Simulated Response of the High Plains Aquifer to Ground-Water Withdrawals in the Upper Republican Natural Resources District, Nebraska

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meter
acre-foot	1,233	cubic meter
acre-foot per mile	766.3	cubic meter per kilometer
acre-foot per year	1,233	cubic meter per year
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
foot per day	0.3048	meter per day
foot per mile	0.1894	meter per kilometer
foot per year	0.3048	meter per day
inch	25.4	millimeter
inch per hour	25.4	millimeter per hour
inch per year	25.4	millimeter per year
mile	1.609	kilometer
million gallons per day	0.04381	cubic meter per second
square mile	2.590	square kilometer

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by using the following equations:

$$°C = 5/9\ (°F-32)$$
$$°F=9/5\ (°C) + 32.$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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By John M. Peckenpaugh[1], Rich A. Kern[2], Jack T. Dugan[1], *and* John M. Kilpatrick[1]

ABSTRACT

A digital finite-difference model of the High Plains aquifer in the Upper Republican Natural Resources District, Nebraska, was deveoped to aid in the assessment of the effects of ground-water withdrawals on water levels in the aquifer and on streamflows in the study area. The model consisted of one layer, with the bottom of the aquifer modeled as a no-flow boundary. The northern and southern boundaries were the South Platte (northern boundary), Republican (southern boundary), and North Fork of the Republican Rivers (southern boundary), which were modeled as constant-head boundaries. The eastern and western boundaries of the model were placed a few miles beyond the eastern and western limits of the Natural Resources District because no natural boundaries were present. These boundaries were represented as general-head boundaries. The model was calibrated under both steady-state and transient (1952–89) conditions. The hydraulic conductivity of the aquifer used in the model ranged from 20 to 155 feet per day, and the specific yield used in the model ranged from 0.09 to 0.22.

The long-term effects of two different pumping scenarios were evaluated for the period 1989–2030. In the first scenario, pumpage was held constant at a rate necessary to supply a crop's consumptive irrigation requirement. Simulated water-level declines resulting from this pumping scenario were greatest in northwestern Chase County. A second scenario held pumpage constant at the rate necessary to apply 13 inches of water on irrigated crops during the irrigation season. Simulated water-level declines resulting from this scenario were larger than those for the first pumping scenario. Simulated water levels declined as much as 90 feet by 2030 in northwestern Chase County.

[1]U.S. Geological Survey.

[2]Nebraska Natural Resources Commission.

INTRODUCTION

Because of concern about declining ground-water levels in the Upper Republican Natural Resources District (NRD) (fig. 1) in the mid-1970's and diminishing inflow into Enders Reservoir, a detailed hydrogeologic study of the area was begun by the U.S. Geological Survey (USGS) in cooperation with the Conservation and Survey Division of the University of Nebraska-Lincoln and the Upper Republican NRD (Lappala, 1978). This study resulted in the development of a digital ground-water-flow model of the Upper Republican NRD north of the Republican and the North Fork of the Republican Rivers, a 5-mile-wide strip between the South Platte and the North Fork of the Republican Rivers in Colorado, and a portion of southern Keith County in Nebraska. This model was used to simulate ground-water flow for 1952–75.

Since the study was completed, the model has been updated twice by the Nebraska Natural Resources Commission (NRC) to incorporate more recent water-use and recharge data. The Upper Republican NRD continued to use the model to predict

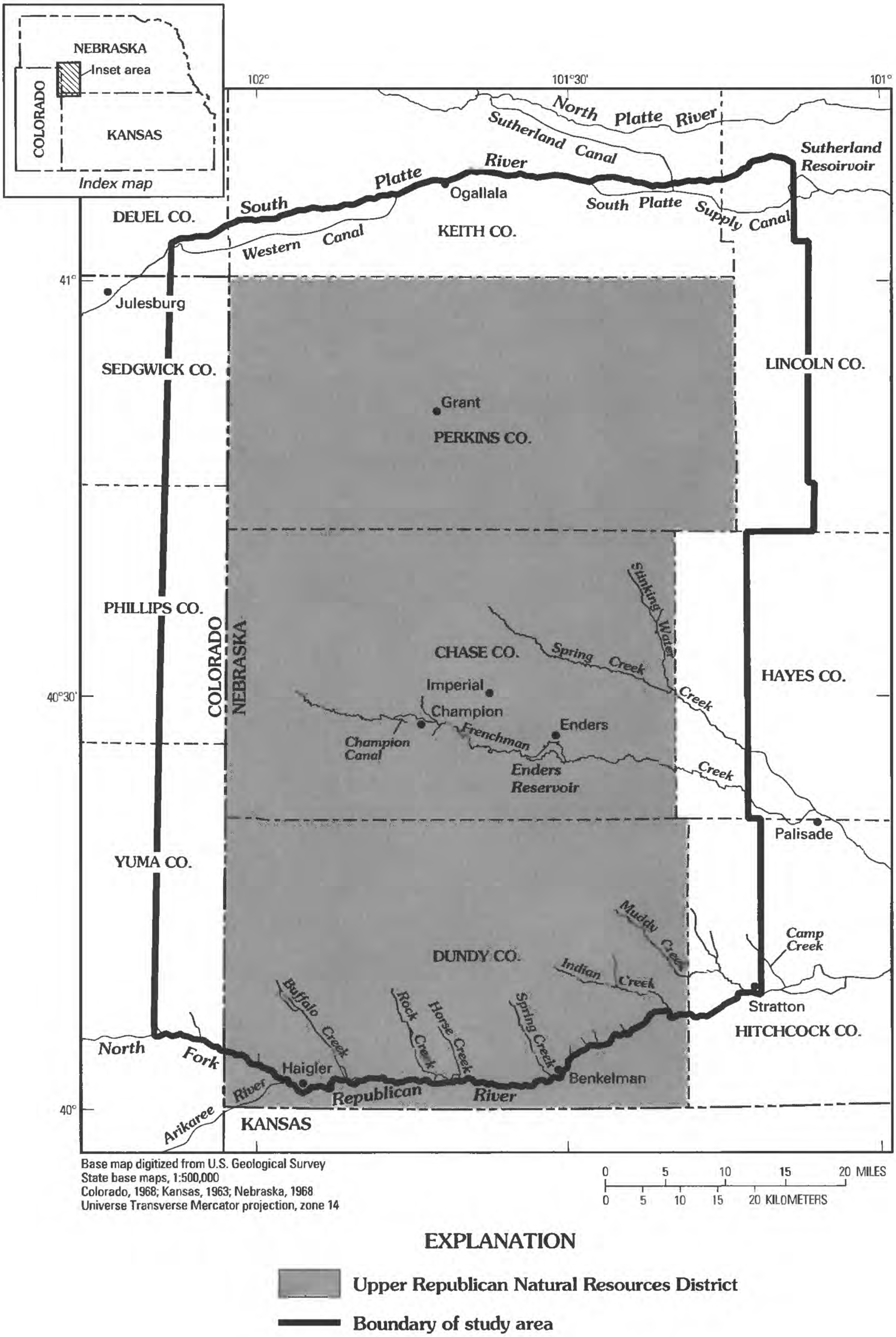


Figure 1. Location of study area and Upper Republican Natural Resources District.

future ground-water-level changes. In recent years, water levels predicted by the model have differed in some areas from measured water levels. The most significant differences between predicted and measured water levels occurred in central Perkins and northwest Chase Counties. These differences may be because irrigation with center-pivot systems has expanded in these areas more rapidly than was foreseen when the model was developed in the mid-1970's. To provide more accurate simulation of ground-water flow in these areas in the Upper Republican NRD, the USGS, as part of continuing cooperative studies with the Upper Republican NRD and the Nebraska NRC, updated this model using recently developed modeling software and incorporating data collected both before and after Lappala's (1978) study. The boundaries of this study are shown in figure 1.

Purpose and Scope

This report describes the hydrogeologic system in the study area and the development of a ground-water-flow model to quantitatively evaluate this system. Specifically, this report describes the hydrogeologic characteristics of the study area. This report also describes data manipulation, discretization, and estimation techniques used to compile the model arrays. Finally, this report describes the calibration of the model and its use in simulating water levels in the High Plains aquifer and streamflows resulting from two different pumping scenarios.

Previous Studies

The hydrogeology of the Republican River Valley was first described by Condra (1907) and was later described by Waite, Reed, and Jones (1946), Waite and others (1948), and Bradley and Johnson (1957). The hydrogeology of the Frenchman Creek Valley was described by Waite and others (1948) and Bradley and Johnson (1957). The hydrogeologic conditions in the South Platte River Valley were discussed by Bjorklund and Brown (1957). These studies included information on water levels, aquifer boundaries, and potential well yields.

Additional hydrogeologic studies that were not restricted to river valleys were conducted by Wenzel and Waite (1941) for Keith County, by Johnson (1960) for the northeast part of the study area, and by Cardwell and Jenkins (1963) for the Frenchman Creek Basin within the study area. These investigations presented information on aquifer boundaries, saturated thickness, water levels, base of the aquifer, and water use. Redell (1967) discussed the distribution of ground-water recharge and discharge for the Colorado part of the study area.

The use of ground water for irrigation within the study area has been described by Cardwell (1953), Cardwell and Jenkins (1963), Boettcher (1966), Luckey (1973), Leonard and Huntoon (1974), Luckey and Hofstra (1974), the U.S. Bureau of Reclamation (1974), Lappala (1976, 1978), and Goeke and others (1992). Cardwell and Jenkins (1963) estimated stream depletion through the year 2000 caused by pumpage of ground water in and adjacent to the valleys of Frenchman, Spring, and Stinking Water Creeks. Their estimates were reasonably accurate until extensive use of center-pivot irrigation systems began in the early 1970's.

Ground-water modeling studies have been used to provide information on the hydrogeologic system and on possible future effects of ground-water irrigation on water levels and streamflows. Investigations on this topic have been performed in parts of the study area or adjacent areas by Luckey (1973), Luckey and Hofstra (1974), Lappala (1978), Lappala and others (1979), Pettijohn and Chen (1983a, b), Luckey and others (1986, 1988), and Goeke and others (1992).

Acknowledgments

The authors appreciate the support, assistance, and cooperation during this study that was provided by the personnel, manager, and Board of Directors of the Upper Republican Natural Resources District and the staff of the Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

DESCRIPTION OF THE STUDY AREA

Location and Physiography

The study area encompasses approximately 3,750 square miles and includes parts or all of 11 counties in Nebraska and Colorado (fig. 1). These counties are Chase, Deuel, Dundy, Hayes, Hitchcock, Keith, Lincoln, and Perkins Counties in Nebraska, and

Phillips, Sedgwick, and Yuma Counties in Colorado. The study area lies in the High Plains Section of the Great Plains Province (Fenneman, 1931). Land-surface altitudes range from 2,800 feet in Hitchcock County, Nebraska, where the Republican River crosses the eastern study-area boundary, to 3,750 feet in northeastern Sedgwick County, Colorado. The land surface generally slopes to the east at about 10 feet per mile. The physiographic features of the study area can be divided into five main categories: loess plains and tablelands, rolling uplands, sand hills and interdune valleys, dissected plains and uplands, and bottom lands along major water courses. A detailed description of each of these areas can be found in Lappala (1978, p. 4–5). Most of the study area can be categorized as rolling uplands or sand hills and interdune valleys.

Climate

The climate of the Upper Republican NRD is transitional between continental subhumid and semiarid, with semiarid conditions predominant in most years. Winters are normally cold, and summers are usually hot. Average annual precipitation (1951–89) ranges from about 17 inches in the northwestern and southwestern parts of the study area to nearly 20 inches in the southeastern part (fig. 2). Annual amounts, however, are quite variable. During 1951–89, Imperial, in Chase County, with an annual average of 19.02 inches, had 5 years of greater than 25 inches and 6 years of less than 15 inches of annual precipitation (National Oceanic and Atmospheric Administration, 1951–89).

About 75 percent of the annual precipitation occurs during the warm season (April–September). This peak precipitation season coincides with large rates of evapotranspiration, which generally results in no seasonal surplus of soil water. Warm-season precipitation, which often occurs as small, scattered thunderstorms, generally is distributed irregularly within the study area. The cool season (October–March) is often very dry.

Annual potential evapotranspiration (PET), which is affected by such factors as solar radiation, air and soil temperatures, humidity, and wind, ranges from about 50 inches in the northeastern part of the study area to about 66 inches in the southwestern part and averages about 53 inches, as computed by the Jensen-Haise method (Jensen and others, 1970). A combination of a high percentage of possible sunshine, high temperatures, low humidity, and high average wind speed, particularly during the warm season, contributes to these large PET values. Warm-season PET (April–September) averages about 42 inches, which is about 80 percent of the annual average for the study area.

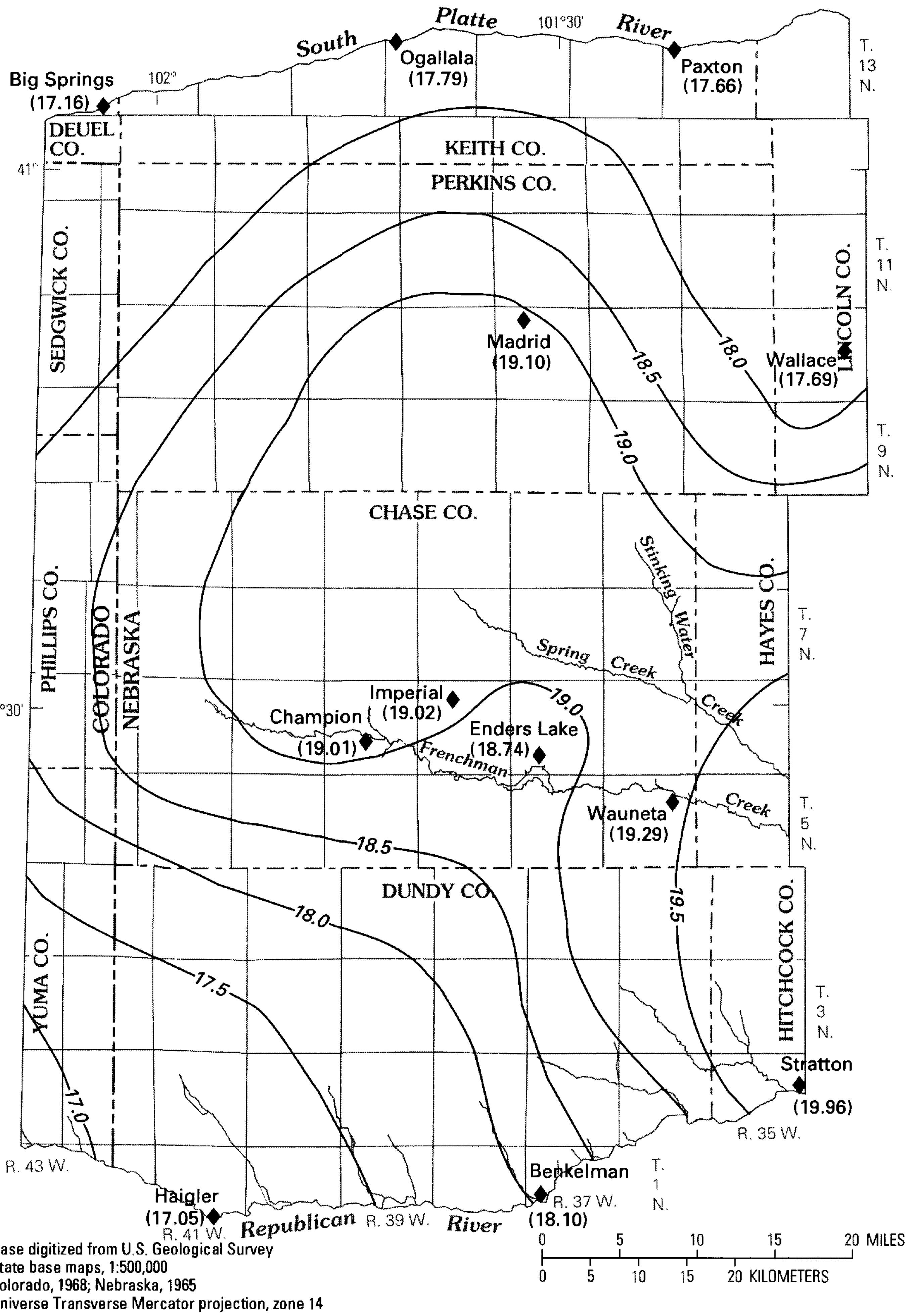
Soils

The soils in the study area are quite variable because of differences in parent materials, but they can be grouped into eight mappable units (fig. 3 and table 1). Each mappable soil unit consists of a soil series grouped principally by hydrologic characteristics including permeability, available water capacity, and slope. The mappable soil units that include soils of the bottom lands and terraces tend to include diverse soils that exhibit great differences among their hydrologic characteristics. The complex distribution and small area often covered by these soils necessitate the grouping of somewhat different soils for mapping considerations.

Classified by texture, permeability, and available water capacity (Dugan, 1984), upland soils can be placed in three groups reflecting the parent-material differences—silt loam to silty clay loam soils (available water capacity, 0.18 to 0.21 inch per inch), sandy soils (available water capacity, 0.05 to 0.08 inch per inch), and sandy loam soils transitional between the silty and sandy soils (available water capacity, 0.11 to 0.17 inch per inch). The silty upland soils are classified further into three slope groups to reflect surface-runoff potential and irrigability—nearly level to undulating (0 to 7 percent), undulating to rolling (7 to 15 percent), and rolling to very steep (15 to 45 percent). Very steep silty soils are severely dissected or eroded.

Bottom land and terrace soils compose only about 5 percent of the soils in the study area. These soils have been classified into two groups—the sandy loam to silt loam soils (available water capacity, 0.13 to 0.19 inch per inch) and the sandy to sandy loam soils (available water capacity, 0.04 to 0.13 inch per inch). The large ranges in available water capacity in these soils reflect the large range of soil-texture types included in these mappable soil units.

The irrigation potential of the soils in the study area is quite variable, ranging from 10 to 100 percent (table 1). The irrigation potential is the percentage of a

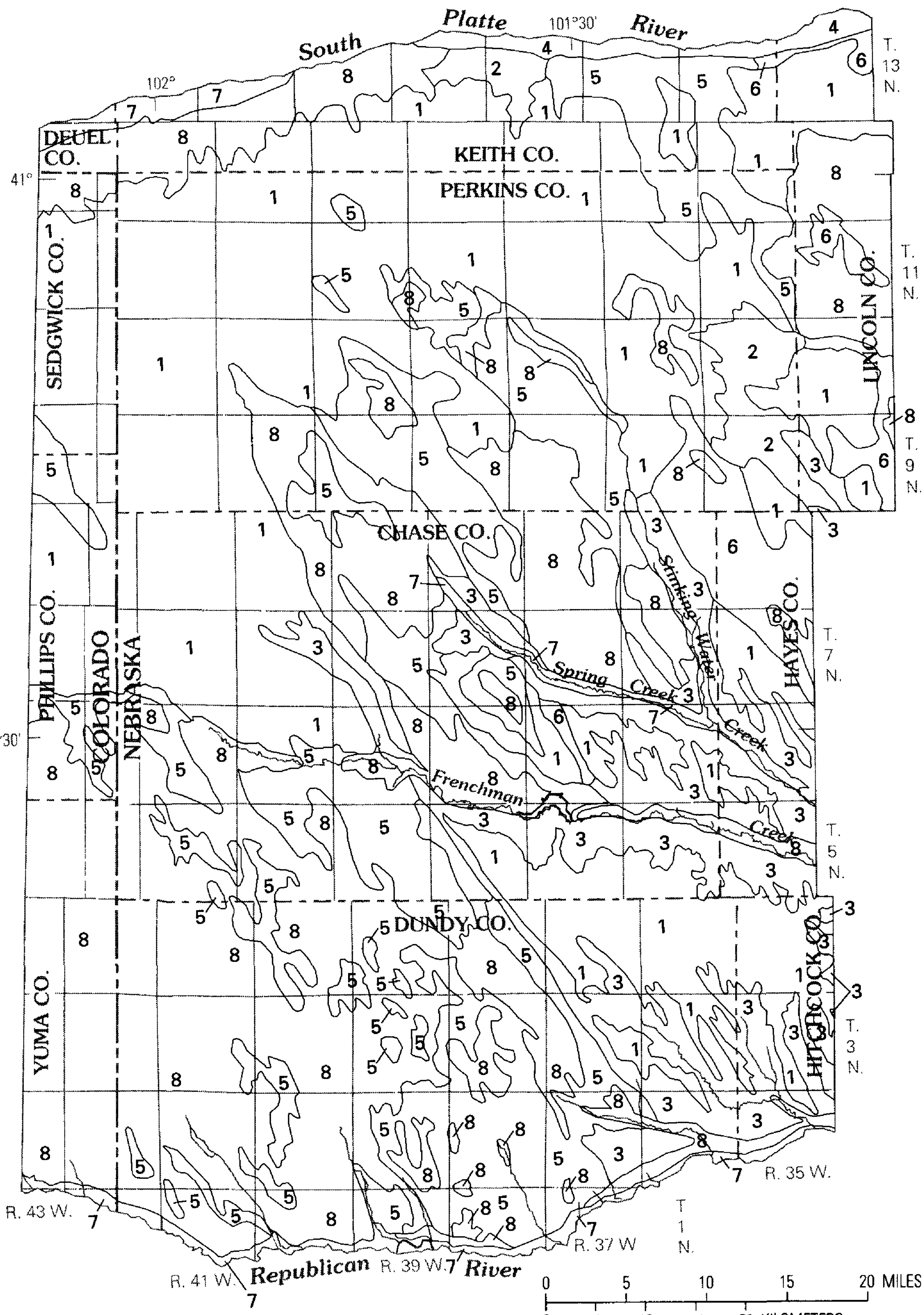


EXPLANATION

——*17.0*—— **Line of equal average precipitation, 1951–89—** Interval 0.5 inch

Haigler (17.05) ♦ **Weather station and name—**Number in parentheses is average annual precipitation, 1951–89, in inches

Figure 2. Average annual precipitation, 1951–89, and location of selected weather stations (data from National Oceanic and Atmospheric Administration, 1951–89).



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

Mappable soil units—See table 1 for a description of each unit

1 2 3 4

5 6 7 8

Figure 3. Distribution of mappable soil units (modified from Dugan, 1984).

