PREPARED IN COOPERATION WITH THE
COLORADO DEPARTMENT OF NATURAL RESOURCES, DIVISION OF WATER RESOURCES,
OFFICE OF THE STATE ENGINEER; THE DENVER BOARD OF WATER COMMISSIONERS;
AND ADAMS AND ARAPAHOE COUNTIES

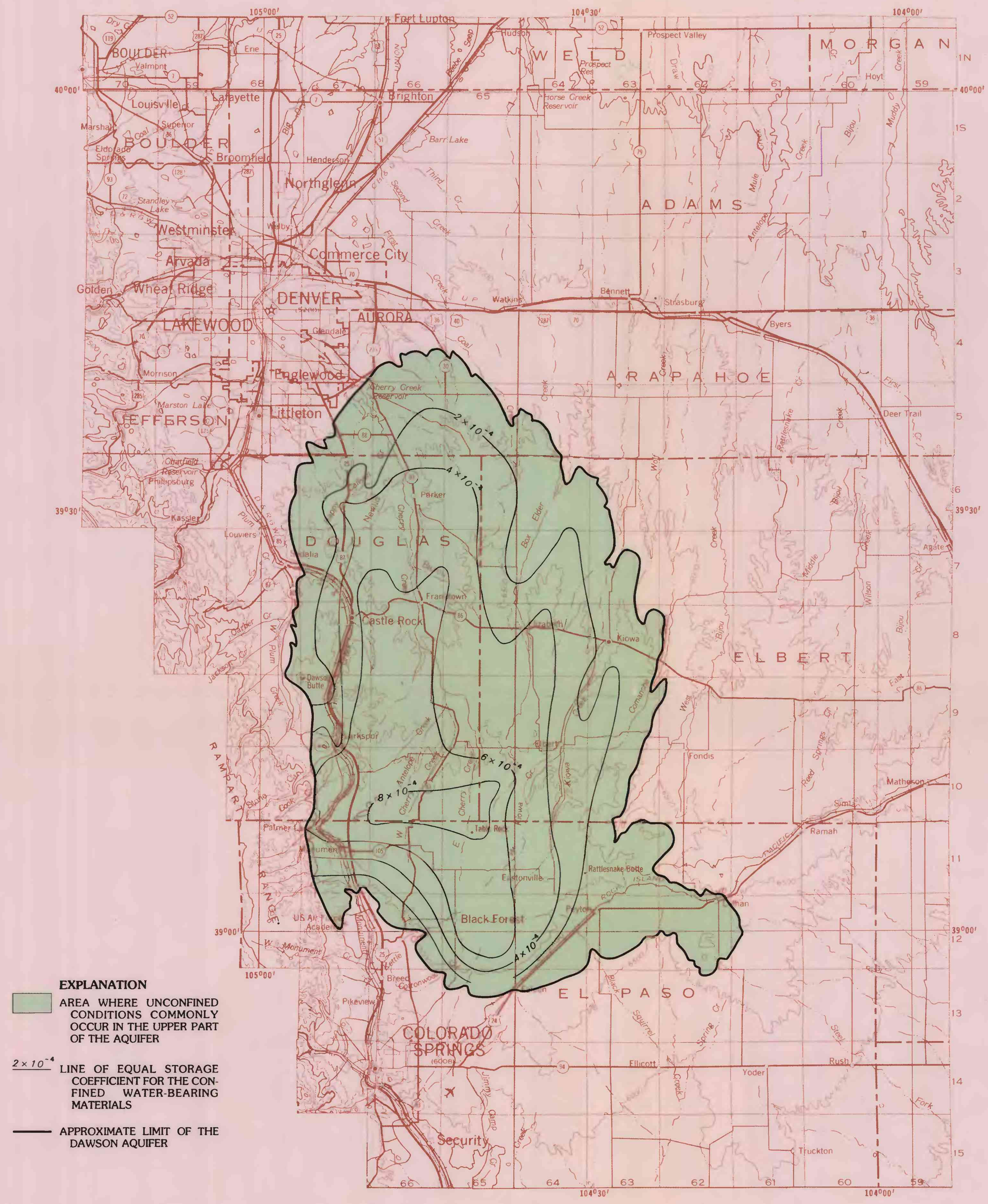

FIGURE 14.—MAP SHOWING ESTIMATED STORAGE COEFFICIENT OF THE DAWSON AQUIFER

SPECIFIC STORAGE AND STORAGE COEFFICIENT

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:

$$S_s = Y(\theta C_w + C_r).$$

where:

S_s = specific storage,
Y = specific weight of water,
θ = porosity,
C_w = compressibility of water, and
C_r = compressibility of the rock.

