5.8 ft³/s of recharge to the regional flow system. Pumpage produces head declines in the aquifer, removes ground water from storage, and may alter vertical head gradients in the outcrop, thereby inducing additional recharge or capturing previous natural discharge. These items are considered as recharge terms in the water budget; they total 3.1 ft³/s. Pumpage is probably the principal means of discharge since natural discharge has been reduced by the declining head in the aquifer. The principal natural discharge from the aquifer in the central part of the Denver Basin is to the major drainages crossing the outcrop along the northern margin; 76 percent of the total discharge occurs in this area.

Hydraulic characteristics of the aquifer are well defined in the extensively developed central Denver Basin. Robson (1983), for example, used the results of about 115 aquifer tests and laboratory permeability determinations to show that the average hydraulic conductivity of the water-yielding material of the aquifer in this area ranges from 0.05 to 6.0 ft/d, with an extensive zone of large hydraulic conductivity (2.0 ft/d) located along the area's northeastern margin. More recent aquifer tests indicate that a zone of small hydraulic conductivity (0.05 ft/d) located north and west of Denver may extend south along the western basin margin to a point south of Castle Rock. The aggregate thickness of the water-yielding material in the aquifer commonly ranges from 100 to 200 ft (figs. 8 and 9). Transmissivities range from less than 5 ft²/d to more than 1,000 ft²/d. The transmissivity distribution is similar to that for hydraulic conductivity; both attain a maximum value in a localized area near Littleton. Porosity of the water-yielding material was shown to range from 21 to 44 percent and to average about 32 percent, based on laboratory analyses of 42 rock samples and interpretation of 21 geophysical logs. Specific-yield values determined from laboratory analyses of 29 samples range from 5 to 38 percent, and storage coefficient of the confined aquifer ranges from about $2 \times 10^{-4}$ to $4 \times 10^{-4}$.

Little development of ground-water resources has occurred in the northern part of the Denver Basin; few wells are available as sites for collecting hydrologic data. However, hydrologic testing in proposed uranium solution-mining areas near the towns of Keota and Grover provides good estimates of aquifer characteristics in these areas. These estimates and data from a few other sites indicate that the hydraulic characteristics of the Laramie-Fox Hills aquifer in the northern part of the Denver Basin are similar to those of the central Denver Basin. Hydraulic conductivity ranges from 0.5 to 1.7 ft/d near Keota (Woodward-Clyde Consultants, 1980); averages about 1.5 ft/d near Grover (Wyoming Mineral Corporation, 1978; Warner, 1981); and is 0.8 ft/d at 8N/63W-24, 0.4 ft/d at 10N/66W-36, and 0.5 ft/d at 11N/61W-4 (Weist, 1965). The aggregate thickness of water-yielding material in the aquifer commonly ranges from 100 to 150 ft, and calculated transmissivities range from 50 to 225 ft²/d using hydraulic conductivities ranging from 0.5 to 1.5 ft/d. Data are not available to define the distribution of hydraulic conductivity or transmissivity, although the lesser aquifer thickness in the outcrop results in smaller transmissivities along the margin of the aquifer. Porosity ranges from 36 to 40 percent near Keota and from 36 to 38 percent near Grover. Storage coefficient of the confined aquifer ranges from $1 \times 10^{-5}$ to $1 \times 10^{-3}$ near Keota ($2 \times 10^{-4}$ is a common value)(Woodward-Clyde Consultants, 1980); near Grover, a value of $3 \times 10^{-5}$ was obtained, and a value of $2 \times 10^{-4}$ was obtained at 8N/63W-24 and 11N/61W-4 (Weist, 1965).