Table 1. Mappable soil units in the study area and their hydrologic characteristics

Mappable soil unit (fig. 3)	Texture	Range of permeability (inches per hour)	Average available water capacity (inch per inch)	Range of slope (percent)	Topographic position	Soil series represented	Irrigation potential[1] (percent)
1	Silt loam to silty clay loam	1.0 to 1.5	0.18	0 to 7	Uplands	Rosebud, Alliance, Kuma, Goshen, Keith	100
2	Silt loam to silty clay loam	1.0 to 1.5	.21	7 to 15	Uplands	Ulysses, Keith, Colby	85
3	Silt loam to silty clay loam	1.0 to 1.5	.20	15 to 45	Uplands	Colby, Canyon, Ulysses	20
4	Sandy loam to silt loam	1.5 to 3.0	.17	0 to 7	Bottom lands and terraces	Bridget, McCook, Duroc, Bankard, Las, Glenburg	100
5	Sandy loam to silt loam	2.5 to 5.0	.15	0 to 7	Uplands	Jayem, Haxtun, Rosebud, Keith	100
6	Fine sand to sandy loam	5.0 to 7.0	.12	0 to 15	Uplands	Jayem, Sarben, Valent, Hersch, Valentine	80
7	Fine sand to sandy loam	7.0 to 12.0	.11	0 to 3	Bottom lands and terraces	Gothenburg, Platte, Las, Las Animas	10
8	Sand to dune sand	12.0 to 20.0	.07	0 to 45	Uplands	Valent, Valentine, Tassel	30

[1]David Lewis, Department of Agronomy, University of Nebraska-Lincoln, written commun., 1988.

soil association that is potentially capable of sustained irrigation with current irrigation technology. This potential irrigability reflects slope and soil-depth characteristics but does not necessarily reflect available water or best-management practices (David Lewis, Department of Agronomy, University of Nebraska-Lincoln, written commun., 1988).

Land Use

Soils and topography largely determine land use in the study area. Soils derived from sand dunes or with large topographic slopes, such as those included in mappable soil unit 8 (table 1), often are left uncultivated and in native vegetation. Soils with less sloping topography and less sandy textures, including mappable soil units 1, 2, 4, 5, and 6 (table 1), generally are well suited for cultivation and irrigation.

About 40 percent of the area is currently grassland (all pasture and rangeland not harvested for hay). Cultivated land, including unharvested crop and fallow, accounts for slightly more than 50 percent of the area. Less than 5 percent of the area is used for nonagricultural purposes, including transportation, communication, farmstead, commercial, and urban functions. Natural woodlands occupy less than 1 percent of the study area (U.S. Department of Commerce, Bureau of the Census, 1989). Natural woodlands generally occur only along permanent streams and consist largely of phreatophytes, such as willows and cottonwoods, that thrive under shallow water-table conditions (Weaver and Albertson, 1956; Kaul and Rolfsmeier, 1993).

Vegetation or land-use changes through time have occurred largely on cultivated land. Although the percentage of land area classified as cultivated has remained generally constant through time, small, short-term fluctuations have occurred as some rangeland has been cultivated temporarily but later allowed to revert to rangeland depending on the agricultural economy. Large changes in cropping patterns have occurred on cultivated land related to irrigation development and changes in the agricultural economy (table 2).

Table 2. Selected crops harvested in Chase, Dundy, and Perkins Counties, Nebraska, for selected years
[data from Nebraska Department of Agriculture (1935–89); values are given in thousands of acres]

Year	Wheat			Corn			Grain sorghum			All hay		
	Chase	Dundy	Perkins	Chase	Dundy	Perkins	Chase	Dundy	Perkins	Chase	Dundy	Perkins
1950	93.3	43.5	161.5	50.1	68.8	42.3	9.5	10.5	9.8	24.5	24.0	11.4
1955	74.4	33.2	153.2	27.2	36.6	33.9	23.8	29.3	31.7	24.7	25.8	20.1
1960	64.6	33.2	138.8	44.6	66.5	19.2	24.8	25.9	48.6	17.3	19.5	12.3
1965	74.0	33.5	147.2	26.1	25.2	4.3	27.1	37.8	18.9	15.4	18.8	19.7
1970	44.2	25.7	145.0	52.5	47.0	15.0	17.0	21.4	8.3	15.3	17.5	15.0
1975	63.2	44.0	169.0	84.8	78.1	48.7	7.1	15.6	3.6	13.3	17.1	14.2
1980	59.5	43.9	162.8	119.4	88.8	86.2	4.4	10.9	3.4	13.0	18.0	8.0
1985	60.7	36.9	155.5	112.4	86.4	114.3	9.0	17.5	7.4	16.0	20.0	12.0
1989	45.9	26.3	133.0	126.3	85.7	102.8	4.1	13.6	2.9	10.5	22.0	12.5

Since 1950, total acreage of crops harvested has not changed substantially in the study area, but crop types have shown considerable variability. Wheat acreages have decreased gradually, while corn acreages have increased substantially. Grain sorghum acreages also have decreased gradually through time. These changes are related principally to the widespread development of ground-water irrigation between the mid-1960's and the late 1970's and, to a lesser extent, to changes in government agricultural programs.

DESCRIPTION OF THE HYDROGEOLOGIC SYSTEM

The study area is characterized by generally plentiful ground-water resources and generally less plentiful surface-water resources. Increased use of ground-water supplies for irrigation since development began has affected the availability of both ground- and surface-water supplies. The following sections briefly describe the hydrogeologic system and the effects of ground-water development on the availability of water.

Surface-Water System

The surface-water system in the study area consists of several major components including streams, canals, and reservoirs. These components interact with each other and the aquifer system in a complex manner. The schematic diagram shown in figure 4 delineates the relations among the different streams, canals, and reservoirs in the study area and also lists average annual streamflow at selected gaging stations.

Streams

The South Platte and Republican Rivers are the major stream systems in the study area. The South Platte River, which forms the northern boundary of the area, has no perennial tributaries in the study area. There are, however, canal diversions, a canal return, and intermittent draws that are connected to the South Platte River. The Republican River and the North Fork of the Republican River, which form the southern boundary of the study area, have several tributaries within the area: Stinking Water, Frenchman, and Spring Creeks in Chase County and Buffalo, Rock, Horse, Spring, Indian, and Muddy Creeks in Dundy County. The Republican River and North Fork of the Republican River have no canal diversions or canal returns within the study area.

Canals

Several canals in the study area divert water from streams for use as irrigation or cooling water (figs. 1 and 4). The Western and Champion Canals provide water for irrigation in the study area. The Champion Canal is not shown in figure 4 because of its small length and small average annual diversion. The Western Canal began operation in 1918 and has diverted an average of 26,900 acre-feet per year since 1952 from the South Platte River. The smaller Champion Canal began operation in 1963 and has diverted about 2,400 acre-feet per year from Frenchman Creek (Nebraska Department of Water Resources, 1935–89).

The South Platte Supply and Sutherland Canals divert water in the study area for use as cooling water. The South Platte Supply Canal diverts water from the South Platte River in Keith County and flows along the south side of the South Platte River until it joins the Sutherland Canal (figs. 1 and 4). The Sutherland Canal carries water diverted from the North Platte River (16 miles to the northwest) and has diverted approximately 638,000 acre-feet of water per year, whereas the South Platte Supply Canal has diverted 216,000 acre-feet per year since 1952 (Nebraska Department of Water Resources, 1935–89). The diversions from these two canals, both of which began operation in 1935, are stored at the Sutherland Reservoir, immediately east of the study area (fig. 1). Water stored in the Sutherland Reservoir is used to provide cooling water for condensers at a steam powerplant adjacent to the reservoir.

A substantial amount of the water diverted into canals in the study area is lost as seepage into the underlying High Plains aquifer. For this study, the seepage losses from the Western Canal were assumed to be 40 percent of the annual diversion, based on losses from other canals in the vicinity. Estimated annual seepage losses from 1952–89 from the Sutherland Canal are listed in table 3. The average annual seepage loss per mile during this time period was about 1,254 acre-feet. The seepage losses from the South Platte Supply Canal were estimated to be about 35 percent of the Sutherland Canal seepage losses or about 500 acre-feet per mile of the canal's

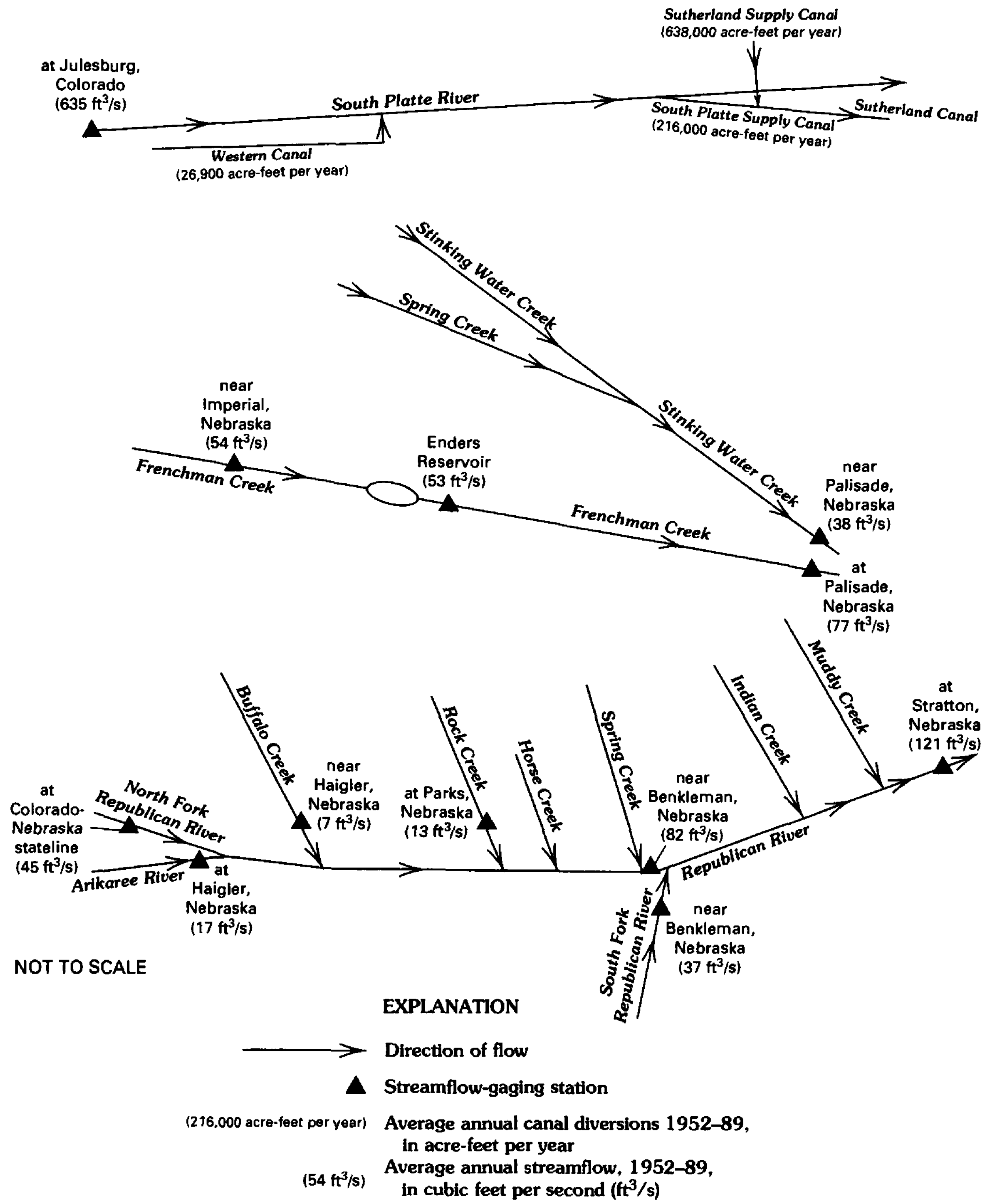


Figure 4. Schematic diagram of the surface-water system in the study area.

length. A detailed description of the methods used to estimate seepage in these and other similar canals can be found in Goeke and others (1992, p. 20).

Lakes and Reservoirs

Enders Reservoir is the only surface-water impoundment in the study area that has a storage capacity greater than 1,000 acre-feet. No permanent natural lakes exist in the study area. Numerous small impoundments exist, but their capacity is unknown; however, surface-water storage rights have been granted for 50,150 acre-feet by the Nebraska Department of Water Resources (Lappala, 1978).

Enders Reservoir has an average surface area of 1,242 acres. Enders Reservoir, which began filling in October 1950, is used for storing irrigation water derived from Frenchman Creek. Water is released from Enders Reservoir into Frenchman Creek during the irrigation season and flows out of the study area to a

Table 3. Estimated seepage from the Sutherland Canal, Keith County, Nebraska, 1952–89

Year	Total annual seepage (acre-feet)	Seepage per mile[1] (acre-feet per mile)
1952	16,864	1,382
1953	22,221	1,821
1954	13,460	1,103
1955	19,361	1,587
1956	17,064	1,399
1957	12,670	1,039
1958	12,194	1,000
1959	11,225	920
1960	11,711	960
1961	11,625	953
1962	9,953	816
1963	15,196	1,246
1964	14,517	1,190
1965	8,622	707
1966	11,952	980
1967	16,241	1,331
1968	14,416	1,182
1969	11,384	933
1970	15,676	1,285
1971	16,603	1,361
1972	16,681	1,367
1973	14,631	1,199
1974	15,775	1,293
1975	9,557	783
1976	14,652	1,201
1977	15,299	1,254
1978	14,579	1,195
1979	16,287	1,335
1980	19,105	1,566
1981	18,288	1,499
1982	13,554	1,111
1983	15,250	1,250
1984	19,740	1,618
1985	16,531	1,355
1986	19,910	1,632
1987	20,899	1,713
1988	20,972	1,719
1989	16,812	1,378
Average annual seepage	15,302	1,254

[1]The Sutherland Canal within the study area is 12.2 miles in length.

diversion dam. Enders Reservoir provides no irrigation water for lands within the study area.

Seepage losses from Enders Reservoir were estimated using monthly inflow-outflow data from 1951 through 1988, collected by the U.S. Bureau of Reclamation, and the following equation, which was modified from Lappala (1978):

$$Q_s = Q_I - Q_E - (E - P) A \pm (\Delta s) / (\Delta t) , \qquad (1)$$

where

Q_S = reservoir seepage $[L^3T^{-1}]$ (positive values represent ground-water recharge, and negative values represent ground-water discharge to surface water);

Q_I = average monthly reservoir inflow, which includes gaged and estimated ungaged flows $[L^3T^{-1}]$;

Q_E = average monthly reservoir release as measured at the streamflow-gaging station near Enders $[L^3T^{-1}]$;

E = monthly lake evaporation at Enders $[LT^{-1}]$;

P = monthly precipitation at Enders $[LT^{-1}]$;

A = end-of-month reservoir surface area $[L^2]$;

Δs = monthly change in storage $[L^3]$; and

Δt = time increment of study (1 month) $[T]$.

The estimated seepage fluxes into and out of Enders Reservoir are listed in table 4 for irrigation and nonirrigation periods from 1952 through 1988. These data indicate that the reservoir was predominately losing water to the High Plains aquifer prior to 1959. However, since 1959, the aquifer has been predominantly discharging water to the reservoir.

Ground-Water System

Geology

The youngest geologic unit underlying the entire study area is the Pierre Shale of Cretaceous age (table 5). The Pierre Shale consists mostly of blue, ochre, or black-colored shale and clay. The Pierre Shale is the uppermost bedrock unit in the study area, except in parts of Chase, Perkins, and Keith Counties, where it is overlain by the White River Group (fig. 5).

The White River Group consists of two formations, the lower of which is the Chadron Formation and the upper of which is the Brule Formation. The Chadron Formation generally consists of olive-green to brick-red silty to sandy clay and claystone (Cardwell and Jenkins, 1963), whereas the Brule Formation, which conformably overlies the Chadron Formation, contains buff to olive-green clayey silt and siltstone. Where present, these units are overlain by the Ogallala Formation of Tertiary age. The Ogallala Formation directly overlies the Pierre Shale where the White River Group is absent.

The Ogallala Formation underlies all but the extreme southern and northwestern parts of the study area (fig. 6). It ranges in thickness from a feathered edge to more than 400 feet (Cardwell and Jenkins, 1963, p. 42). The Ogallala Formation consists of beds of silt, sand, gravel, caliche, and clay, with considerable variability in lithology within short vertical or horizontal distances. These variations are consistent with the fluvial environment in which the Ogallala was deposited. This environment was characterized by a series of braided streams carrying sediment eastward. Some of the sand and gravel deposits are weakly cemented by calcium carbonate into rocks ranging from friable sandstone to relatively hard, ledge-forming mortar beds (Cardwell and Jenkins, 1963, p. 42). Except in a few areas, most notably western Perkins and Chase Counties, the Ogallala Formation is overlain by unconsolidated Quaternary deposits.

The unconsolidated Quaternary deposits, which comprise the land surface of most of the study area, consist of sand, gravel, silt, and clay of fluvial origin and sand, silt, and clay of eolian origin. These deposits range in thickness from a feathered edge to more than 100 feet. These deposits occur as alluvium and terraces in stream valleys and dune sand and loess deposits in upland areas and on high terraces.

High Plains Aquifer

The uppermost aquifer in the study area is the High Plains aquifer (Pettijohn and Chen, 1983a). It consists of the saturated parts of the Quaternary deposits and the underlying Ogallala Formation. This aquifer is unconfined, and its upper surface is the water table. In the spring of 1989, water-table altitudes in the study area ranged from more than 3,600 feet in Yuma County, Colorado, to less than 2,800 feet in Hitchcock County, Nebraska (fig. 7). In general, the direction of regional ground-water flow in

Table 4. Estimated seepage gains and losses for Enders Reservoir during irrigation and nonirrigation periods, 1952–88

Year	Fluxes[1] (scre-feet) Irrigation[2]	Nonirrigation[2]
1952	500	3,400
1953	-400	900
1954	400	4,600
1955	-100	2,000
1956	-700	1,000
1957	100	1,700
1958	-600	800
1959	-1,400	-1,800
1960	-1,600	-200
1961	-3,200	-3,100
1962	-2,500	-4,300
1963	-3,100	-1,500
1964	-2,500	-1,900
1965	-3,800	-500
1966	-5,000	-1,700
1967	-2,500	-1,200
1968	-5,100	-2,600
1969	-3,200	-3,200
1970	-3,200	-2,300
1971	-3,700	-1,500
1972	-700	-2,500
1973	-3,400	-2,400
1974	-2,300	-800
1975	-1,700	-1,500
1976	-2,600	-1,500
1977	-2,500	-1,900
1978	-800	-2,700
1979	-1,700	-3,400
1980	-1,600	-3,200
1981	-1,000	-1,400
1982	-1,600	8,300
1983	-900	-1,500
1984	-1,300	-2,400
1985	-900	-1,200
1986	-2,200	-2,500
1987	-3,500	-2,600
1988	-800	-1,900

[1]Negative (-) fluxes are ground-water seepage losses to surface water; positive fluxes are ground-water gains from surface water.

[2]Irrigation period is June through August, and nonirrigation period is January through May and September through December.

Table 5. Generalized stratigraphic column for the study area
[modified from Cardwell and Jenkins, 1963]

Erathem	System	Series	Stratigraphic unit	
Cenozoic	Quaternary	Holocene	Alluvium and terrace deposits	
		Holocene and Pleistocene	Dune sand	
	Tertiary	Pliocene	Ogallala Formation	
		Oligocene	White River Group	Brule Formation
				Chadron Formation
Mesozoic	Cretaceous	Upper Cretaceous	Pierre Shale	

the study area is west to east except in the vicinity of the Republican River, a prominent discharge area. Average ground-water-flow velocities range from less than 50 to more than 200 feet per year.

The White River Group and the Pierre Shale are relatively impermeable in the study area (Cardwell and Jenkins, 1963, p. 34, 36, 40) and form the base of the High Plains aquifer (fig. 8). Figure 8 was constructed on the basis of analysis of driller's or geologist's logs from 149 test holes and 1,174 irrigation wells. Several drainage channels are distinguishable on this erosional surface, which slopes generally to the east at about 20 feet per mile (Lappala, 1978).

The volume of ground water in storage in the High Plains aquifer is a function of the saturated thickness of the aquifer, the area that the aquifer covers, and the porosity of the aquifer. The porosity of the aquifer is estimated to range from 0.30 to 0.40 (Lappala, 1978). Therefore, the volume of water in storage is estimated to be 189 million acre-feet in 1952 and 168 million acre-feet in 1989 using the same method as Lappala (1978). All of this water cannot be withdrawn by dewatering or pumping because some water molecules cling to rock or soil particles due to the surface tension of water. On the basis of a typical specific-yield value for the aquifer of 0.18, the amount of recoverable or available water in the High Plains aquifer was estimated to be 97 and 86 million acre-feet in 1952 and 1989, respectively.

Aquifer Development and Associated Effects

The first irrigation well in the area was completed in 1913 in Champion, Nebraska, and only a few additional wells were dug in the following 20 years (Cardwell and Jenkins, 1963, p. 88). Between the mid-1930's and mid-1950's, more than 90 additional irrigation wells were constructed (fig. 9). The earliest measured water levels date from this period and were used to estimate the spring 1952 water table shown in figure 10. This water-table map was developed by Lappala (1978) from water levels measured from 1937 to 1952. A detailed discussion describing the sources of the water levels used to construct figure 10 is presented in Lappala (1978). During the 1960's and 1970's, the number of irrigation wells greatly increased so that by 1975 there were more than 1,700 registered irrigation wells in the study area (fig. 11). Almost one-half of these wells were in Chase County. A rapid increase in drilling during the late 1970's brought the number of registered irrigation wells to approximately 2,800 in 1980. Drilling activity leveled off in the 1980's, with only about 400 additional wells drilled by 1989 (fig. 12). Water use for irrigation from the High Plains aquifer in Chase, Perkins, and Dundy Counties was estimated to be about 520,000 acre-feet per year in 1985 (Steele, 1988).

Increased utilization of ground water from the High Plains aquifer has had a substantial effect on water levels in the aquifer and on rates of ground-water seepage from the aquifer into area streams.