In the siltstone, sandstone, and conglomerate strata of the bedrock aquifers, porosity commonly ranges from 0.20 to 0.40 and the compressibility of similar rock in other areas ranges from about 7×10^{-7} to 7×10^{-6} inch squared per pound under moderate overburden load (Fatt, 1958; Clark, 1966). The compressibility of water is about 3.0×10^{-6} inch squared per pound and the specific weight of water is 3.6×10^{-2} pound per cubic inch (Freeze and Cherry, 1979). If the maximum and minimum values for porosity and rock compressibility are used in solving the above equation, the specific storage of the confined aquifers is shown to range from about 5.6×10^{-7} to 3.5×10^{-6} $foot^{-1}$. The mean value is about 2×10^{-6} $foot^{-1}$. This value is the volume of water the confined water-yielding strata release from or take into storage per unit volume per unit change in head due to the compressible character of the water and the rock.

In an unconfined aquifer the volume of water released from or taken into storage by this process is insignificant when compared to the volume involved in the gravity drainage or filling of the pore space in the rock. As a result, the storage coefficient of an unconfined aquifer is approximately equal to the specific yield of the aquifer. The results of 59 specific-yield determinations performed on samples of siltstone, sandstone, and conglomerate from the bedrock formations are listed in table 2 (see sheet 2). The samples were analyzed by one of two laboratory techniques. The centrifuge-moisture equivalent technique (American Society of Testing and Materials, 1964) was used to analyze those samples that were medium to coarse grained and relatively friable. This technique determines the specific retention of the sample, and specific yield is calculated as the difference between porosity and specific retention. The mercury-injection, moisture-tension curve technique was used to analyze those samples that were fine grained or were well indurated (Prill and Johnson, 1967; Purcell, 1949). This technique was found to provide more accurate results for these samples than did the centrifuge technique. Effective porosity and specific yield are measured and specific retention is calculated as the difference between porosity and specific yield. Specific-yield data for a few samples reported to have greater than 48-percent porosity by McConaghy and others (1964) were considered to be questionable and were not used in this study.

Specific-yield data from table 2 and selected data from McConaghy and others (1964) indicate that the specific yield of the permeable materials ranges from about 1 to 38 percent. The large range is due to the variable composition of the aquifer materials, with clay content a principal factor. A moderately consolidated sandstone with minimal clay content commonly will have a relatively large porosity and correspondingly large specific yield. A clayey sandstone, by contrast, can have a relatively large porosity and a small specific yield due to the presence of the clay (Todd, 1967). Because of the variable composition of the permeable materials, specific yield can be expected to vary considerably from one permeable bed to another and from one area to another within the basin. Although of limited number, the available analyses are the best data currently (1981) available for use in estimating the specific yield of the water-yielding materials. The mean specific yield of the samples from the siltstone, sandstone, and conglomerate members of each aquifer is shown to range from 14 to 20 percent in table 4. The standard deviation of the data are 1 to 3 percent greater than the standard deviation of the laboratory determined porosity data (table 3), indicating that the mean specific yield is based on a more widely scattered distribution of data than is the mean porosity.

Results of aquifer tests conducted on 15 shallow wells completed in unconfined bedrock aquifers indicate a range in specific yield from 1 to 35 percent. The small number, limited areal distribution, and short duration of these tests do not allow meaningful estimation of the specific yield of the aquifers.