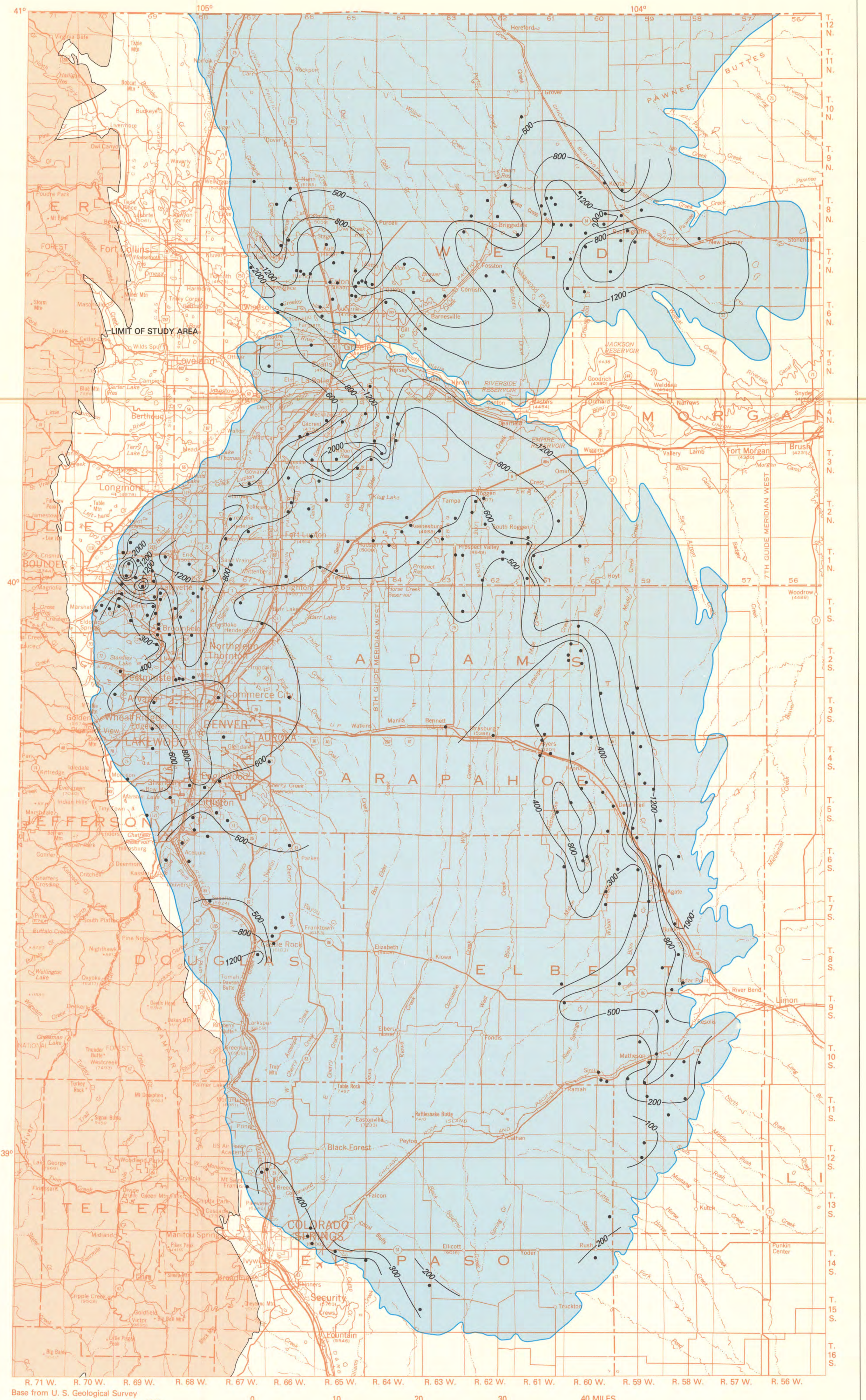
Hydraulic conductivity of the Laramie-Fox Hills aquifer in the Raton Basin is shown by Geldon (1984) to range from $2 \times 10^{-3}$ to 45 ft/d and to average about 2 ft/d. This average value, multiplied by the aggregate thickness of water-yielding material (200 ft is common), yields a transmissivity of about 400 ft²/d. The distributions of hydraulic conductivity and transmissivity are poorly defined by the available data, and little data are available to define other aquifer characteristics.