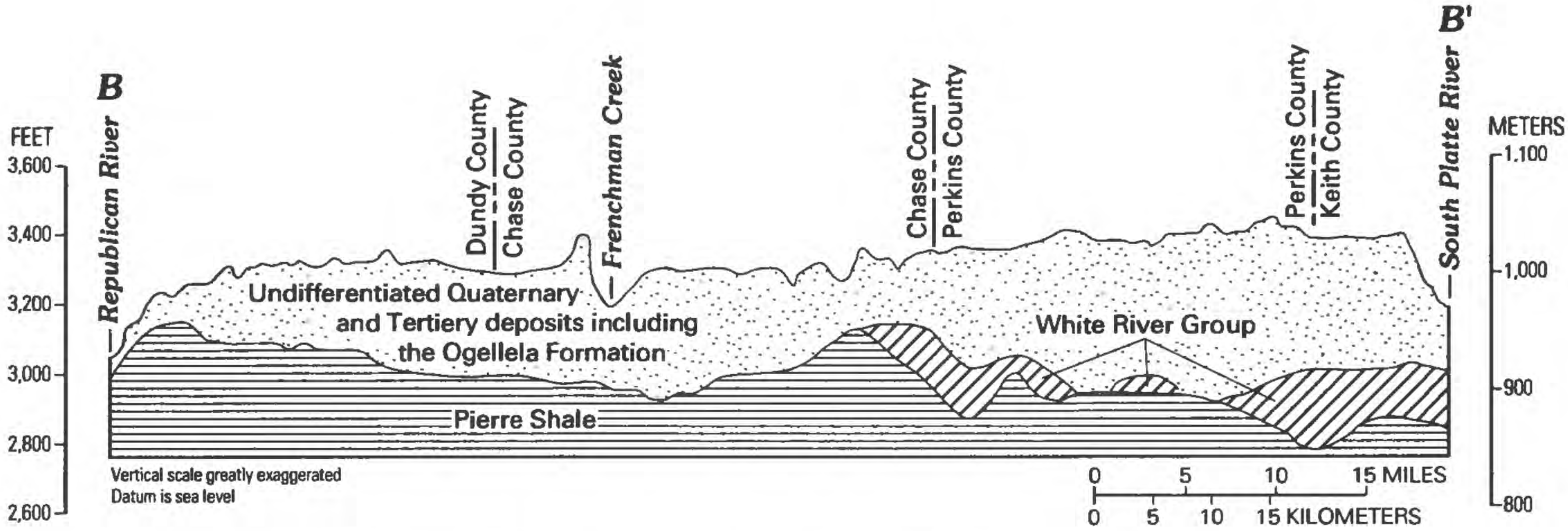


Figure 5. Geologic section *B–B'*, modified from Lappala (1978). Trace of section shown in figure 6.

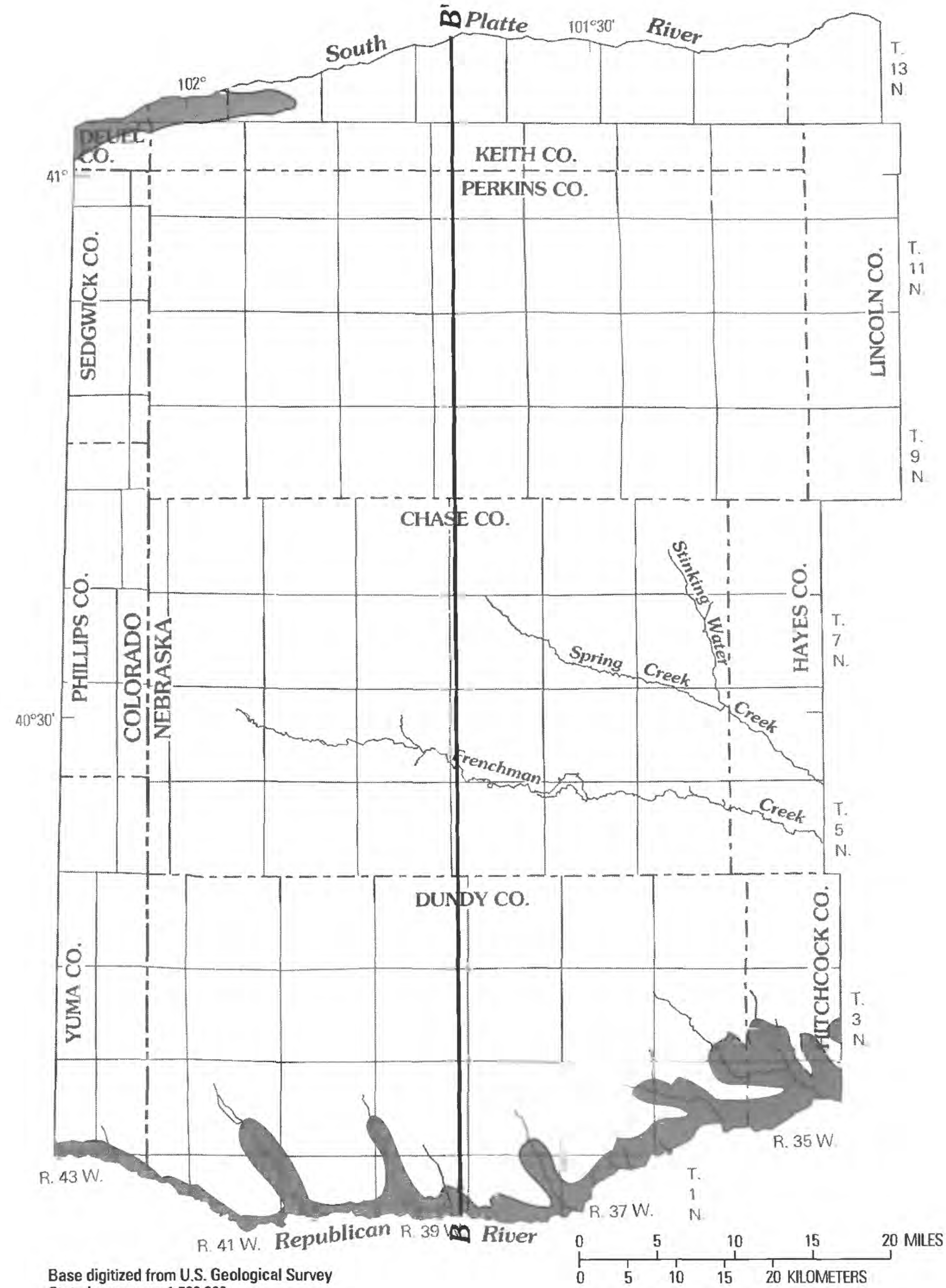
These effects are readily apparent by comparing hydrologic conditions before substantial use of ground water for irrigation (1952) with those in 1989. A comparison of the water-level surface in the High Plains aquifer in 1952 (fig. 10) with the same surface in 1989 (fig. 7) reveals extensive water-level declines in Dundy and Chase Counties. This is most apparent in figure 13, which illustrates the difference in water levels from these two time periods. As expected, the areas with the greatest declines in water levels were also areas with the greatest irrigation-well densities (figs. 9, 11–12). Rises in water levels in northeastern Perkins and southeastern Keith Counties are likely the result of seepage from canals in the vicinity.

Increased utilization of the ground-water resources also has had a noticeable effect on the surface-water system in the study area. The perennial reaches of the streams in the study area were delineated based on seepage measurements made in the fall of 1952 (Lappala, 1978), the spring and fall of 1975 (Lappala, 1978), the fall of 1983 (U.S. Geological Survey, 1976–90), and the spring of 1989 (U.S. Geological Survey, 1976–90). Decreased seepage to streams from the High Plains aquifer shortened the perennial reaches of many of the streams in the study area by between 2 and 3 miles from 1975 to 1989 (fig. 14).

Another indication that seepage of ground water from the aquifer into streams decreased is the noticeable decline in base flow (table 6). The most substantial decreases appear to have occurred between 1975 and 1989. Base-flow values were measured during seepage runs or computed from daily flow values at gaging stations in the fall or early spring when runoff events are unusual. Average streamflows gener-ally also appear to have been smaller between 1975 and 1989 than between 1951 and 1975, as indicated by the streamflow data in table 7. It is important to note that there were no substantial differences in climatic conditions for those two periods.

SIMULATION OF GROUND-WATER FLOW

The movement of ground water in an anisotropic, heterogeneous aquifer can be described by a partial differential equation where the partial derivatives represent the movement of water in three dimensions. Analytical solutions of this equation are rarely possible, so several different numerical techniques commonly are used to obtain approximate solutions (McDonald and Harbaugh, 1988). One of these techniques involves subdividing the aquifer into a set of smaller blocks or cells of porous material and solving the finite-difference equation that describes flow through each cell. The resulting set of equations can be solved using several numerical techniques. For this study, the modular, three-dimensional, finite-difference, ground-water-flow model MODFLOW (McDonald and Harbaugh, 1988) was used to approximate the differential equation, and the strongly implicit procedure was used as the numerical solution technique.



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

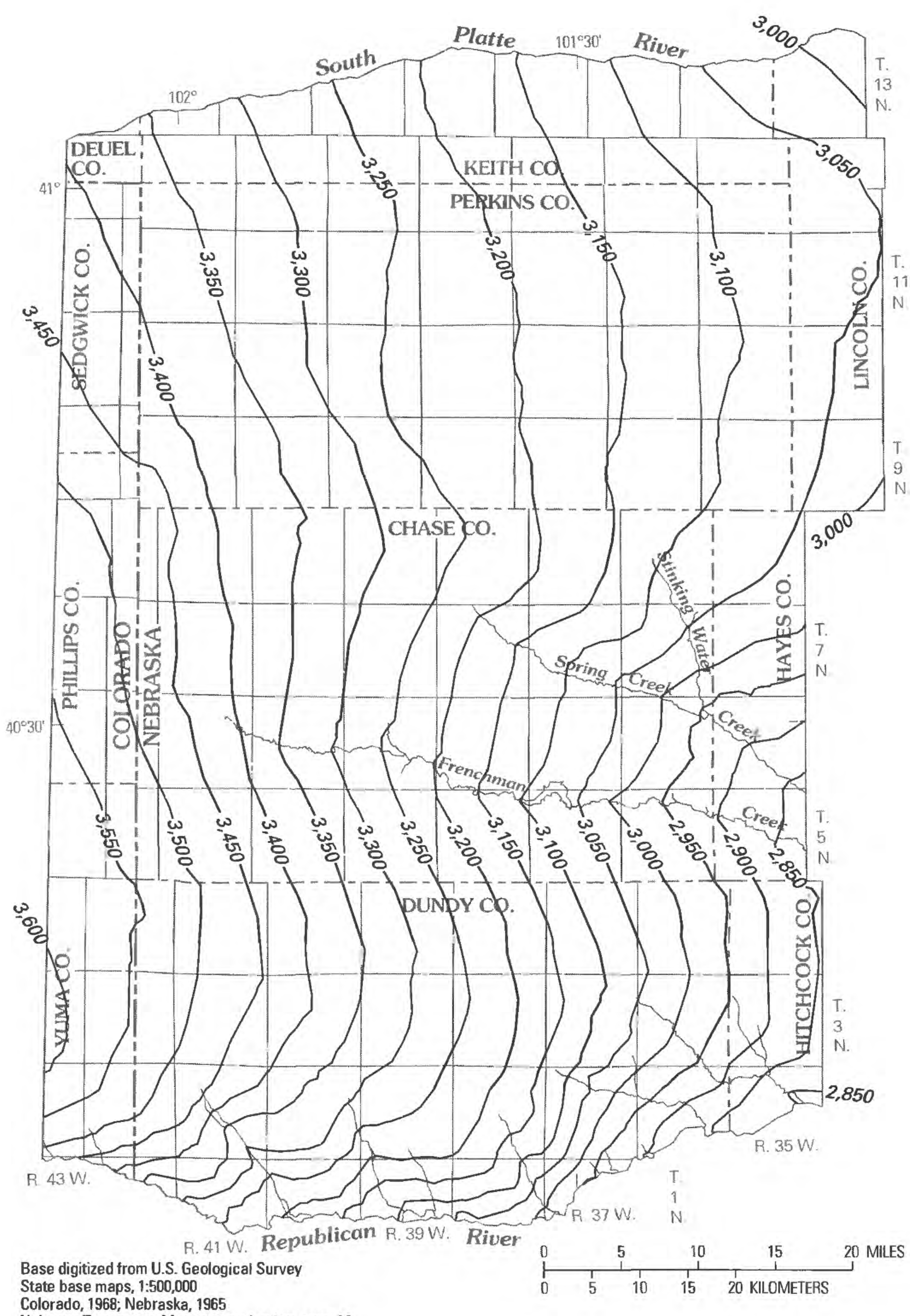
EXPLANATION

Area underlain by the Ogallala Formation

Area underlain by rocks other than the Ogallala Formation

B——*B'* Trace of geologic section—Shown in figure 5

Figure 6. Lateral extent of the Ogallala Formation (Lappala, 1978; Eversoll and others, 1988) and trace of geologic section *B–B'* from Lappala (1978).

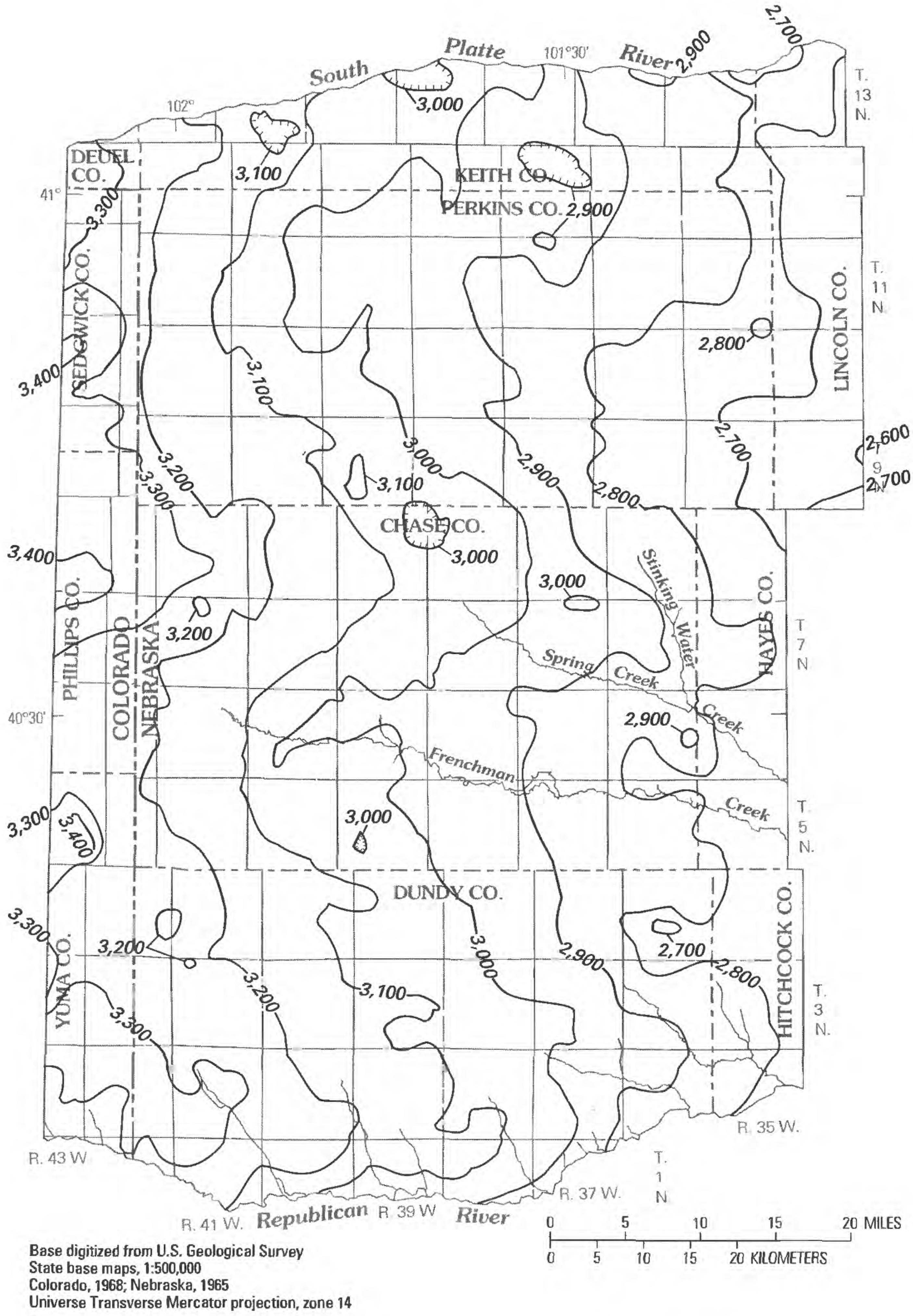


Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

—*3,600*— **Water-table contour**—Shows altitude of water table, spring 1989. Datum is sea level. Contour interval 50 feet

Figure 7. Water-table altitude in the High Plains aquifer, spring 1989.



EXPLANATION

—*2,900*— **Base-of-aquifer contour**—Shows altitude of the base of the High Plains aquifer. Datum is sea level. Contour interval 100 feet

Figure 8. Altitude of the base of the High Plains aquifer.

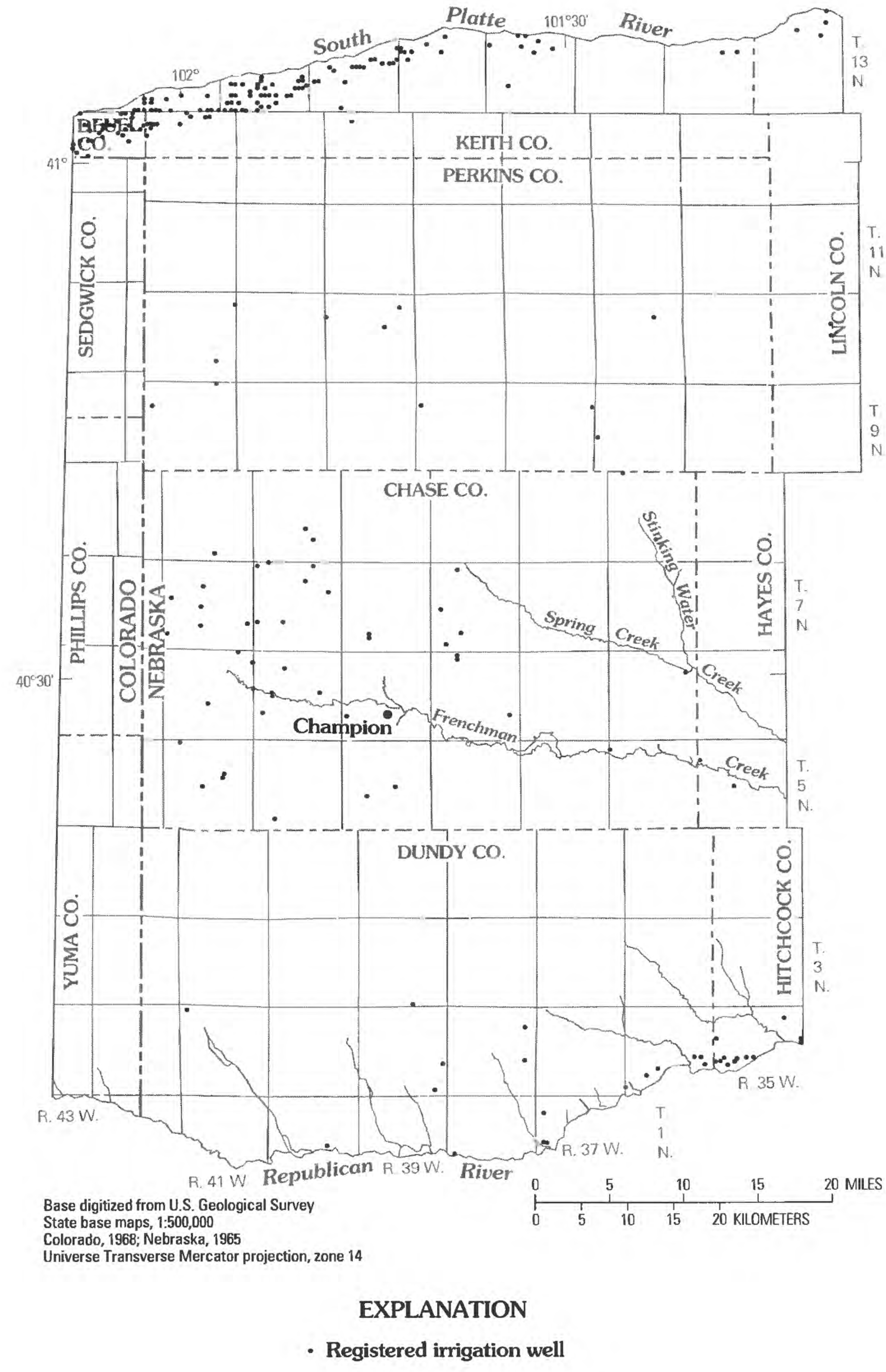


Figure 9. Location of registered wells in the Nebraska part of the study area drilled before 1952 (Susan France, Nebraska Department of Water Resources, written commun., 1990).