Aquifer-test results also were used to estimate specific storage and are available for about 50 bedrock wells in the basin. Specific storage from these tests ranged from 1×10^{-8} to 3×10^{-2} $foot^{-1}$ with large variation in values in some geographic areas. Although the data (fig. 13) correctly show small specific storage in those areas where the aquifers are undoubtedly confined (have a high head), they indicate that a large range in specific storage may occur in those areas where the aquifers are likely unconfined (have a low head) or may become unconfined during pumping stress. In thin aquifers having significant hydraulic connection between upper and lower layers, the transition from confined specific storage to unconfined specific storage should occur as a rapid and nearly complete change in specific storage at the time the upper layer first develops water-table conditions. This situation does not always occur in the Denver basin because significant hydraulic connection commonly does not exist across the shale layers that intervene between the upper and lower parts of each aquifer. As a result, both confined and unconfined conditions may coexist at different depths in the same aquifer. The differences in specific storage with depth are most pronounced during a short-term pumping period of a few hours or a few days and become less pronounced during a long-term pumping period of several years. Aquifer tests are short-term tests and, thus, may give markedly different values of specific storage in nearby wells of different depths completed in the same aquifer. This accounts for some of the scatter of data points shown in figure 13. Other factors contributing to the scatter include errors in data collection or test interpretation, rate of pumping, and anomalous well construction or completion practices. Attempts to estimate specific yield or specific storage by use of existing aquifer-tests results, thus, seem to be of minimal value.

The estimated confined storage coefficients for the four aquifers are shown in figures 14, 15, 16, and 17. These storage coefficients apply to the confined water-bearing material and are computed as the product of the average specific storage determined from equation 1 and the thickness of the water-yielding material in each aquifer as shown in reports by Robson and Romero (1981a, 1981b), Robson, Romero, and Zawistowski (1981), and Robson, Wacinski, Zawistowski and Romero (1981). In those areas where the 1978 water levels were below the base of the overlying aquifer, or where no overlying aquifer occurs, it is possible for water-table conditions to exist in the upper (near-surface) parts of each aquifer. The principal areas where these unconfined conditions commonly occurred are shown in figures 14, 15, 16, and 17. In addition to the mapped areas, a narrow band of unconfined conditions also may occur near the formation outcrops along the western edge of the basin.

Water-level drawdown that occurred in wells during the aquifer tests commonly ranged from a few feet to about 300 feet. If the water level in a well is drawn down below the base of an overlying confining layer during pumping, temporary unconfined conditions may occur near the well. The unconfined conditions would revert to confined conditions when pumping ceased and the static water level rose back above the base of the confining layer. If the static water level in an aquifer is more than 300 feet above the top of the aquifer it is assumed that drawdown during pumping would not exceed 300 feet and thus would not produce unconfined conditions. Those areas in the Denver, Arapahoe, and Laramie-Fox Hills aquifers where less than 300 feet of drawdown could produce unconfined conditions also are shown in figures 15, 16, 17.

Table 4.—Specific yield statistics for water-yielding materials

Aquifer	Specific yield based on laboratory analysis of samples			
	Mean (percent)	Range (percent)	Number of samples	Standard Deviation (percent)
Dawson	18	3.6-34	18	8.4
Denver	14	2-29	11	9.7
Arapahoe	16	3.3-33	25	8.2
Laramie-Fox Hills	20	4.8-38	29	9.1