The thick sequence of shale in the upper part of the Laramie Formation forms a relatively impermeable barrier to the vertical movement of fluids. This confining layer is most effective in the central Denver Basin and is likely less effective in the northern part of the Denver Basin because of the greater prevalence of interlayered sandstone in the upper member of the Laramie in this area.

Water in the Laramie-Fox Hills aquifer is generally of a sodium bicarbonate type in deeply buried areas distant from surface recharge. The water in the upper part of the aquifer northeast of Greeley is commonly of a calcium bicarbonate type, and it is similar to, and likely derived from, water in overlying formations. At greater depth in this area and at greater distances down the flow path, sodium concentrations increase, probably due to calcium-sodium cation-exchange reactions on the clay minerals prevalent in the aquifer. Near outcrops or subcrops local recharge water dissolves soluble minerals from the oxidizing soil and regolith causing an increase in dissolved solids and sulfate concentrations in the aquifer. Sodium sulfate is the most common water type in these areas and in areas where coal mine spoil piles and abandoned workings may be sources of oxidation reaction compounds.

Dissolved-solids concentrations range from less than 200 mg/L to more than 4,000 mg/L and correlate with specific conductance (fig. 12). Small dissolved-solids concentrations are present in the deeply buried central parts of the basins; larger concentrations near the margins of the aquifer generally are associated with ground-water discharge or with local recharge of more mineralized water from outcrops (fig. 13). Dissolved-solids concentrations of more than 1,200 mg/L occur along the South Platte River and the eastern margin of the aquifer. Sulfate concentrations of 100 to 1,200 mg/L are common in these areas, but concentrations generally are less than 50 mg/L in the deeper parts of the northern Denver Basin and generally range from 2 to 20 mg/L in the central Denver Basin. Ground water is soft (less than 60 mg/L of hardness as calcium carbonate) in the deep parts of the basin but may range from moderately hard to hard (60 to 180 mg/L of hardness as calcium carbonate) in areas where surface recharge introduces calcium bicarbonate water into the aquifer. In the northern part of the Denver Basin, such recharge produces a zone of hard water in the upper part of the Laramie Formation. This hard water overlies soft water contained in the underlying Fox Hills Sandstone. Very hard water (more than 180 mg/L of hardness as calcium carbonate) generally is restricted to basin margin areas where erosion has markedly decreased the thickness of the aquifer, thereby allowing locally recharged water to dominate the quality of the ground water in storage.

Coal and lignitic material in and adjacent to the aquifer produce reducing conditions that allow the formation, dissolution, and transport of ferrous iron, methane, and hydrogen sulfide. Dissolved-iron concentrations of 10 to 100 μg/L are common, but concentrations in excess of 10,000 μg/L have been detected in a few scattered locales in the central Denver Basin. Where large concentrations of methane and hydrogen sulfide are encountered, pumped water may effervesce and have a putrid odor and objectionable taste. The change from oxidizing to reducing conditions in the aquifer has precipitated uranium minerals in some outcrop areas of the Denver Basin and has produced ore-grade deposits near the towns of Grover, Keota, and Briggsdale. Dissolved-uranium concentrations generally are less than 10 μg/L in the bedrock aquifers but exceed 100 μg/L in some alluvial aquifers.



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

EXPLANATION

OUTCROP OF PRECAMBRIAN ROCKS

AREA UNDERLAIN BY LARAMIE-FOX HILLS AQUIFER

APPROXIMATE LIMIT OF THE LARAMIE-FOX HILLS AQUIFER

500 LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION—Interval, in milligrams per liter, is variable

DATA POINT

Figure 13.—Dissolved-solids concentration of water from the Laramie-Fox Hills aquifer in the northern and central Denver Basin.



# GEOLOGY AND HYDROLOGY OF THE DEEP BEDROCK AQUIFERS IN EASTERN COLORADO

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

1987