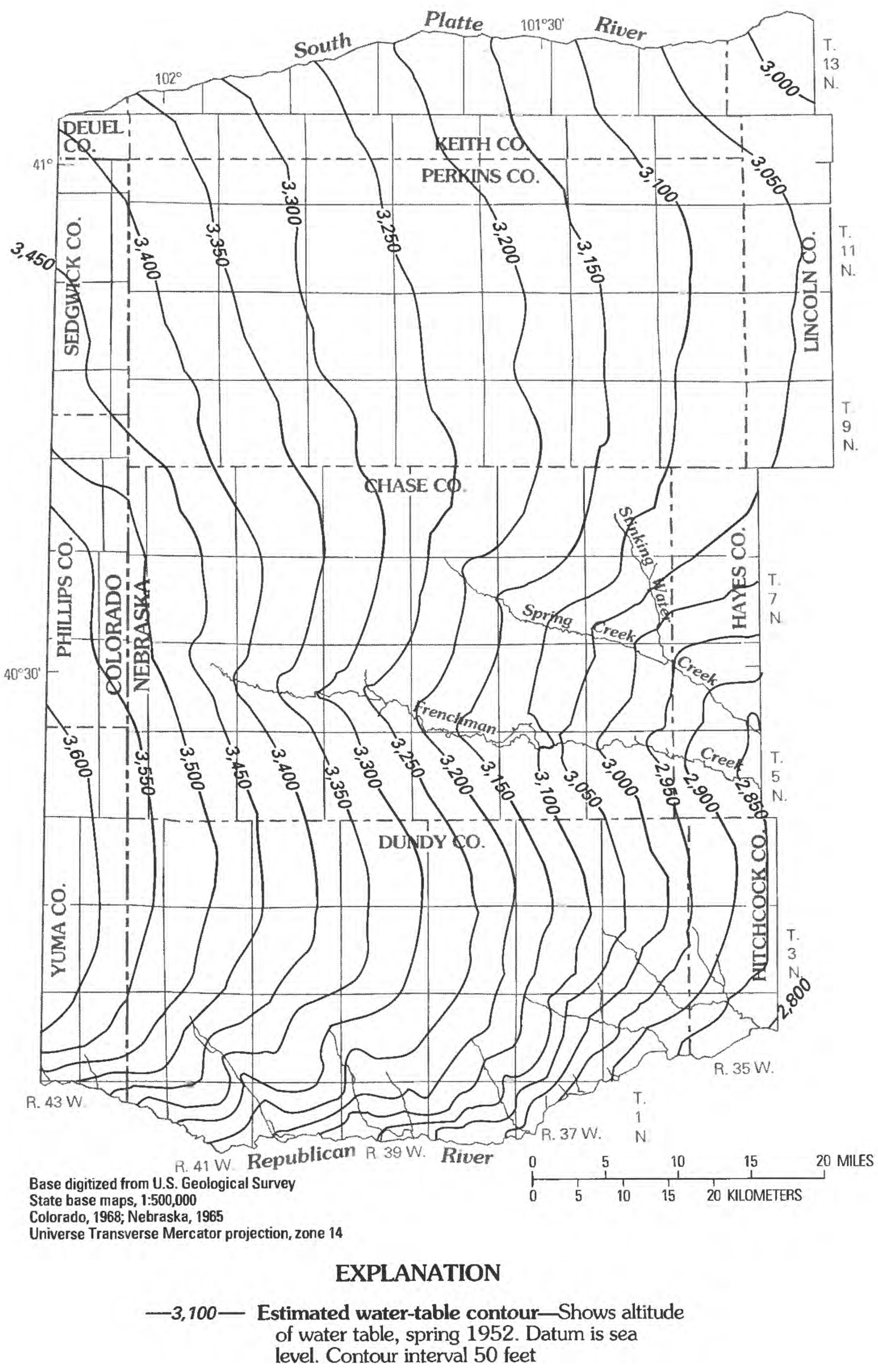


Figure 10. Estimated water-table altitude in the High Plains aquifer, spring 1952 (modified from Lappala, 1978).

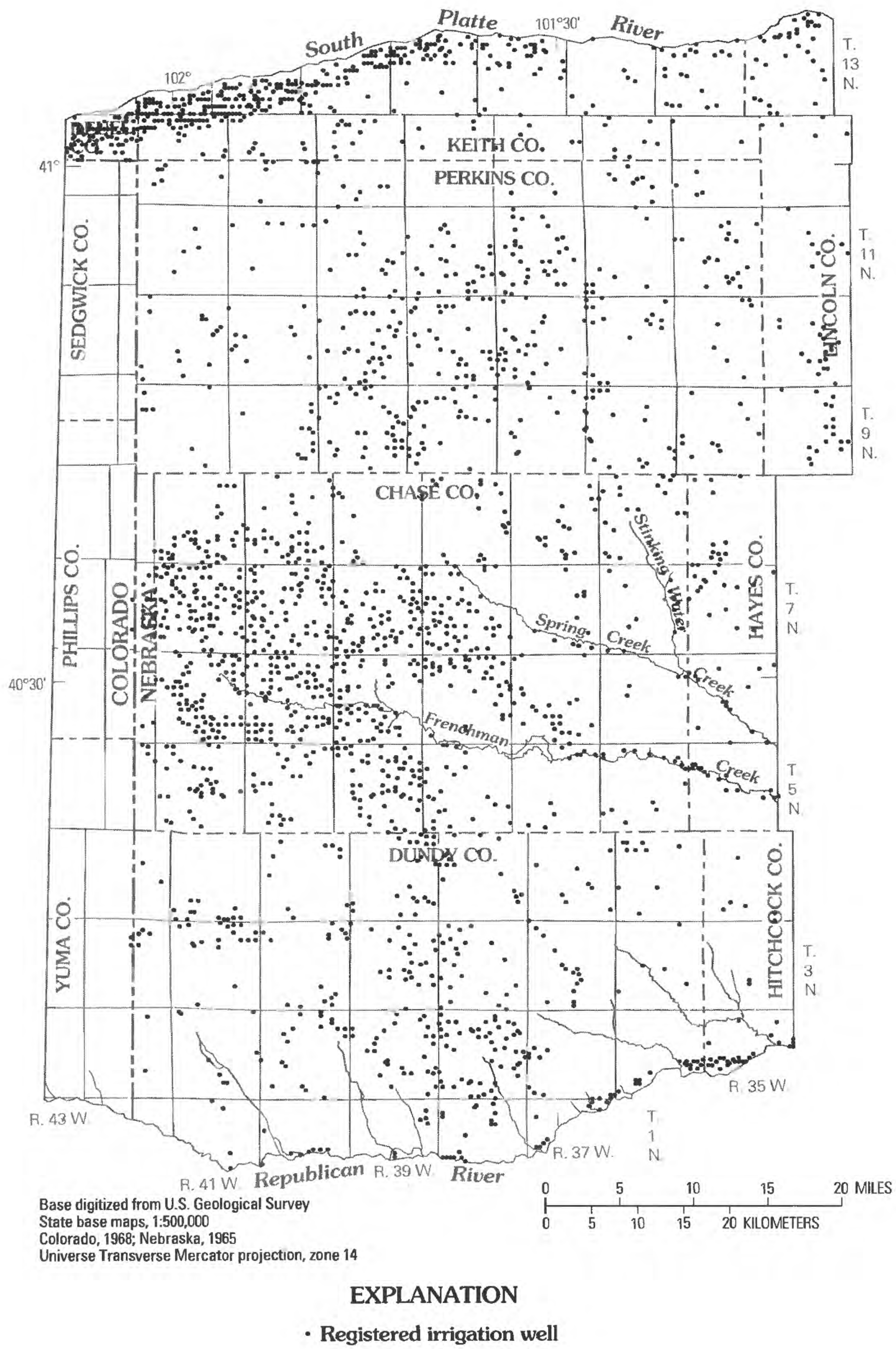


Figure 11. Location of registered wells in the Nebraska part of the study area drilled before 1975 (Susan France, Nebraska Department of Water Resources, written commun., 1990).

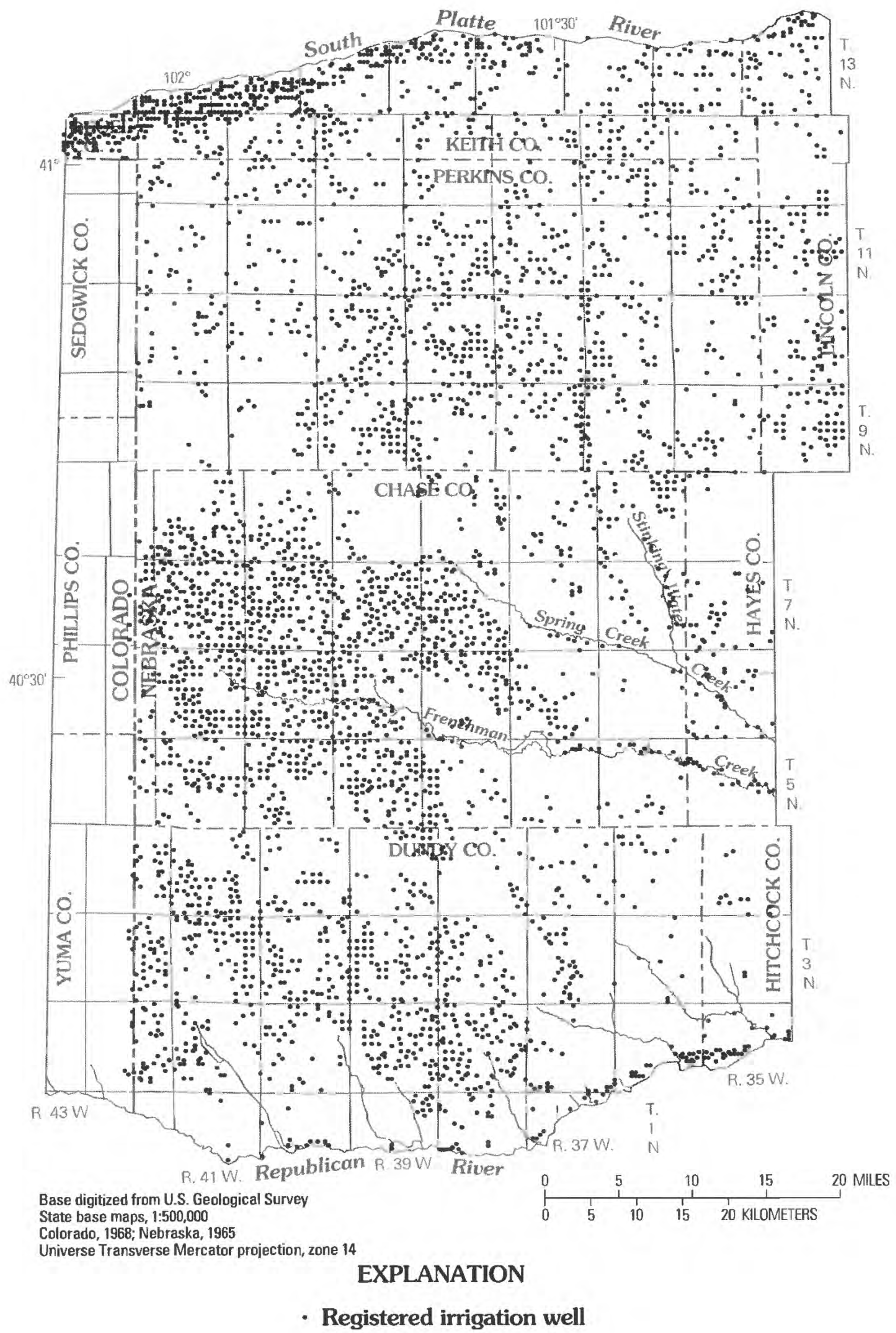
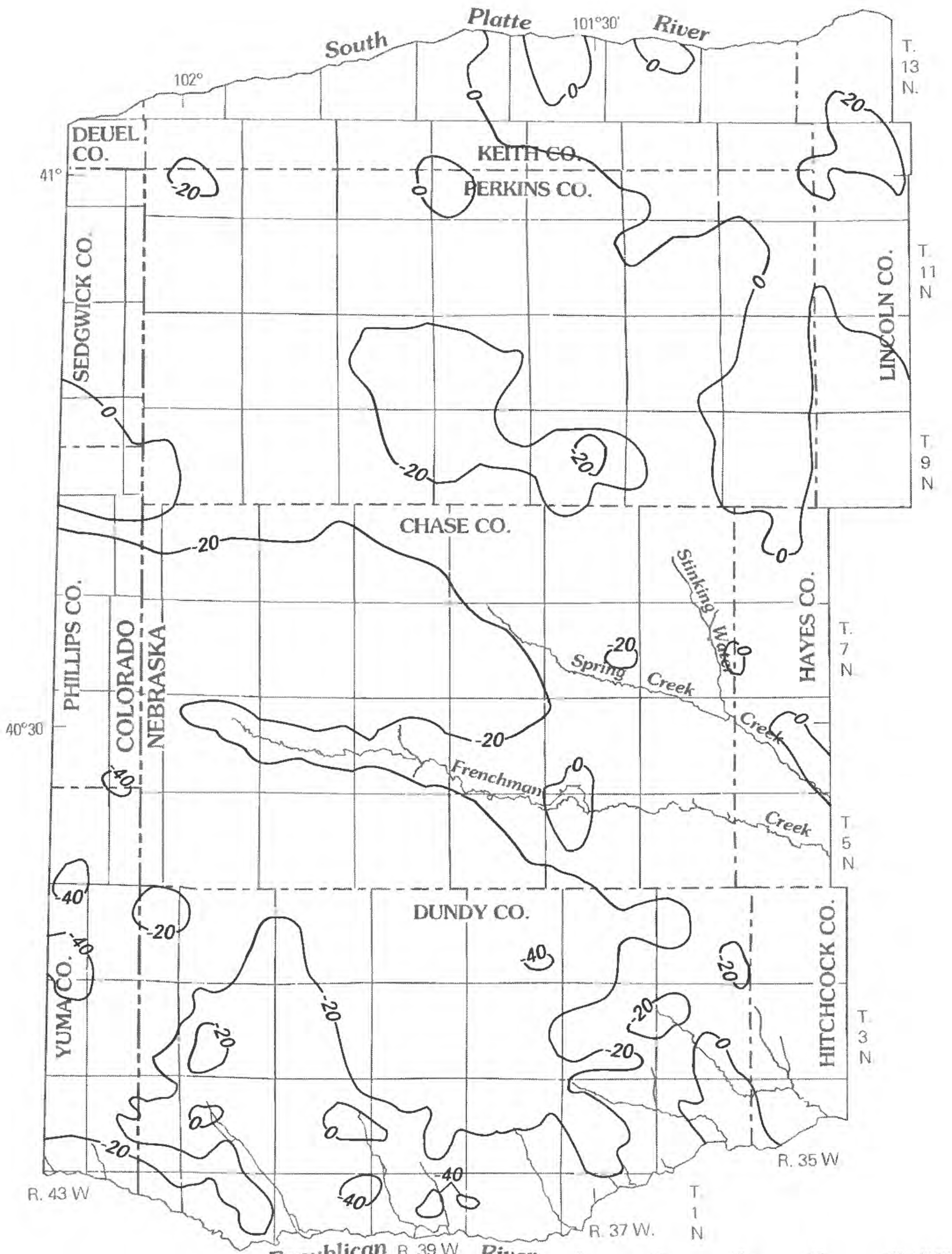


Figure 12. Location of registered wells in the Nebraska part of the study area drilled before 1989 (Susan France, Nebraska Department of Water Resources, written commun., 1990).



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

—*20*— **Line of equal water-level change**—Negative (-) value indicates water-level decline. Positive value indicates water-level rise. Interval 20 feet

Figure 13. Water-level changes in the High Plains aquifer, 1952–89.

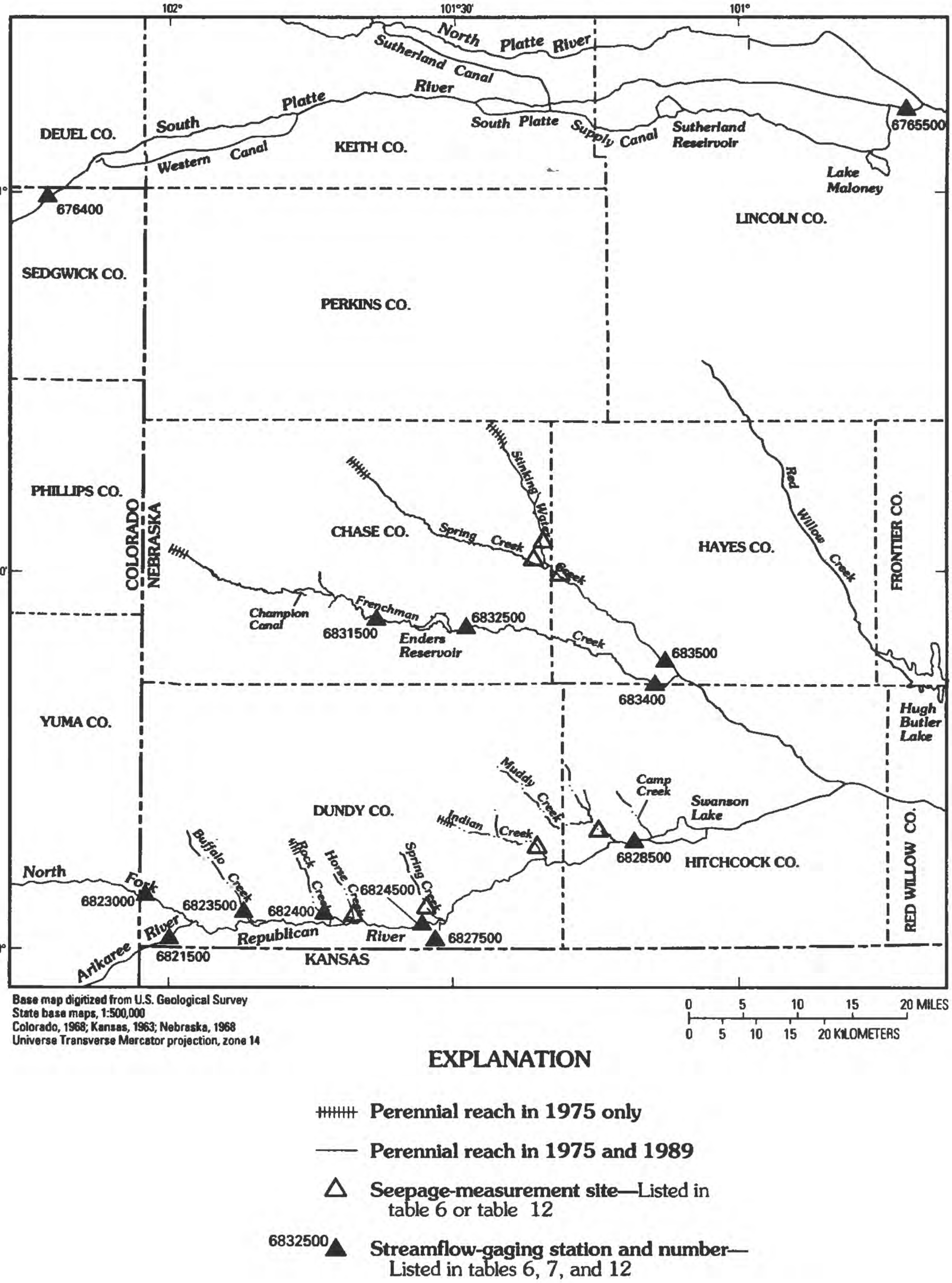


Figure 14. Perennial reaches of streams in 1975 and 1989 and location of seepage-measurement sites and streamflow-gaging stations [based on data from Lappala (1978) and U.S. Geological Survey (1990)].

Table 6. Base flow in 1952, 1975, and 1989 at selected seepage-measurement sites
[--, not measured]

Site name and streamflow-gaging station number (fig. 14)	Measured base flow, in cubic feet per second		
	Fall 1952 (Lappala, 1978)	Spring 1975 (Lappala, 1978)	Spring 1989
Frenchman Creek near Imperial (6831500)	66	53	26.4
Frenchman Creek near Enders (6832500)	--	--	.3
Stinking Water Creek near Wauneta (includes Spring Creek in Chase County)[1]	21	19	20.1
Buffalo Creek near Haigler (6823500)	11	9	6.4
Rock Creek at Parks (682400)	15	14	11.2
Horse Creek near Parks[1]	--	.1	.6
Spring Creek near Benkelman[1]	--	.6	.2
Indian Creek near Max [1]	--	4	3.7
Muddy Creek near Republican River[1]	--	--	1.7

[1]Active streamflow-gaging station not present at this site.

Model Construction

The High Plains aquifer was modeled using a 1-layer, regularly spaced grid consisting of 79 rows and 54 columns (fig. 15). Each row and column represents a 1-mile-wide strip of aquifer, so each cell represents 1 square mile of the aquifer. Of the 4,266 cells, 3,638 were active. The active model-area boundary coincides with the boundary of the study area. It was assumed, on the basis of results from previous investigations (Lappala, 1978), that there is no regional anisotropy of transmissivity within the aquifer; therefore, the grid was oriented north to south for convenience (fig. 15).

Boundary Conditions

Boundary conditions for the ground-water-flow model were chosen to reasonably represent hydrologic conditions at the study-area boundary. Boundary types used in the model were either no flow, constant head, general head, or variable head.

The upper boundary of the model is the water table in the High Plains aquifer, which is simulated as a variable-head surface. The lower boundary of the model is the base of the High Plains aquifer because the underlying units are relatively impermeable (Cardwell and Jenkins, 1963, p. 24). The base of the aquifer was simulated as a no-flow boundary.

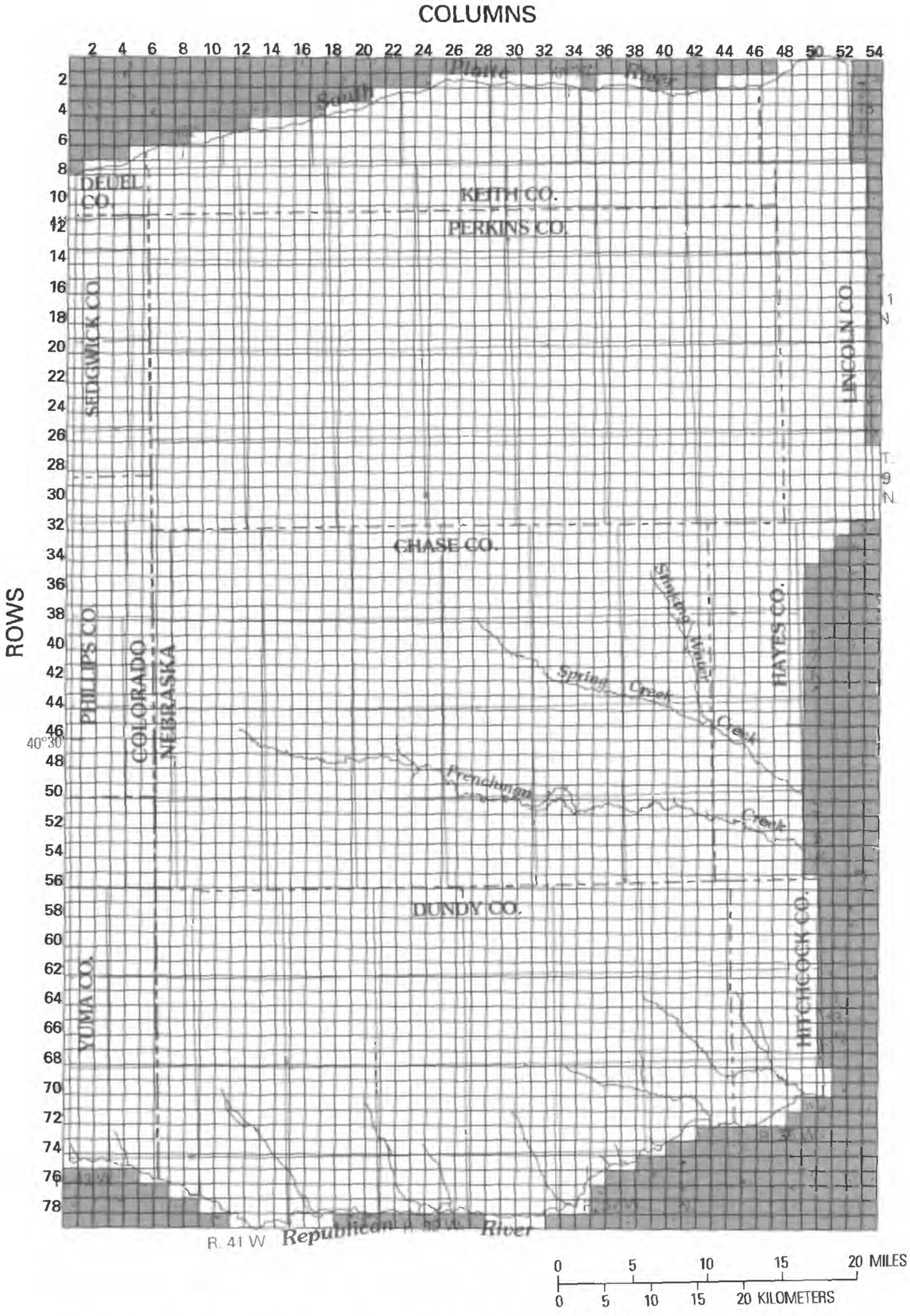
The lateral boundary conditions are shown in figure 16. Cells along the southern and northern edges of the model area simulate the hydraulic connection between the aquifer and the South Platte, Republican, or North Fork of the Republican Rivers. These cells are designated as constant head, meaning that water levels in these cells were held constant at a specified level throughout the simulations. Constant-head cells were used only to simulate streams regulated by upstream reservoirs. This boundary condition is similar to the actual hydrologic conditions in these areas where the river is connected directly to the aquifer and maintains the head in the aquifer at a near constant level. The constant-head values were selected based on water-table altitudes near the rivers.