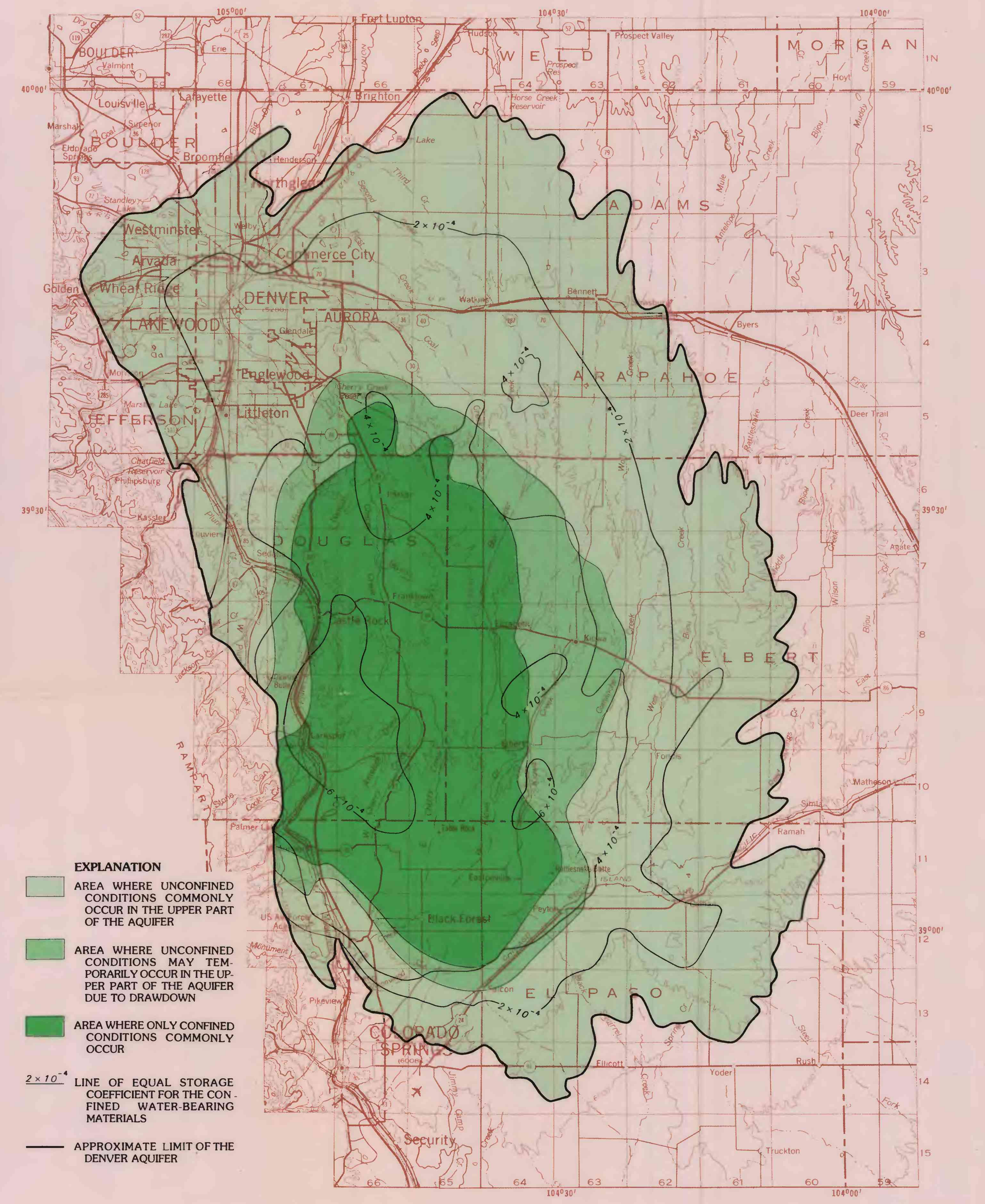

FIGURE 15.—MAP SHOWING ESTIMATED STORAGE COEFFICIENT OF THE DENVER AQUIFER AND 1978 LOCATION OF CONFINED AND UNCONFINED CONDITIONS