Table 7. Average streamflow at gaging stations within and near the study area, 1951–89

Station name and number (fig. 14)	Average streamflows during pumping and nonpumping periods (acre-feet per year)					
	1951–75		1975–89		1951–89	
	Pumping[1]	Nonpumping[2]	Pumping[1]	Nonpumping[2]	Pumping[1]	Nonpumping[2]
South Platte River at Julesburg, Colo. (6764000)	93,873	260,217	180,824	460,135	127,316	332,821
South Platte River at North Platte, Nebr. (6765500)	76,525	157,310	163,998	327,941	110,169	219,278
Frenchman Creek near Imperial (6831500)	11,908	36,836	5,374	17,838	9,395	29,936
Frenchman Creek near Enders (6832500)	28,852	17,551	23,184	1,029	26,672	11,551
Frenchman Creek at Palisade (683400)	31,495	33,467	24,709	16,018	28,885	27,130
Stinking Water Creek near Palisade (683500)	7,693	23,550	4,845	16,521	6,597	20,997
Arikaree River at Haigler (6821500)	5,322	9,796	1,908	5,473	4,009	8,226
North Fork Republican River at Colorado-Nebraska stateline (6823000)	5,008	30,086	3,163	25,483	4,298	28,414
Buffalo Creek near Haigler (6823500)	700	4,523	366	3,808	572	4,263
Rock Creek at Parks (682400)	2,416	7,779	2,010	6,587	2,260	7,346
Republican River at Benkelman (6824500)	12,399	53,057	6,636	42,258	10,182	49,135
South Fork Republican River near Benkelman (6827500)	11,162	21,548	4,366	12,381	8,549	18,219
Republican River at Stratton (6828500)	25,737	75,455	11,028	53,991	20,080	67,660

[1]Pumping period is June through August.
[2]Nonpumping period is January through May and September through December.

No barriers to ground-water movement exist along the eastern and western edges of the study area; therefore, model boundaries in these areas were chosen to minimize the effects of the model boundaries on simulated water levels in the primary area of interest, the Upper Republican NRD. Flow into the aquifer along the western boundary was calculated to be 42,430 acre-feet in 1952 and 32,800 acre-feet in 1989 using the same equation as Lappala (1978):



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

Active cell

Nonactive cell

Figure 15. Finite-difference grid used in modeling ground-water flow in study area.

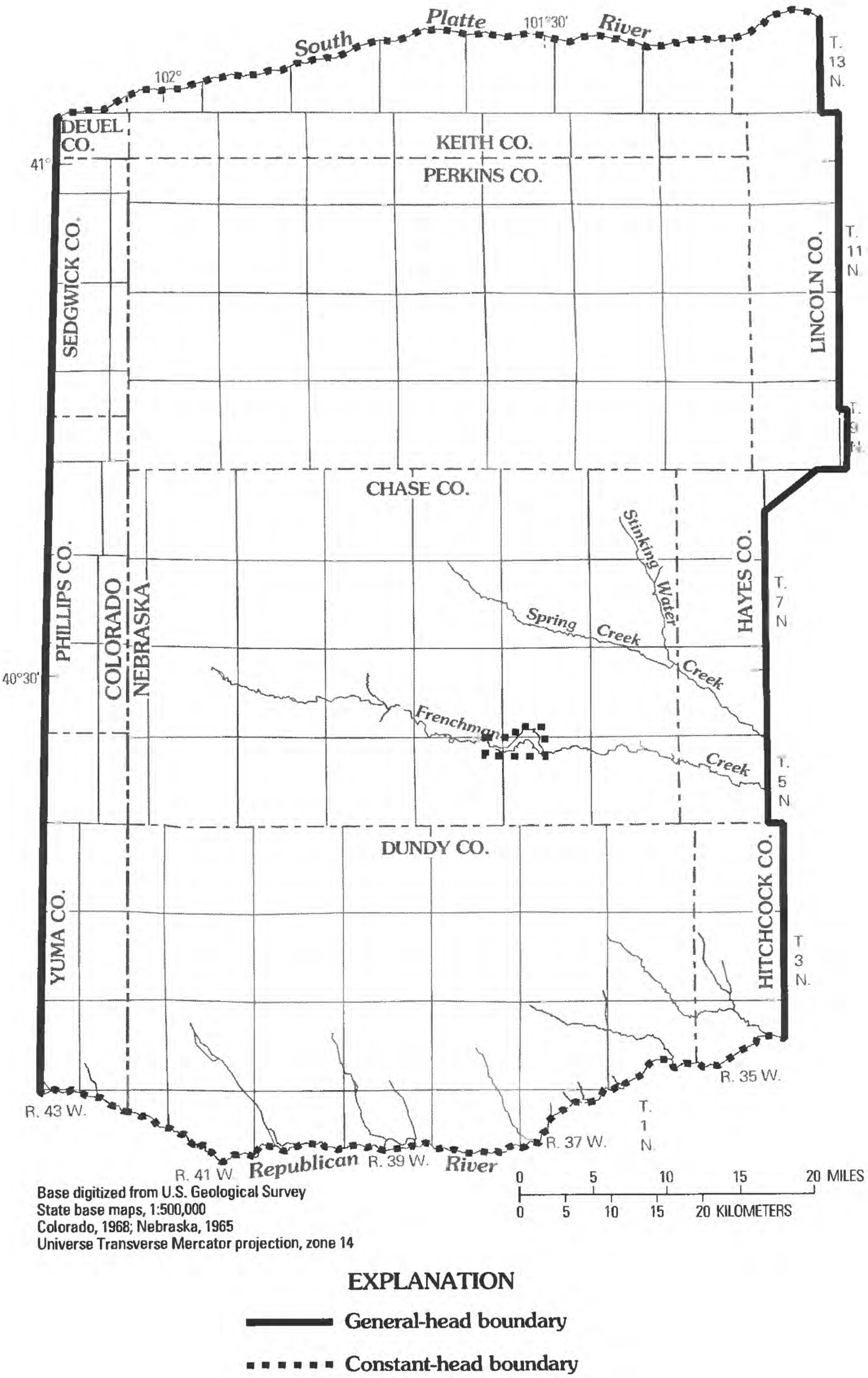


Figure 16. Model-boundary conditions.

$$Q = \sum_{i=1}^{m} -\hat{K}_i b_i w_i \left(\frac{\partial h}{\partial l}\right)_i , \qquad (2)$$

where

Q = flow into the study area (+) or flow out of the study area (-) [L^3/T];

i = an index on the interval used;

m = total number of intervals;

$\hat{K}_i$ = average hydraulic conductivity over b_i and w_i [L/T];

b_i = average aquifer thickness over interval i [L];

w_i = width of the increment i [L]; and

$\left(\frac{\partial h}{\partial l}\right)_i$ = the hydraulic gradient normal to the boundary interval i [dimensionless].

Flow out of the study area along the eastern edge was calculated to be 52,750 acre-feet in 1952, and 50,130 acre-feet in 1989 using the same equation. Cells along the eastern and western edges of the study area were designated general-head boundary cells, which means that the rate of flow into or out of these cells is proportional to the difference between the hydraulic head in the cell and the hydraulic head assigned to an external source of water, in this case those parts of the aquifer outside, but immediately adjacent to, the study area. Flow into a cell at a general-head boundary is calculated as follows:

$$Q_b = C_b (h_b - h) , \qquad (3)$$

where Q_b = flow into the cell from an external source [L^3/T];

C_b = conductance between the external source and the cell [L^2/T];

h_b = hydraulic head assigned to external source [L]; and

h = hydraulic head in the cell [L].

Because water levels in the aquifer outside the study area change through time, it was necessary during the simulation to change the hydraulic-head values assigned to the external sources of general-head boundary cells. For this purpose, the entire simulation period was divided into five simulation intervals, and revised external head values were assigned for each general-head boundary cell at the beginning of each simulation interval (table 8). Conductance values (C_b) were calculated for each of the general-head boundary cells for each simulation period using the formula:

$$C_b = \frac{KA}{l} , \qquad (4)$$

where C_b = conductance between the external source and the cell [L^2/T];

K = hydraulic conductivity [L/T];

A = cross-sectional area of flow [L^2]; and

l = length of flow path [L].

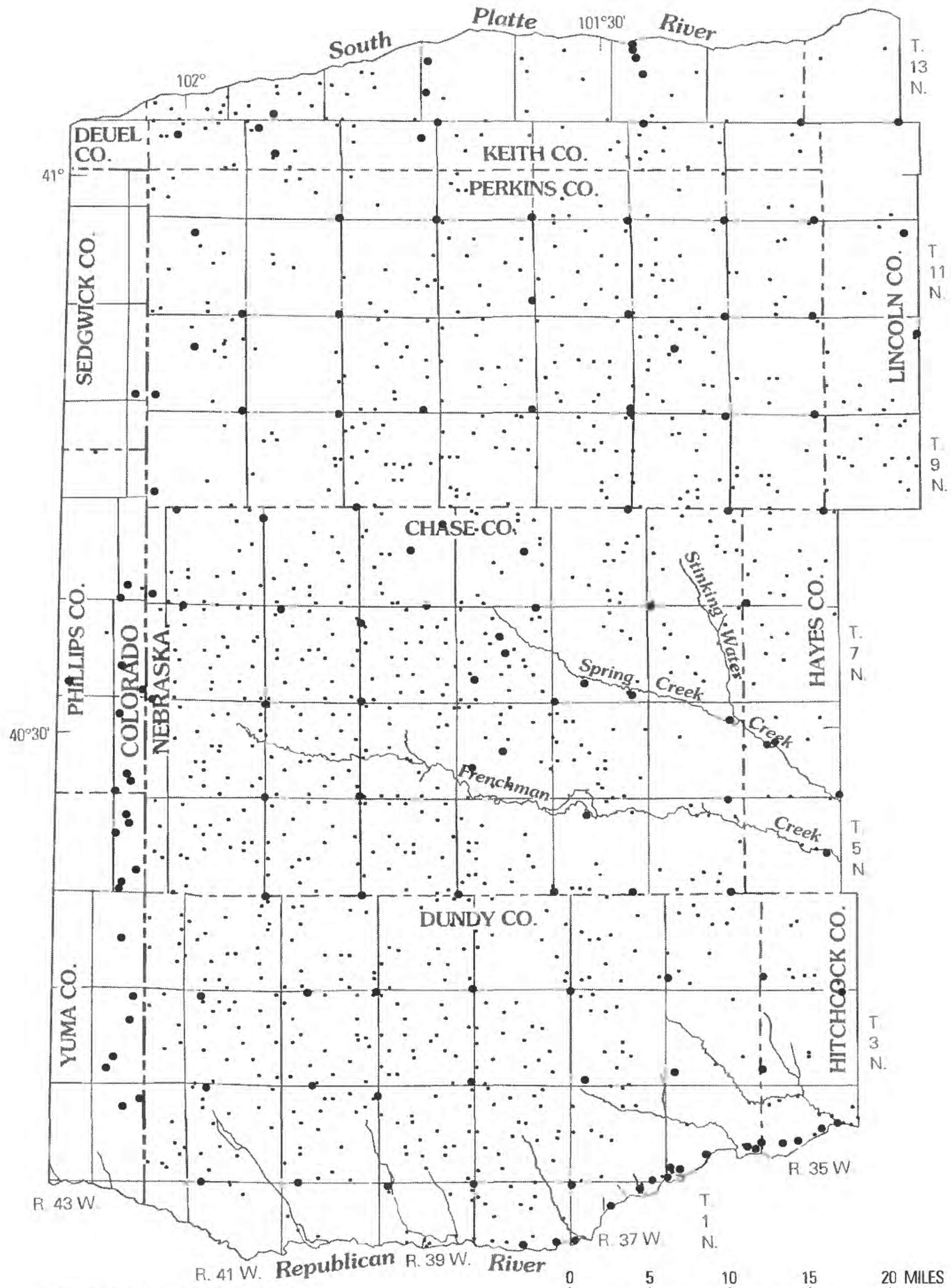
Hydraulic Properties

The hydraulic properties of the aquifer in the study area were estimated from the analysis of 149 test-hole and 1,174 irrigation-well logs, which represent more than one-third of the irrigation wells in the study area. The location of the test holes and irrigation wells is shown in figure 17. Hydraulic properties estimated from these logs include hydraulic conductivity and specific yield. The hydraulic conductivity and specific yield of the aquifer were calculated using data from table 9, which was modified from Peckenpaugh and Dugan (1983, p. 41 and 98). For each lithologic unit noted on the test-hole and irrigation-well logs, hydraulic-conductivity (K) and specific-yield (Sy) values from table 9 were assigned

Table 8. Simulation time intervals during which external hydraulic-head values assigned to general-head boundary cells remained the same

Simulation period	Time interval	Data year[1]
1	1952–63	1952
2	1964–73	1964, interpolated
3	1974–80	1975
4	1981–87	1982, interpolated
5	1988–89	1989

[1]Year for which assigned external hydraulic-head values are selected to represent given time interval.



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

- **Test hole**
- **Irrigation well**

Figure 17. Location of test holes and irrigation wells from which data were used to estimate aquifer properties.

Table 9. Hydraulic conductivity and specific yield estimated from description of materials comprising a lithologic unit (modified from Peckenpaugh and Dugan, 1983)
[--, not estimated]

Grain-size class or range from sample description	Hydraulic conductivity, in feet per day[1]						Specific yield[2] (percent)
	Estimated from degree of sorting			Estimated from silt content			
	Poor	Moderate	Well	Slight	Moderate	Large	
FINE-GRAINED MATERIALS:							
Clay	--	--	--	2.0	--	--	2.0
Silt, slightly clayey	--	--	--	18	--	--	17.0
Silt, moderately clayey	--	--	--	11	--	--	11
Silt, very clayey	--	--	--	7.0	--	--	7.0
Silt; loess; sandy silt	--	--	--	20	--	--	24.0
SANDS AND GRAVELS[3]:							
Very fine sand	13	20	27	23	19	13	21.0
Very fine to fine sand	27	27	--	24	20	13	21.5
Very fine to medium sand	36	41–47	--	32	27	21	22.4
Very fine to coarse sand	48	--	--	40	31	24	22.5
Very fine to very coarse sand	59	--	--	51	40	29	22.4
Very fine sand to fine gravel	76	--	--	67	52	38	22.3
Very fine sand to medium gravel	99	--	--	80	66	49	22.2
Very fine sand to coarse gravel	128	--	--	107	86	64	22.1
Fine sand	27	40	53	33	27	20	22.0
Fine to medium sand	53	67	--	48	39	30	24.5
Fine to coarse sand	57	67–72	--	53	43	32	25.0
Fine to very coarse sand	70	--	--	60	47	35	24.5
Fine sand to fine gravel	88	--	--	74	59	44	24.4
Fine sand to medium gravel	114	--	--	94	75	57	24.3
Fine sand to coarse gravel	145	--	--	107	87	72	24.2
Medium sand	67	80	94	64	51	40	27.0
Medium to coarse sand	74	94	--	72	57	42	27.5
Medium to very coarse sand	84	98–111	--	71	61	49	27.4
Medium sand to fine gravel	103	--	--	84	68	52	27.3
Medium sand to medium gravel	131	--	--	114	82	66	27.2
Medium sand to coarse gravel	164	--	--	134	108	82	27.1
Coarse sand	80	107	134	94	74	53	28.0
Coarse to very coarse sand	94	134	--	94	75	57	27.5
Coarse sand to fine gravel	116	136–156	--	107	88	68	27.3
Coarse sand to medium gravel	147	--	--	114	94	74	27.1
Coarse sand to coarse gravel	184	--	--	134	100	92	26.8
Very coarse sand	107	147	187	114	94	74	27.0
Very coarse sand to fine gravel	134	214	--	120	104	87	26.5
Very coarse sand to medium gravel	170	199–227	--	147	123	99	26.3
Very coarse sand to coarse gravel	207	--	--	160	132	104	25.8
Fine gravel	160	214	267	227	140	107	26.0
Fine to medium gravel	201	334	--	201	167	134	25.5
Fine to coarse gravel	245	289–334	--	234	189	144	24.5
Medium gravel	241	321	401	241	201	160	25.0
Medium to coarse gravel	294	468	--	294	243	191	24.0
Coarse gravel	334	468	602	334	284	234	23.0

[1]Hydraulic-conductivity values are from an unpublished, undated paper by E.C. Reed and R. Piskin, Conservation and Survey Division, University of Nebraska, Lincoln.

[2]Specific-yield values are modified from Johnson (1967).

[3]Reduce hydraulic conductivity by 10 percent if grains are subangular.

according to grain size of the material composing the unit and the degree of sorting or silt content of the unit. A thickness-weighted average value of hydraulic conductivity and specific yield then was calculated for each test hole or irrigation well.

Hydraulic Conductivity

The distribution of hydraulic conductivity used in the model is shown in figure 18. Hydraulic-conductivity values for individual test holes or wells were averaged by quarter township throughout the study area because of the extreme variability of these values within short distances. A model array of hydraulic-conductivity values was generated by assigning the average value for each quarter township to cells representing that quarter township in the model. Hydraulic-conductivity values assigned in areas with little or no test-hole or well data were based on data from Lappala's (1978) model. Assigned hydraulic-conductivity values ranged from 20 to 155 feet per day and most commonly ranged from 50 to 75 feet per day.

Specific Yield

The distribution of specific yield used in the model is shown in figure 19. Specific-yield values for individual test holes or wells also were averaged, just as hydraulic-conductivity values were, by quarter township throughout the study area. Assigned specific-yield values ranged from 0.09 to 0.22 and were most commonly from 0.15 to 0.20.

Stresses on the Aquifer System

The most significant stresses on the High Plains aquifer in the study area are well pumpage, recharge from precipitation, and interaction with streams and rivers. Evapotranspiration (ET) losses directly from a shallow water table were considered to be insignificant except in the valley bottoms near major streams where the stream supplies most of the loss. Therefore, direct ET losses do not affect the aquifer appreciably and were not considered in the model. Data on the locations and magnitudes of the most substantial stresses on the aquifer were not available for the study area for the entire transient calibration period, 1952–89. The following sections describe how the magnitude of these stresses was estimated and how these stresses were simulated in the model.

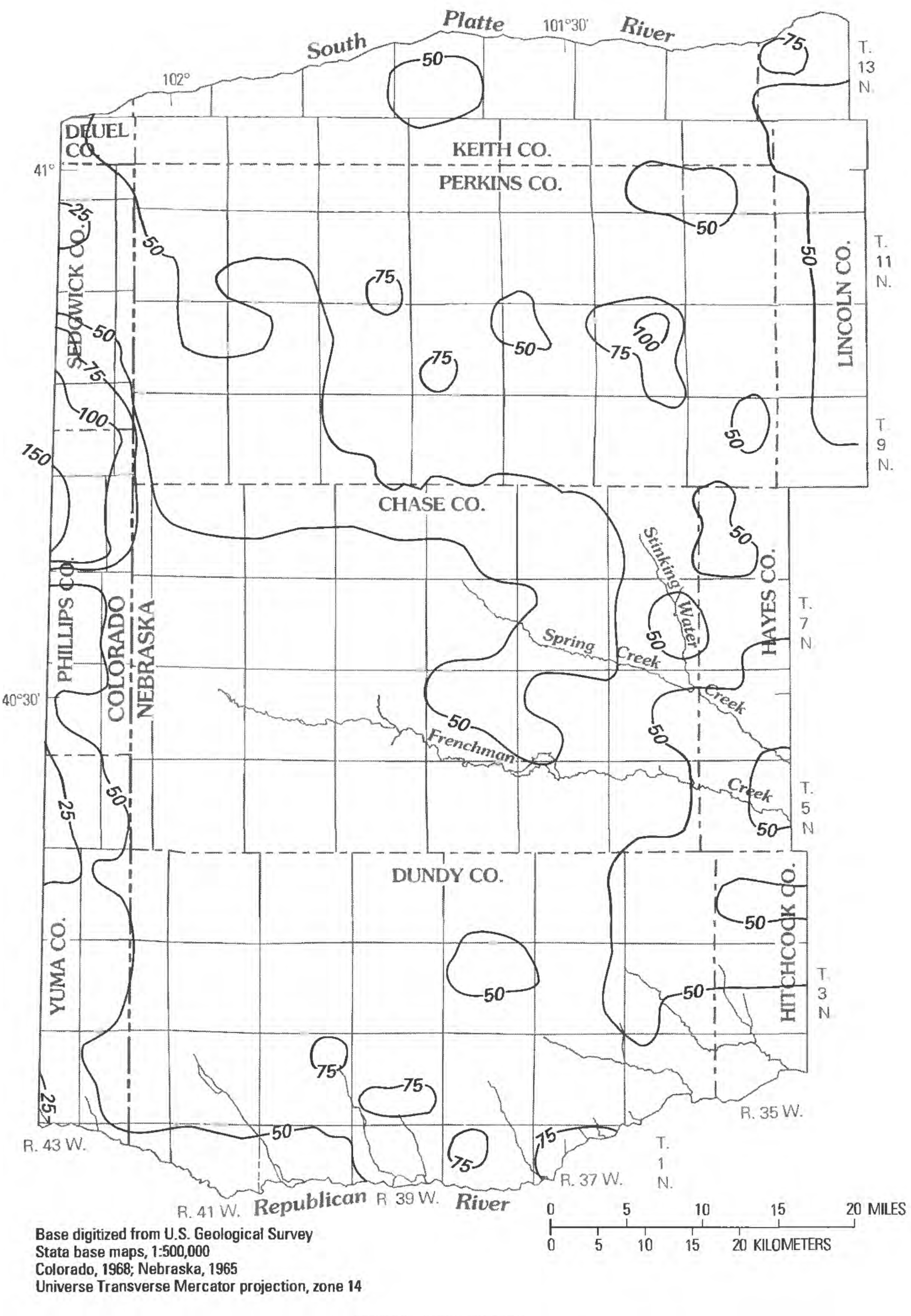
Recharge and Pumpage

Recharge and pumpage used in the ground-water-flow model were estimated using two computer programs referred to herein as the PET and the soil-water programs. These programs are documented in Cady and Peckenpaugh (1985), and earlier program versions have been used in other studies by Lappala (1978), Peckenpaugh and Dugan (1983), Peckenpaugh and others (1987), and Goeke and others (1992) to make similar estimates.