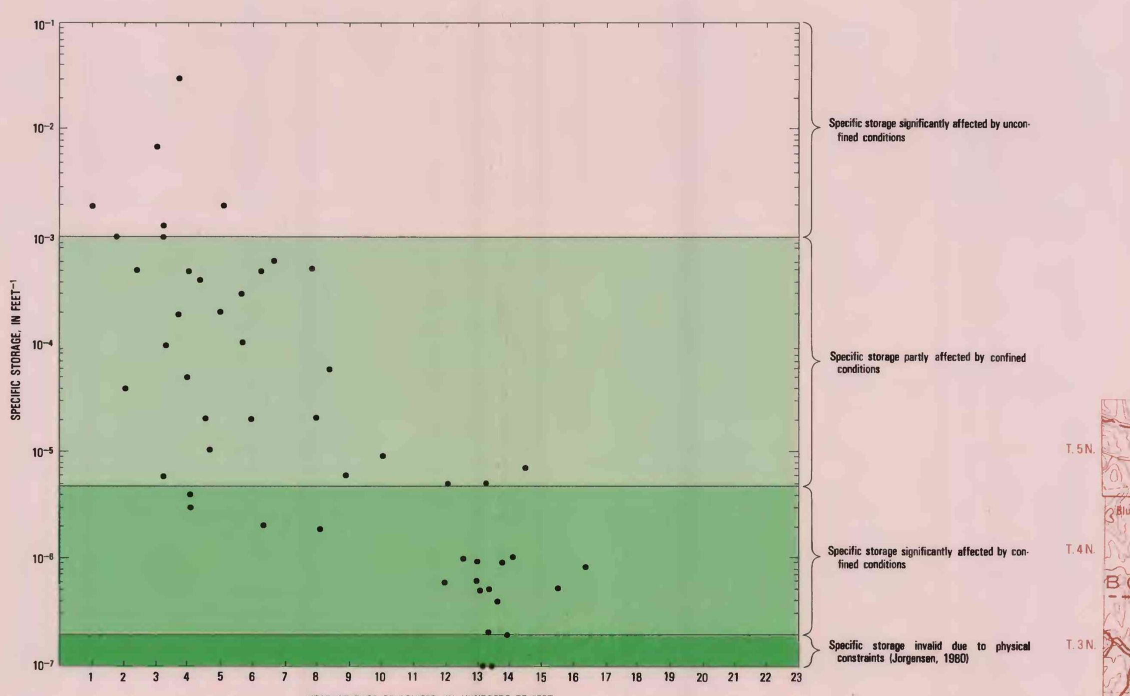

FIGURE 13.—GRAPH SHOWING RELATION OF SPECIFIC STORAGE TO HEAD IN THE AQUIFER

DEFINITION OF TERMS

The complex subject matter of this report has been discussed through use of technical terminology, which may be unfamiliar to some readers. The following definitions of terms are adopted after those presented by Lohman and others (1972) and are provided as an aid to improve the reader's understanding of the terminology.

Aquifer—An aquifer is a geologic unit that contains sufficient saturated permeable material to yield significant quantities of water to wells. Aquifers may be classified as either confined or unconfined.

Confined aquifer—An aquifer is confined when the water it contains is under pressure significantly greater than atmospheric pressure. This pressure causes the water level in a well completed in a confined aquifer to rise above the top of the water-yielding material.

Drawdown—Drawdown is the difference between the static water level and the pumping water level in a well.

Head—Head is the height above a datum of the surface of a column of water that can be supported by the static pressure within the formation.

Hydraulic conductivity—Hydraulic conductivity is a measure of the relative ease with which a porous material can transmit water at the existing Kinematic viscosity under a unit potential gradient per unit volume of water-yield material per unit of time. Hydraulic conductivity is equal to transmissivity divided by saturated thickness.

Porosity—Porosity is defined as the ratio of the void volume of a porous medium to the total volume and is commonly expressed as a percentage. The void volume may be calculated as either the volume of all the pore space or as the volume of only the interconnected pore space. Total porosity, which in this report will be called "porosity," is calculated by considering all the pore space without regard to interconnection. Effective porosity considers only the pore spaces that are interconnected and, therefore, effective in transmitting fluids.

Specific storage—The specific storage of an aquifer is the volume of water the aquifer releases from or takes into storage per unit volume per unit change in head. Specific storage is equal to storage coefficient divided by the saturated thickness of the aquifer.

Specific yield—The specific yield of a porous material is the ratio of the volume of water that will drain by gravity from a saturated rock to the volume of the rock. The measure of the water left in the rock after gravity drainage is termed specific retention. Specific yield is equal to porosity minus specific retention.

Storage coefficient—The storage coefficient of an aquifer is the volume of water the aquifer releases from or takes into storage per unit surface area per unit change in head. Storage coefficient is equal to the specific storage times the saturated thickness of the aquifer.

Transmissivity—Transmissivity is a measure of the relative ease with which a porous material can transmit water under a unit potential gradient per unit surface area. Transmissivity is equal to hydraulic conductivity times saturated thickness.

Unconfined aquifer—An aquifer is unconfined when the water it contains is not under pressure significantly greater than atmospheric pressure. The water level in an unconfined aquifer commonly is called the water table.