These programs were used to estimate recharge and pumpage because these stresses had not been measured for the entire period of interest in the entire study area. Also, using measured pumpage data would not account for excess water that is pumped but not transpired or evaporated and, therefore, recharges the aquifer. These programs account for this excess by estimating water used by crops or evaporated and thus lost from the hydrogeologic system. These estimates are used instead of metered pumpage values, which are larger.

The PET program estimates potential ET using the Jensen-Haise method (Jensen and others, 1970) and climate data from 19 weather stations in or near the study area (table 10). Data needed for each station by the PET program include: (1) average monthly values for precipitation, air temperature, and percentage of possible sunshine, (2) the mean minimum and maximum air temperatures for the warmest month of the year (July), and (3) the mean daily solar-radiation values on cloudless days for each month. Results from the PET program consist of mean monthly precipitation, mean monthly air temperature, and monthly potential ET for the period of interest for each weather station. These data are used in the soil-water program.

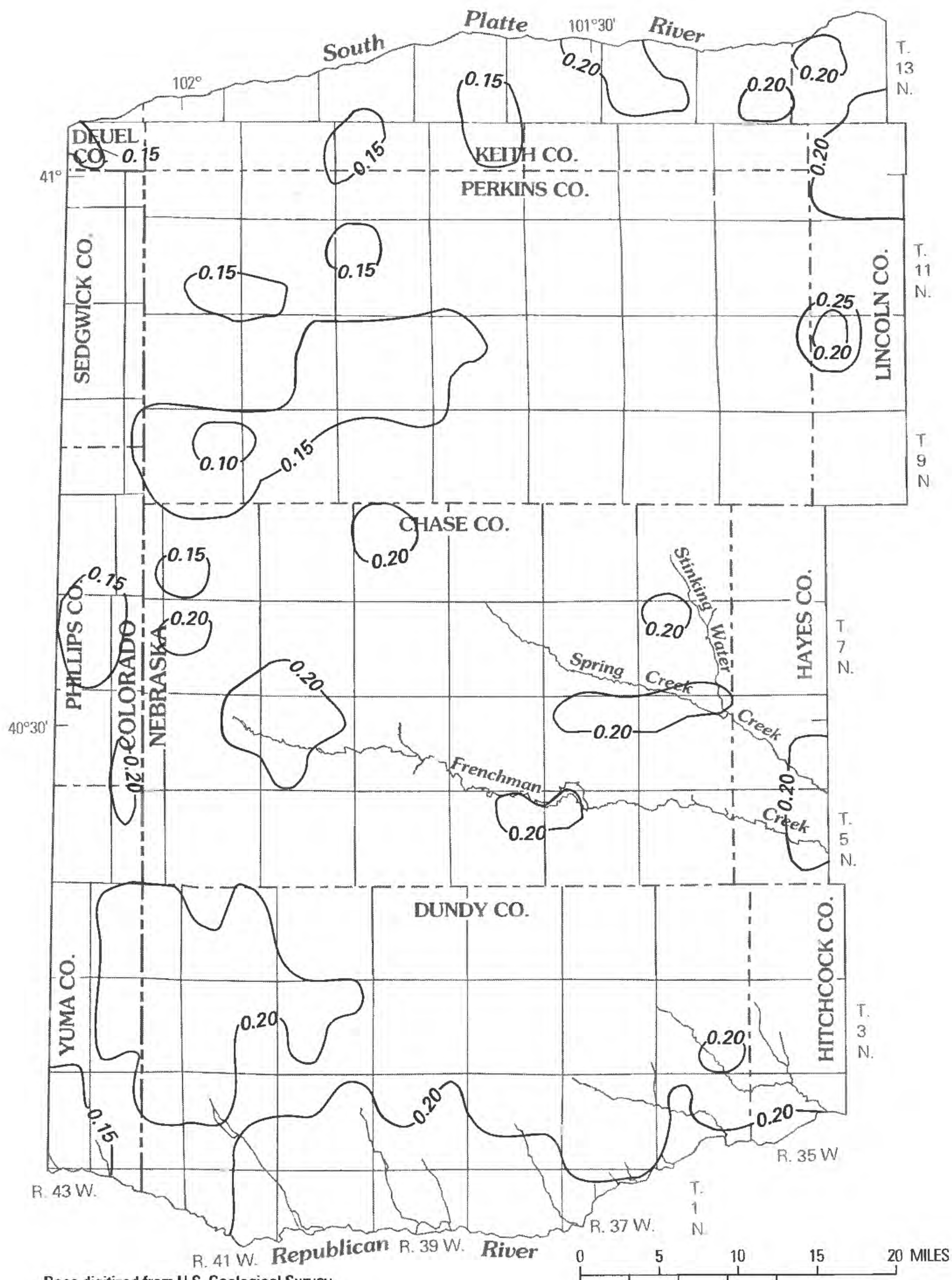
The soil-water program estimates recharge to the water table and the consumptive irrigation requirement (CIR) of crops based on ET estimates from the PET program and data on soil characteristics, monthly precipitation, and crop characteristics. The CIR of a crop is the amount of supplemental water required by the crop to thrive and is defined to be equal to the amount of supplemental water required to maintain the root zone at 50 percent of its available water capacity. Data needed by the soil-water program include: (1) monthly potential ET calculated by the PET program; (2) monthly precipitation; and (3) several coefficients selected based on soil, crop, and topographic characteristics. A more detailed description of the data needed and coefficient selection can be found in Cady



EXPLANATION

—*20*— **Line of equal hydraulic conductivity**—Interval 25 feet per day

Figure 18. Distribution of hydraulic conductivity in the High Plains aquifer.



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

—*0.10*— **Line of equal specific yield**— Interval 0.05

Figure 19. Distribution of specific yield in the High Plains aquifer.

and Peckenpaugh (1985). Results from the soil-water program include the annual estimates of the following items for each soil group, land use, and weather station from 1951–89: infiltration, surface runoff, ET, irrigated land recharge, CIR, dryland recharge, and dryland water shortage. Table 11 lists output from the soil-water program for three selected weather stations.

Pumpage and recharge values were distributed in the model through time by dividing the simulation period into 111 intervals or stress periods, with each full year represented by three stress periods—January–May, June–August, and September–December. The first stress period simulated was June–August 1952, and the last stress period simulated was January–May 1989. Pumpage and recharge values were assigned to designated cells for each stress period on the basis of soil and land-use characteristics and the number of irrigation wells in that cell for the time period being simulated. Average recharge values assigned to each cell from 1952 through 1988 using the MODFLOW recharge package are shown in figure 20. Pumpage in each cell for each stress period was calculated based on output from the soil-water program. For each cell the total pumpage was calculated by summing the pumpage for each crop in the cell, which was calculated by multiplying the CIR for the crop times the total number of acres of that crop in the cell. The CIR values for each crop were selected from soil-water program output based on the soil types in the cell, the proximity of the cell to the nearest weather stations, and the period of time being simulated. Pumpage values assigned to each cell for the June–August 1988 stress period using the MODFLOW well package are shown in figure 21.

Streams, Rivers, and Canals

The South Platte, Republican, and North Fork of the Republican Rivers are lateral boundaries simulated as constant-head cells. Enders Reservoir also was simulated using constant-head cells. Other perennial streams and rivers and large irrigation canals were simulated in the model using the stream-routing package written by Prudic (1989) for use with MODFLOW. According to Lappala (1978), the perennial streams in the study area are directly connected to the aquifer; therefore, streambed conductances were assigned equal to the aquifer conductance so that streambeds did not restrict flow. Cells that were used to simulate interior streams and rivers using the stream-routing package are shown in figure 22. Streams, rivers, or canals that were simulated include the Western and Sutherland Canals; Stinking Water, Spring, and Frenchman Creeks in Chase County; and Buffalo, Rock, Horse, Spring, Indian, and Muddy Creeks in Dundy County.

Model Calibration

The model was calibrated under both steady-state and transient conditions to ensure that the final model adequately represented the response of the High Plains aquifer to stress. In general terms, calibration consisted of minor and reasonable adjustment of hydraulic characteristics, such as hydraulic conductivity, until a reasonable match was obtained between computed and observed water levels and streamflows. The following sections describe in more detail the calibration of the model under both steady-state and transient conditions.

Steady-State Conditions

The model was calibrated under steady-state conditions to simulate the flow system in the aquifer before extensive pumping for irrigation began. The model was calibrated under steady-state conditions by adjusting input data, including hydraulic conductivity, streamflows assigned to the upstream reach of each stream segment (Prudic, 1989), and boundary head and conductance at general-head boundary cells, so that the simulated spring 1952 water levels adequately matched the estimated spring 1952 water levels. These data were adjusted only by small percentages and only in certain areas. Data from spring 1952 were assumed to be reasonably representative of predevelopment water levels.

Two different recharge arrays were tested as fluxes for the steady-state simulations. One recharge array tested was the average recharge from 1952 through 1988, and the other recharge array tested was the average recharge from January 1 through May 31, 1953. The latter recharge array was tested because it allowed climatic conditions prior to May 1953 to affect the recharge. This is because climatic conditions in 1952 determined the available soil water at the beginning of the January 1 through May 31, 1953, recharge period. Pumpage was not used in the steady-state simulations because these simulations were designed to represent predevelopment conditions.

Both of the steady-state recharge arrays produced a root mean square error (RMSE) of approx-

Table 10. Average annual precipitation for weather stations in and near the study area, 1951–89
[data from National Oceanic and Atmospheric Administration, 1951–89]

Weather station (shown in figure 2, except as indicated)	Average annual precipitation from 1951–89 (inches)
Benkelman	18.10
Big Springs	17.16
Champion	19.01
Enders Lake	18.74
Haigler	17.05
Hayes Center[1]	19.95
Imperial	19.02
Madrid	19.10
Ogallala	17.79
Palisade[1]	20.43
Paxton	17.66
Stratton	19.96
Wallace	17.69
Wauneta	19.29
Holyoke[1]	17.93
Julesburg[1]	17.09
Wray[1]	16.91
St. Francis[1]	17.16
St. Francis-8[1]	17.27

[1]Not shown in figure 2.

imately 30 feet using water levels for the 3,638 active cells within the study area. The RMSE's were calculated by summing the squared difference between the simulated and observed water levels for each active cell, by dividing this summation by the number of active cells (the 111 constant-head cells were not considered active cells) and then taking the square root of the result. The mean absolute error was 23.5 feet and the maximum absolute error was 80 feet. The standard deviation of the differences was 28.1 feet.

The size of the RMSE is assumed to have been the result of uncertainties related to the estimated 1952 water levels and the recharge arrays, which cannot adequately represent the historical fluxes that produced the spring 1952 water levels. Goeke and others (1992, p. 58) observed a RMSE of 157 feet for a modeled area immediately east of the study area because the simulated recharge could not adequately represent those that generated the steady-state water levels.

Transient Conditions

The model was calibrated under transient conditions by simulating the period from 1952 through 1989. Estimated spring 1952 water levels (fig. 10) were used as initial water levels, and computed 1989 water levels were compared with observed spring 1989 water levels. During calibration, adjustments were made in hydraulic conductivity, specific yield, pumpage, recharge, and the streamflows assigned to the upstream reach of each stream segment (Prudic, 1989). All values were adjusted within the ranges that were considered reasonable for the particular parameters as determined from previous studies (Cardwell and Jenkins, 1963; Lappala, 1978) and from other measured data for that parameter. The resultant computed 1989 water levels were compared against the observed 1989 water levels.

Four methods were used to assess the accuracy of the transient calibration of the model. The first

Table 11. Output from soil-water program, given as annual averages, 1951–89, using data from the Haigler, Imperial, and Madrid weather stations

[I, infiltration; RO, surface runoff; ET, evapotranspiration; DPI, deep percolation (recharge) from irrigated lands; CIR, consumptive irrigation requirements; DPD, deep percolation (recharge) from drylands; STD, water shortage on drylands]

Soil series	Land use	Annual average (inches)						
		I	RO	ET	DPI	CIR	DPD	STD
		Haigler (precipitation, 17.1 inches per year)						
Rosebud, Alliance, Kuma, Goshen, and Keith	Corn	16.3	0.78	36.1	1.0	17.5	0.94	20.8
	Dry beans, grain sorghum	16.3	.78	31.8	2.1	16.5	1.9	17.4
	Winter wheat	16.3	.78	34.8	.77	10.8	.20	18.7
	Pasture, range	16.8	.24	37.2	.30	16.9	.27	20.6
	Fallow	15.3	1.7	20.9	1.3	5.97	1.1	6.58
	Alfalfa	16.8	.24	42.4	.16	17.5	.12	25.7
Colby, Canyon, and Ulysses	Corn	15.0	2.1	36.1	.62	18.4	.56	21.7
	Dry beans, grain sorghum	15.0	2.1	31.8	1.5	17.2	1.3	18.1
	Winter wheat	15.0	2.1	34.8	.45	11.4	.06	19.9
	Pasture, range	15.3	1.7	37.2	.13	18.0	.10	22.0
	Fallow	15.0	2.1	20.9	1.0	6.16	.82	6.72
	Alfalfa	15.3	1.7	42.4	.07	18.4	.04	27.2
Bridget, McCook, Duroc, Bankard, Las, Glenburg	Corn	16.3	.78	36.1	1.2	17.5	1.1	20.9
	Dry beans, grain sorghum	16.3	.78	31.8	2.3	16.6	2.1	17.7
	Winter wheat	16.3	.78	34.8	.79	10.6	.24	18.7
	Pasture, range	16.8	.24	37.2	.41	16.8	.37	20.8
	Fallow	16.3	.78	20.9	1.9	5.59	1.7	6.27
	Alfalfa	16.8	.24	42.4	.19	17.4	.16	25.8
Jayem, Haxtun, Rosebud, Keith	Corn	16.3	.78	36.1	1.3	17.5	1.3	21.1
	Dry beans, grain sorghum	16.3	.78	31.8	2.5	16.6	2.4	17.9
	Winter wheat	16.3	.78	34.8	.85	10.3	.32	18.8
	Pasture, range	16.8	.24	37.2	.56	16.8	.52	20.9
	Fallow	16.3	.78	20.9	2.1	5.65	1.9	6.49
	Alfalfa	16.8	.24	42.4	.25	17.2	.21	25.8
Valent, Valentine, Tassel	Corn	16.8	.24	36.1	2.6	17.5	2.5	21.8
	Dry beans, grain sorghum	16.8	.24	31.8	3.9	16.9	3.8	18.8
	Winter wheat	16.8	.24	34.8	1.5	9.20	1.2	19.1
	Pasture, range	16.8	.24	37.2	1.5	16.6	1.5	21.9
	Fallow	16.3	.78	20.9	3.0	5.84	2.9	7.53
	Alfalfa	16.8	.24	42.4	.77	16.6	.74	26.4

Table 11. Output from soil-water program, given as annual averages, 1951–89, using data from the Haigler, Imperial, and Madrid weather stations—Continued

Soil series	Land use	Annual average (inches)						
		I	RO	ET	DPI	CIR	DPD	STD
		Imperial (precipitation, 19.0 inches per year)						
Rosebud, Alliance, Kuma, Goshen, Keith	Corn	18.0	1.0	33.2	1.7	14.3	1.6	16.8
	Dry beans, grain sorghum	18.0	1.0	29.3	3.4	13.8	3.1	14.4
	Winter wheat	18.0	1.0	31.7	1.1	9.08	.24	13.9
	Pasture, range	18.7	.32	34.2	.72	13.6	.61	16.1
	Fallow	16.8	2.2	19.1	2.4	4.12	2.1	4.31
	Alfalfa	18.7	.32	38.9	.27	14.6	.19	20.4
Ulysses, Keith, Colby	Corn	16.4	2.6	33.2	.95	15.3	.86	17.7
	Dry beans, grain sorghum	16.4	2.6	29.3	2.4	14.5	2.0	14.9
	Winter wheat	16.8	2.2	31.7	.75	9.80	.09	14.9
	Pasture, range	18.0	1.0	34.2	.41	14.1	.34	16.5
	Fallow	16.4	2.6	19.1	1.9	4.20	1.6	4.27
	Alfalfa	18.0	1.0	38.9	.19	15.3	.12	21.0
Colby, Canyon, Ulysses	Corn	16.4	2.6	33.2	1.0	15.3	.96	17.7
	Dry beans, grain sorghum	16.4	2.6	29.3	2.5	14.5	2.2	15.0
	Winter wheat	16.4	2.6	31.7	.66	9.85	.07	15.3
	Pasture, range	16.8	2.2	34.2	.32	15.0	.27	17.6
	Fallow	16.4	2.6	19.1	2.0	4.25	1.7	4.38
	Alfalfa	16.8	2.2	38.9	.15	15.9	.10	22.2
Jayem, Haxtun, Rosebud, Keith	Corn	18.0	1.0	33.2	2.2	14.5	2.1	17.3
	Dry beans, grain sorghum	18.0	1.0	29.3	3.9	14.1	3.7	14.9
	Winter wheat	18.0	1.0	31.7	1.2	8.61	.38	14.0
	Pasture, range	18.7	.32	34.2	1.1	13.7	1.1	16.5
	Fallow	18.0	1.0	19.1	3.5	3.88	3.2	4.29
	Alfalfa	18.7	.32	38.9	.43	14.4	.36	20.6
Valent, Valentine, Tassel	Corn	18.7	.32	33.2	3.8	14.8	3.7	18.2
	Dry beans, grain sorghum	18.7	.32	29.3	5.4	14.4	5.3	15.9
	Winter wheat	18.7	.32	31.7	2.1	7.40	1.7	14.6
	Pasture, range	18.7	.32	34.2	2.4	13.9	2.4	17.8
	Fallow	18.0	1.0	19.0	4.3	4.3	4.2	5.34
	Alfalfa	18.7	.32	38.9	1.2	14.0	1.2	21.4
		Madrid (precipitation, 19.1 inches per year)						
Rosebud, Alliance, Kuma, Goshen, Keith	Corn	18.1	1.0	33.9	1.7	14.6	1.5	17.3
	Dry beans, grain sorghum	18.1	1.0	29.9	3.5	14.3	3.3	15.0
	Winter wheat	18.1	1.0	31.8	.89	8.51	.26	13.9
	Pasture, range	18.8	.30	34.7	.61	13.9	.49	16.4
	Fallow	17.0	2.1	19.4	2.3	4.20	2.1	4.44
	Alfalfa	18.8	.30	39.7	.23	15.0	.15	21.0

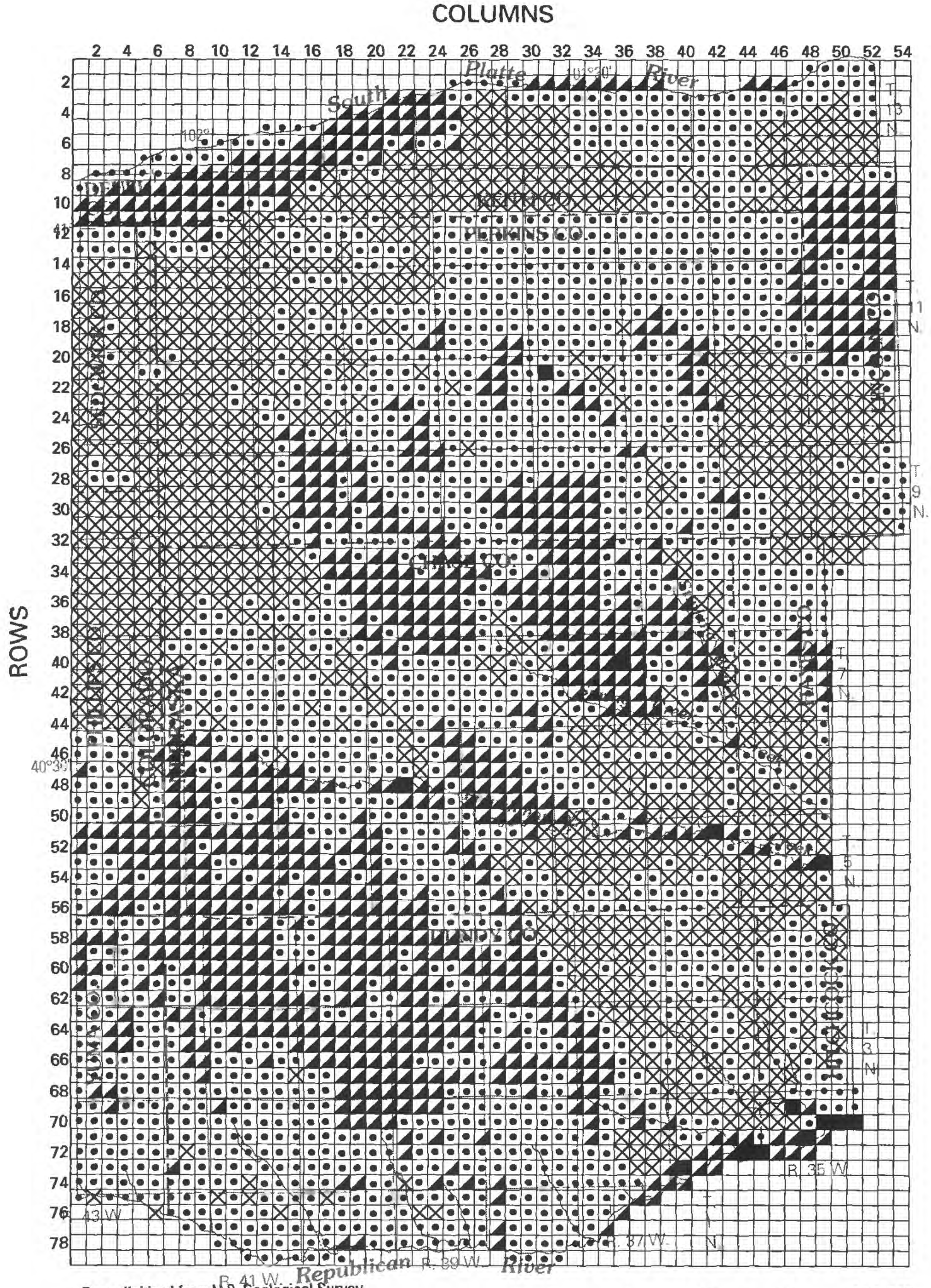
Table 11. Output from soil-water program, given as annual averages, 1951–89, using data from the Haigler, Imperial, and Madrid weather stations—Continued