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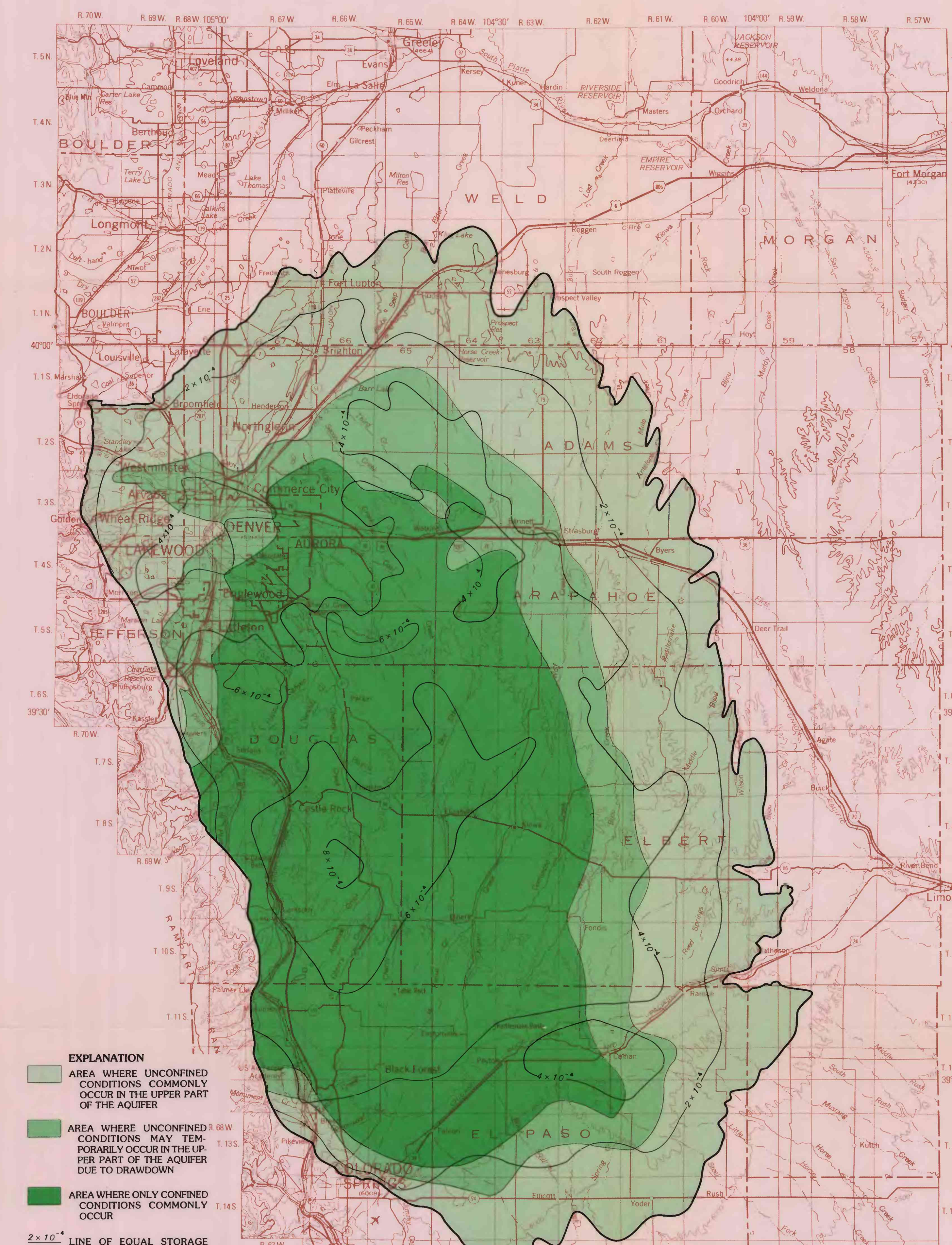

FIGURE 16.—MAP SHOWING ESTIMATED STORAGE COEFFICIENT OF THE ARAPAHOE AQUIFER AND 1978 LOCATION OF CONFINED AND UNCONFINED CONDITIONS