Soil series	Land use	Annual average (inches)						
		I	RO	ET	DPI	CIR	DPD	STD
	Madrid (precipitation, 19.1 inches per year)—Continued							
Jayem, Haxtun, Rosebud, Keith	Corn	18.1	1.0	33.9	2.2	14.9	2.1	17.9
	Dry beans, grain sorghum	18.1	1.0	29.9	4.0	14.6	3.9	15.6
	Winter wheat	18.1	1.0	31.8	.95	8.03	.38	14.0
	Pasture, range	18.8	.30	34.7	1.1	14.0	1.0	16.9
	Fallow	18.1	1.0	19.4	3.5	4.04	3.3	4.54
	Alfalfa	18.8	.30	39.7	.37	14.8	.30	21.2
Jayem, Sarben, Valent, Hersch, Valentine	Corn	18.1	1.0	33.9	2.7	15.1	2.6	18.4
	Dry beans, grain sorghum	18.1	1.0	29.9	4.4	14.8	4.3	16.0
	Winter wheat	18.1	1.0	31.8	1.0	7.66	.53	14.1
	Pasture, range	18.1	1.0	34.7	1.3	14.5	1.2	17.8
	Fallow	18.1	1.0	19.4	3.9	4.20	3.7	4.96
	Alfalfa	18.1	1.0	39.7	.53	15.0	.47	22.0
Gothenburg, Platte, Las, Las Animas	Corn	18.1	1.0	33.9	2.8	15.2	2.8	18.6
	Dry beans, grain sorghum	18.1	1.0	29.9	4.6	14.9	4.5	16.2
	Winter wheat	18.8	.30	31.8	1.3	7.29	.80	13.8
	Pasture, range	18.8	.30	34.7	1.7	14.1	1.6	17.5
	Fallow	18.1	1.0	19.4	4.0	4.25	3.9	5.10
	Alfalfa	18.8	.30	39.7	.70	14.6	.64	21.5
Valent, Valentine, Tassel	Corn	18.8	.30	33.9	3.9	15.3	3.9	19.0
	Dry beans, grain sorghum	18.8	.30	29.9	5.6	15.0	5.5	16.6
	Winter wheat	18.8	.30	31.8	1.7	6.83	1.4	14.4
	Pasture, range	81.8	.30	34.7	2.4	14.2	2.3	18.2
	Fallow	18.1	1.0	19.4	4.5	4.45	4.4	5.69
	Alfalfa	18.8	.30	39.7	1.3	14.4	1.2	22.1

method was a qualitative comparison of simulated and observed water-level surfaces for spring 1989. This comparison is subjective because of the interpretive character of the contoured surfaces. The simulated spring 1989 water table (fig. 23) compares favorably with the observed spring 1989 water table (fig. 7). The differences between these two water tables are illustrated in figure 24. The differences are within 10 feet for much of the study area, with maximum differences less than 40 feet in a small area in Dundy County near the Republican River.

A second, more objective, method was an error analysis of simulated and observed 1989 water tables. The RMSE was used as an indication of how closely these two water tables match. The RMSE of the computed and observed 1989 water tables is 8.8 feet for the 3,638 active cells within the study area. This error is less than the 10-foot contour interval used in drawing the observed 1952 and 1989 water-table configuration maps.

A third method consisted of comparing measured and simulated streamflows in the study area (table 12). Only the interior streams were evaluated because the boundary streams are regulated by upstream reservoirs and were simulated as constant-head cells. The simulated streamflows are calculated for January 1 through May 31, 1989. Measured streamflows are the mean seasonal values. An examination



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

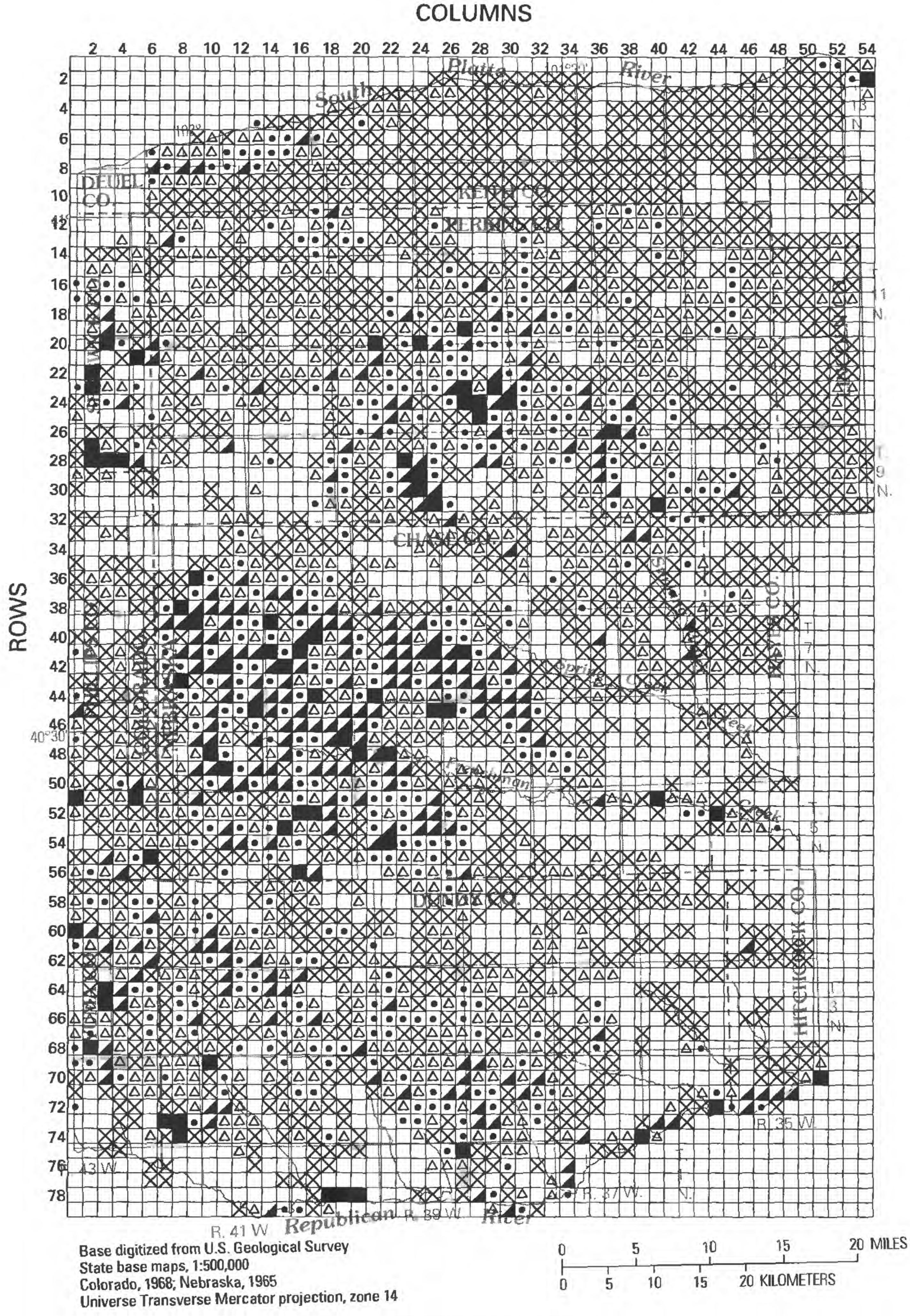
0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS

EXPLANATION

Average recharge 1952–88, in inches per year

- ☐ Inactive cell
- ☒ 0 to 1.00
- ⊡ 1.01 to 2.00
- ◪ 2.01 to 3.00
- ■ more than 3.00

Figure 20. Average recharge assigned to model cells for 1952–88.



EXPLANATION

Pumpage for June–August 1988 stress period, in inches

- No water applied
- 0 to 2.50
- 2.51 to 5.00
- 5.01 to 7.25
- 7.26 to 10.00
- More than 10.00

Figure 21. Pumpage assigned to cells for the June–August 1988 stress period.

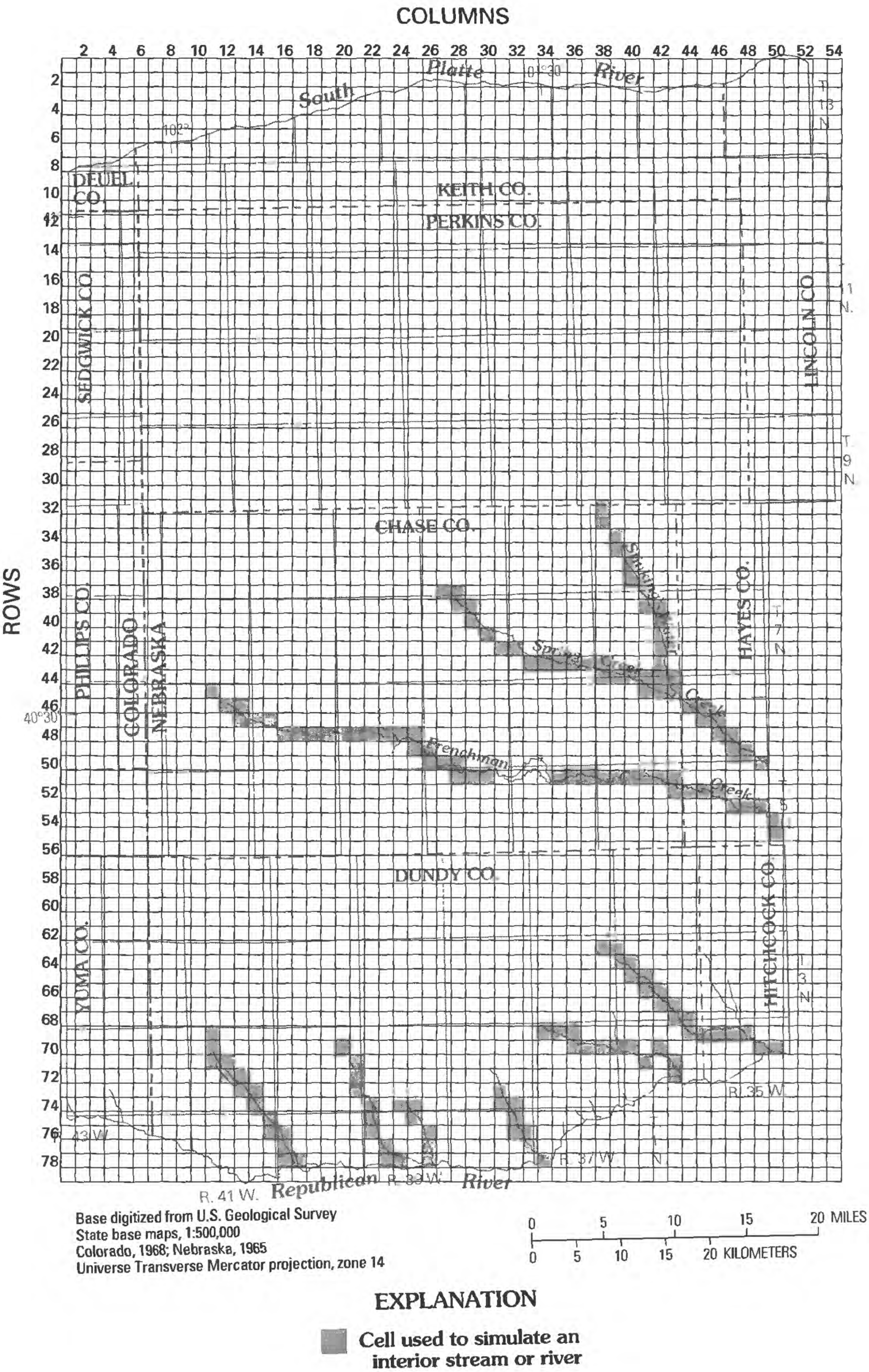
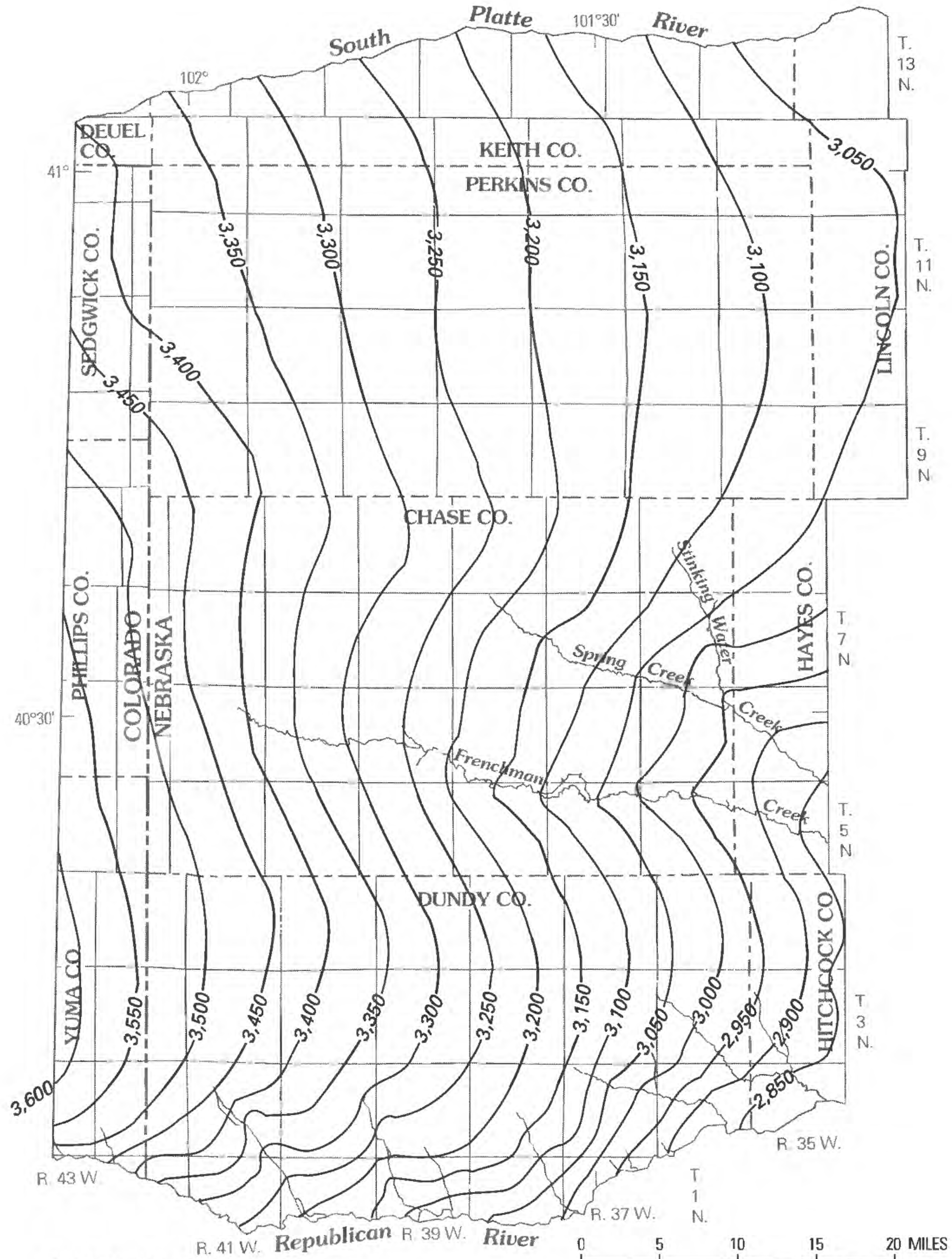


Figure 22. Cells used to simulate interior streams and rivers using the stream-routing package.

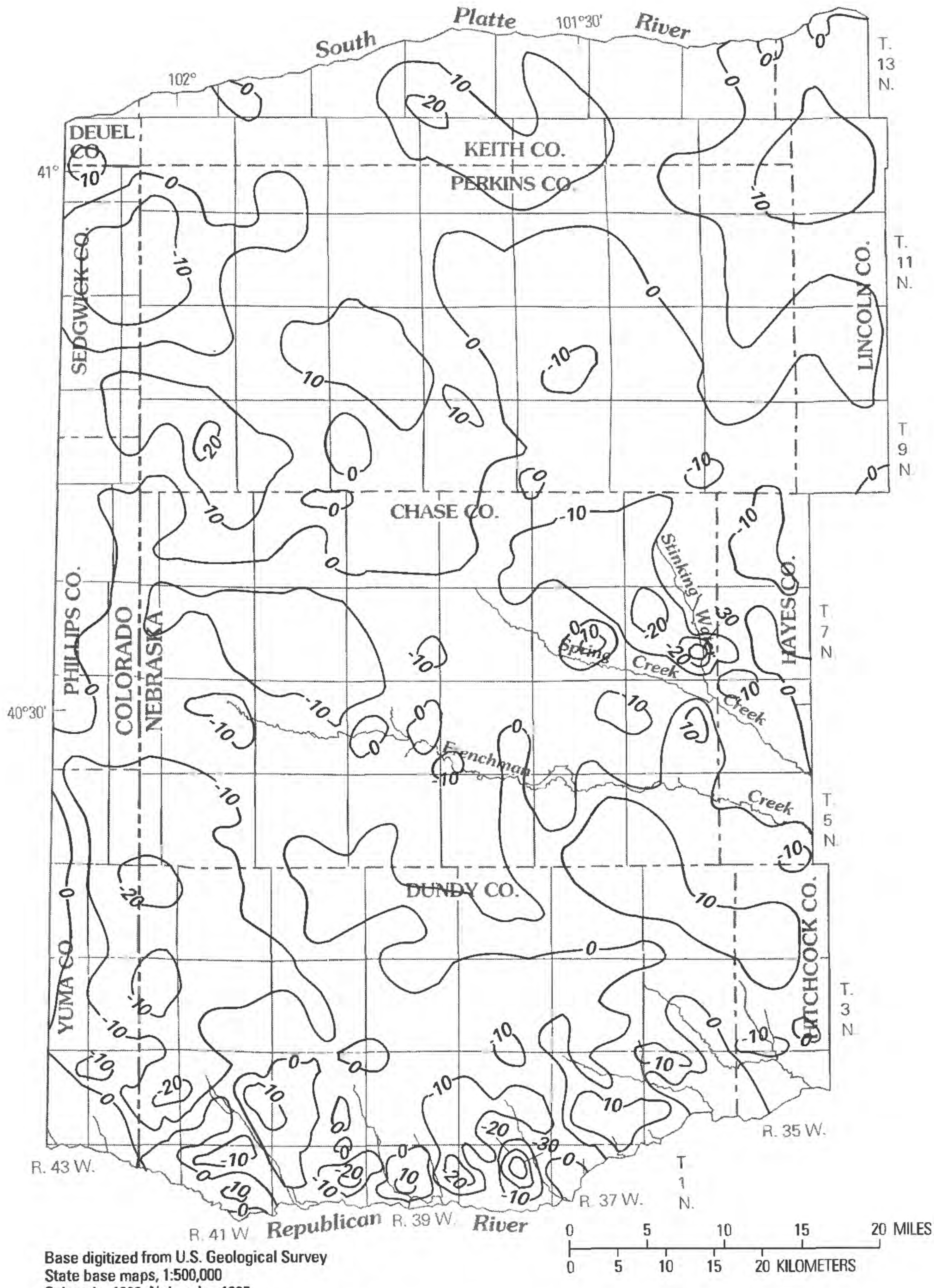


Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

—*3,100*— **Simulated water-table contour**—Shows altitude of water table, spring 1989. Datum is sea level. Contour interval 50 feet

Figure 23. Simulated water-table altitude in the High Plains aquifer, spring 1989.



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

—20— **Line of equal difference between simulated and observed water-table altitudes**—Positive value indicates that simulated value is greater than observed. Negative (-) value indicates that simulated value is less than observed. Interval 10 feet

Figure 24. Difference between simulated and observed spring 1989 water-table altitudes in the High Plains aquifer.

Table 12. Comparison of measured and simulated streamflow at selected seepage-measurement sites in the study area

[1952 measured flow from Lappala (1978); 1989 measured flow from U.S. Geological Survey (1990); --, no measurement]

Seepage-measurement site and streamflow-gaging station number (fig. 14)	Cell (row, column) (fig. 15)	Streamflow, in cubic feet per second		
		Measured fall 1952	Measured spring 1989	Simulated May 31, 1989
Stinking Water Creek (above Spring Creek)	(44, 43)	--	7.0	3.9
Spring Creek	(45, 42)	--	10.4	12.2
Stinking Water Creek near Wauneta (includes Spring Creek in Chase County)	(50, 49)	21	22.9	32.2
Frenchman Creek near Imperial (6831500)	(51, 31)	66	26.4	32.6
Buffalo Creek near Haigler (6823500)	(78, 17)	11	6.1	11.8
Rock Creek at Parks (682400)	(78, 24)	15	11.2	11.4
Horse Creek near Parks	(78, 26)	2[1]	.56	.59
Spring Creek near Benkelman	(78, 34)	1[1]	.18	.19
Indian Creek near Max	(72, 43)	4[2]	3.7	10.1
Muddy Creek near Republican River	(70, 50)	--	1.7	6.6

[1]Average, daily flow, October.