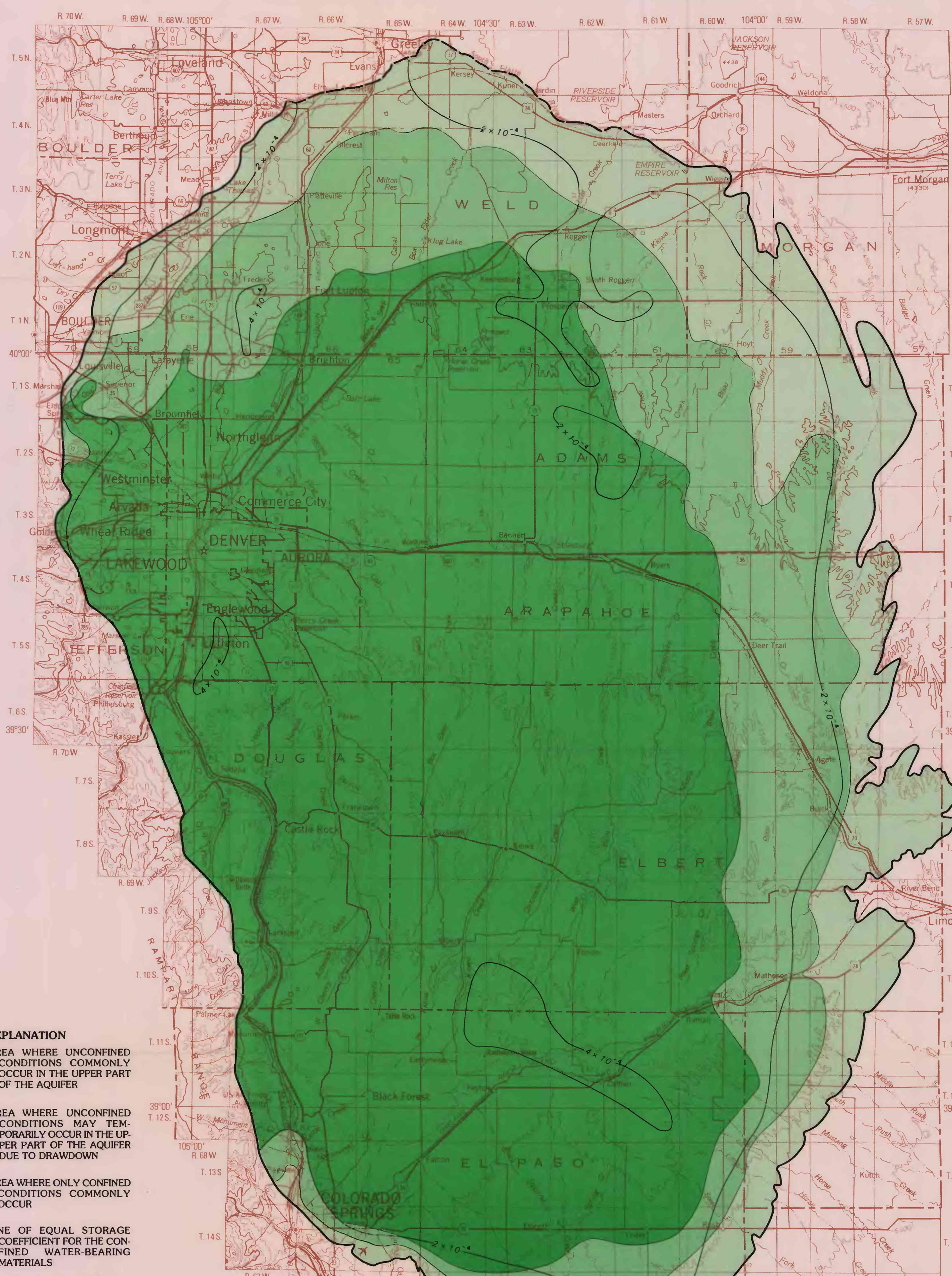

FIGURE 17.—MAP SHOWING ESTIMATED STORAGE COEFFICIENT OF THE LARAMIE-FOX HILLS AQUIFER AND 1978 LOCATION OF CONFINED AND UNCONFINED CONDITIONS

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

SCALE 1:500 000
10 0 10 20 30 40 50 MILES
10 0 10 20 30 40 50 KILOMETERS
CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

HYDRAULIC CHARACTERISTICS OF THE PRINCIPAL BEDROCK AQUIFERS IN THE DENVER BASIN, COLORADO

By
S. G. Robson

1983