[2]Computed analytically by Lappala (1978, p. 123, using equation on p. 104).

of measured and simulated streamflows shows a reasonable match between these values.

A fourth method of assessing the accuracy of the transient calibration of the model is a comparison through time of simulated versus measured water levels at observation wells. Measured water levels in six observation wells (fig. 25) and simulated water levels in the model cell in which the wells are located were plotted and compared for the period 1952–89. Hydrographs of these six wells are shown in figures 26–28. The simulated and measured water levels for all these sites have similar trends and show reasonable agreement in their water levels for this time period. Because the simulated water levels follow the same trends as the measured water levels in the observation wells, the ground-water-flow model appears to be accurately simulating the response of the High Plains aquifer to stress through time.

Water Budget

Analysis of model-simulated ground-water flow revealed the magnitude of flow into and out of the High Plains aquifer in the study area. During the cali-bration period of June 1, 1952, through May 31, 1989, the net decrease in ground-water storage was 6.25×10^6 acre-feet (table 13). The recharge to the ground-water system from deep percolation of precipitation was 1.03×10^7 acre-feet. The stream leakage of ground water into streams was 7.16×10^6 acre-feet. The net volume of ground water moving into or out of the constant-head cells was 1.48×10^6 acre-feet from the aquifer to the constant-head cells. Also, the net volume of ground water moving into or out of the general-head boundaries was 3.87×10^5 acre-feet from the aquifer into the general-head boundaries. Finally, pumpage from the aquifer removed 7.51×10^6 acre-feet of water from storage during the calibration period.

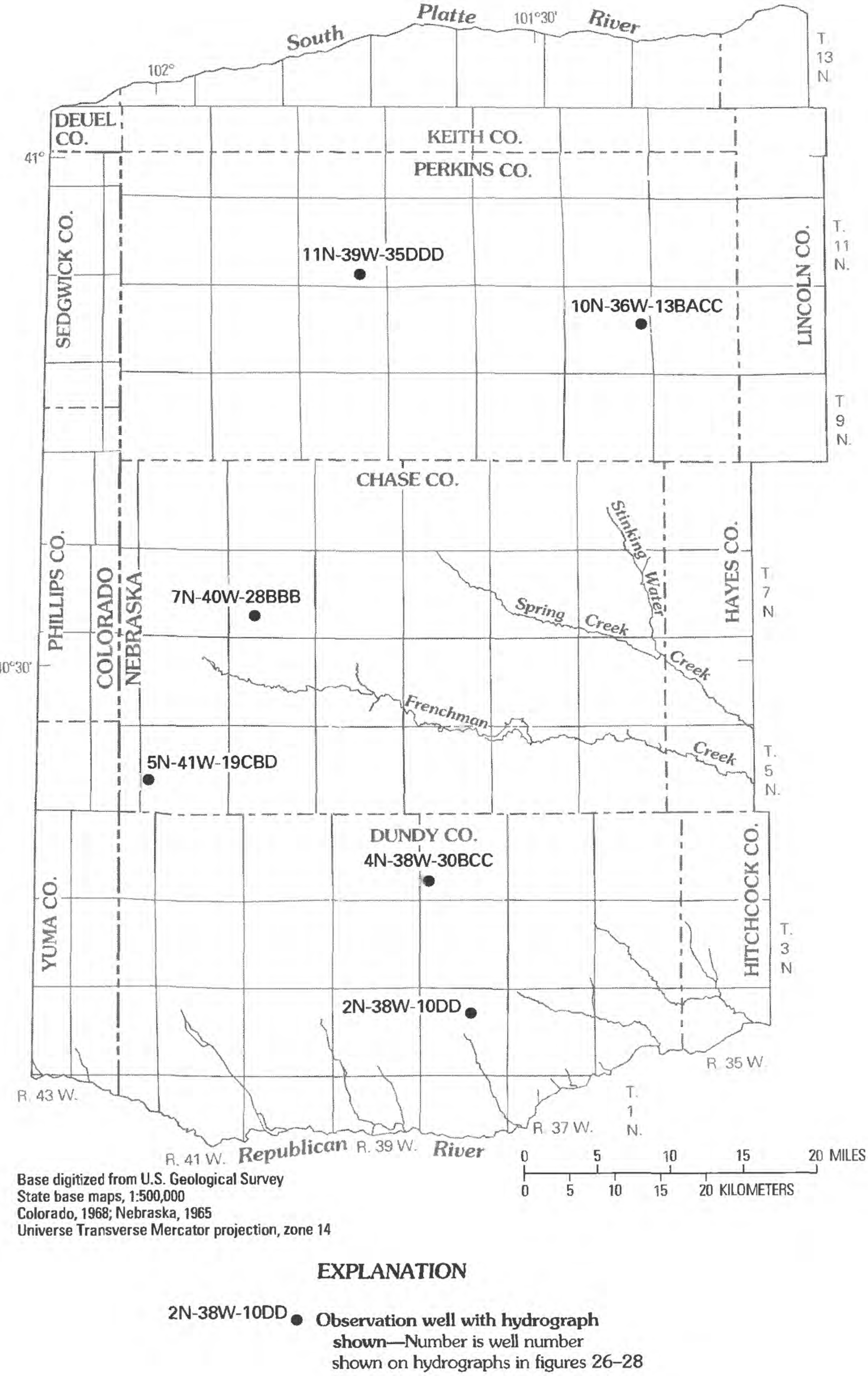


Figure 25. Location of observation wells with long-term hydrographs shown in figures 26–28.

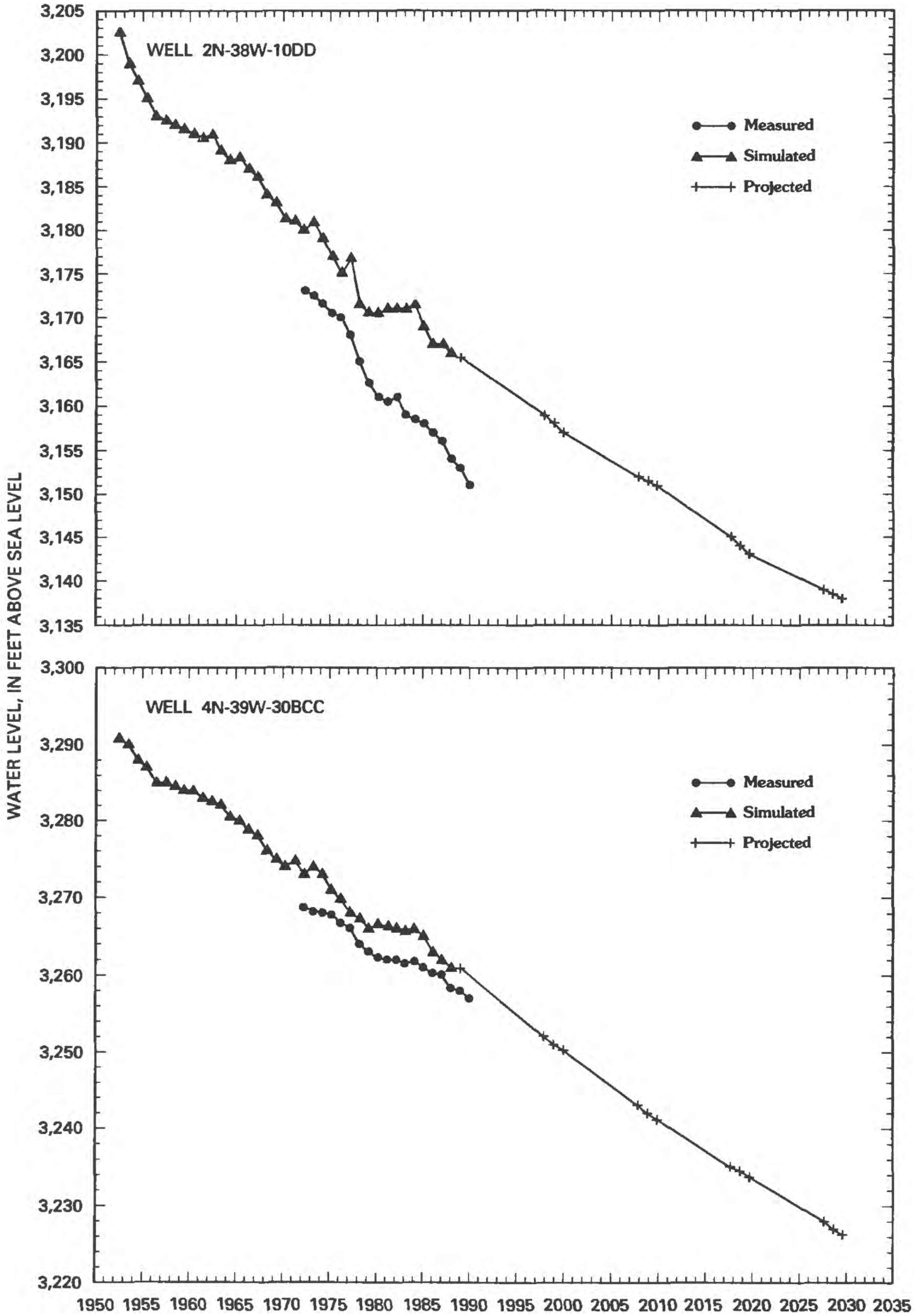


Figure 26. Hydrographs showing measured, simulated, and projected water levels for observation wells 2N-38W-10DD and 4N-38W-30BCC.

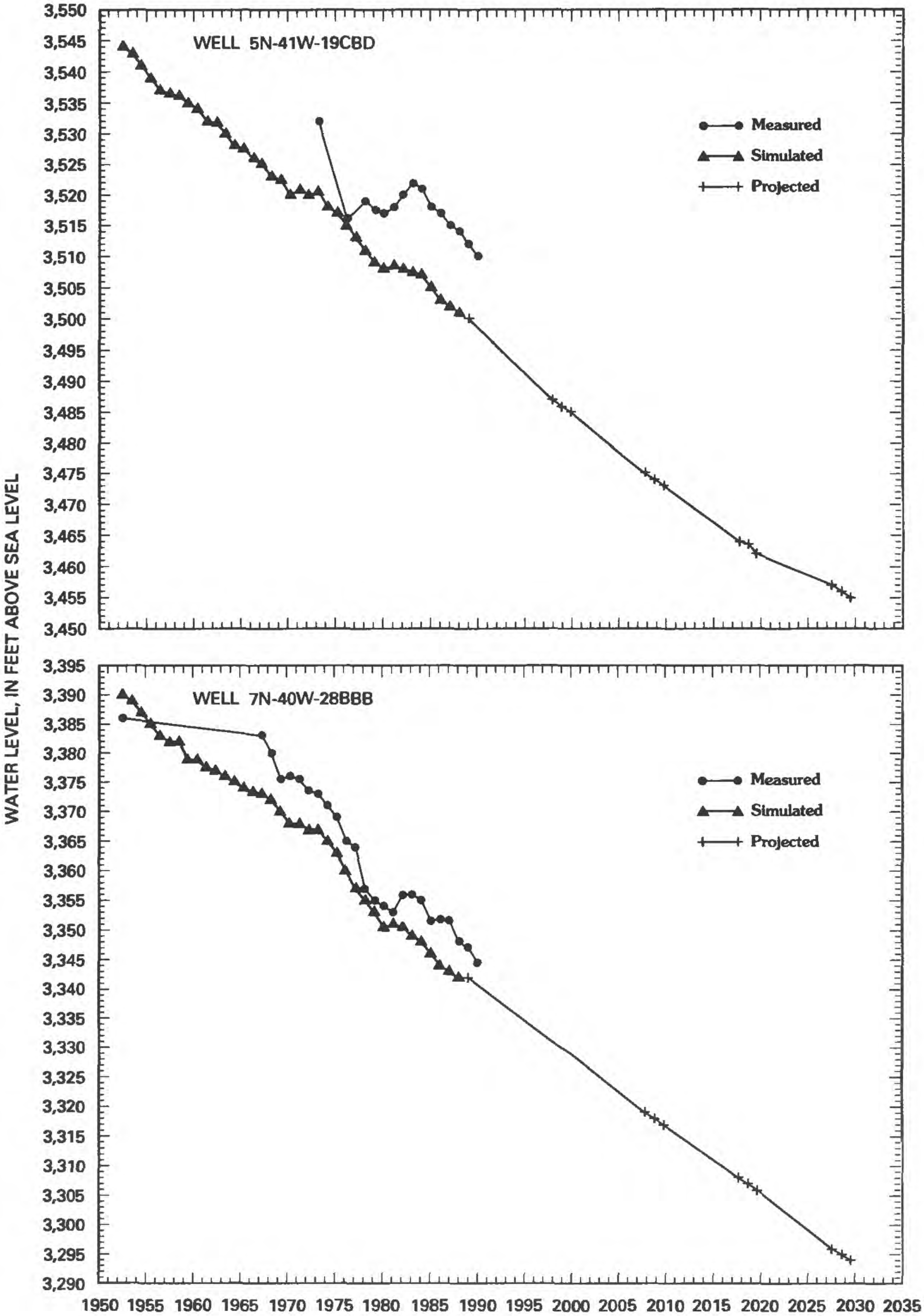


Figure 27. Hydrographs showing measured, simulated, and projected water levels for observation wells 5N-41W-19CBD and 7N-40W-28BBB.

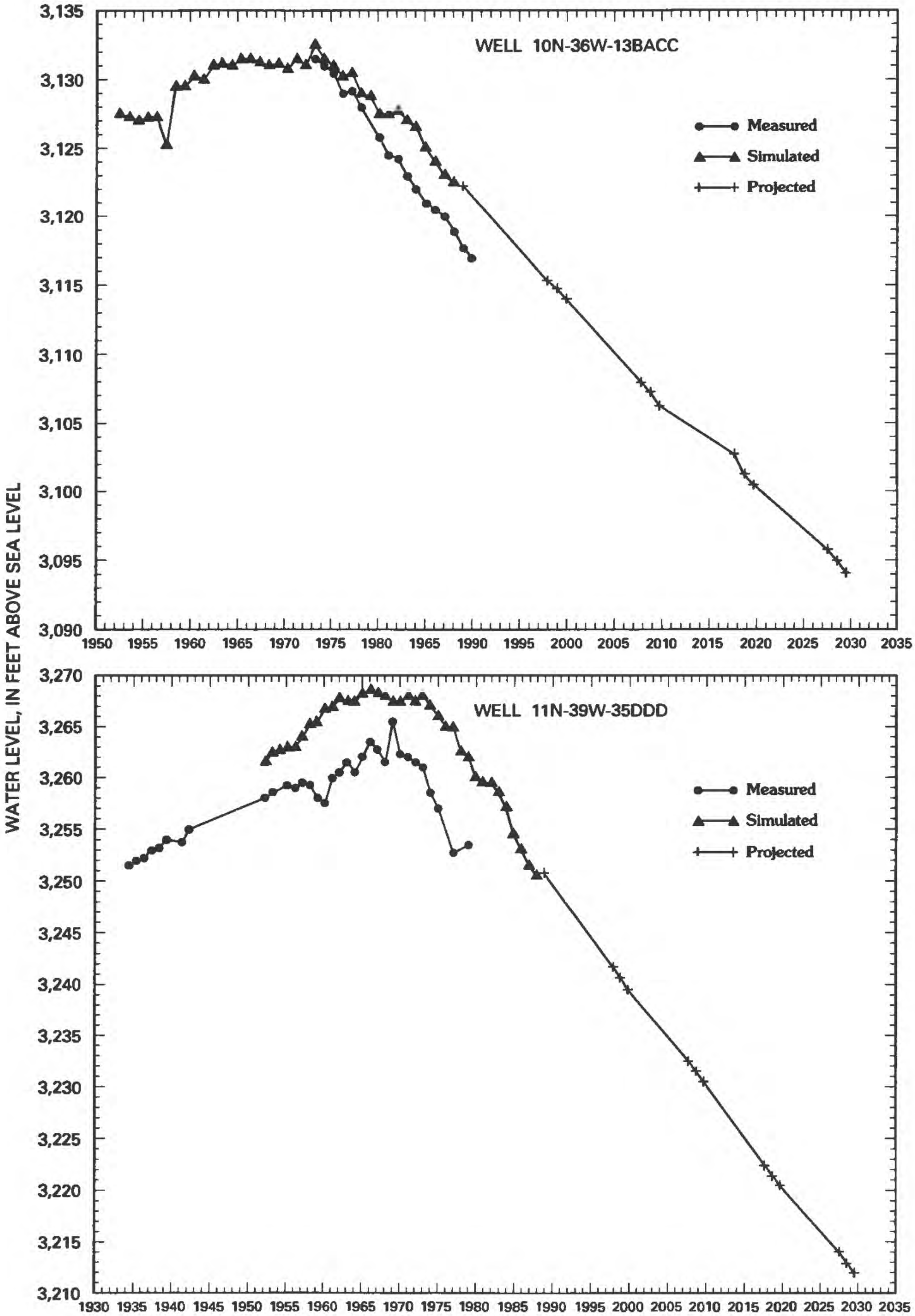


Figure 28. Hydrographs showing measured, simulated, and projected water levels for observation wells 10N-36W-13BACC and 11N-39W-35DDD.

Table 13. Simulated water budget for summer 1952 to spring 1989, and 1988

Source or sink	Volume of water moved into aquifer (thousands of acre-feet)		Volume of water moved out of aquifer (thousands of acre-feet)
	For summer 1952 to spring 1989		
Constant head	712		2,192
Wells	0		7,514
Recharge	10,288		0
General head	1,666		2,052
Interior streams	457		7,613
Total	13,123		19,371
Change in storage =		-6,248	
	For 1988		
Constant head	20		59
Wells	0		483
Recharge	386		0
General head	52		54
Interior streams	15		136
Total	473		732
Change in storage =		-259	

Sensitivity Analysis

The sensitivity of the model to changes in hydraulic conductivity, specific yield, recharge, and pumpage was evaluated by numerous steady-state and transient simulations in which only one of these model parameters was varied at a time, and the model results were compared with calibration model results. On the basis of these simulations, the model was determined to be most sensitive to variations in recharge and pumpage and more sensitive to variations in specific yield than to variations in hydraulic conductivity.

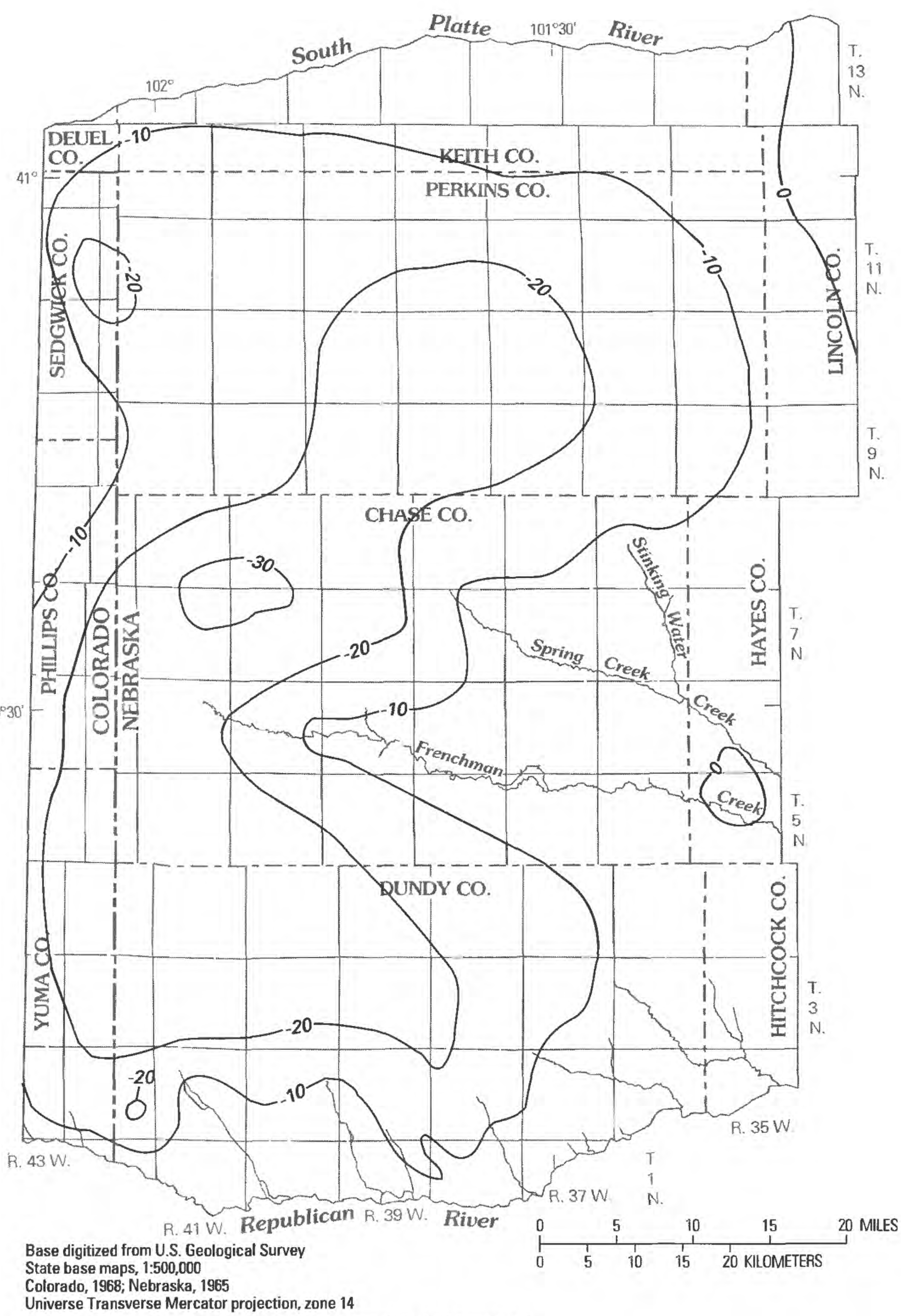
SIMULATED RESPONSE TO GROUND-WATER WITHDRAWALS

For this study, the calibrated model was used to estimate possible effects of future ground-water withdrawals on water levels in the High Plains aquifer and on streamflows in the study area. The long-term effects of two different pumping scenarios, the consumptive-irrigation-requirement scenario and the 13-inch scenario, were estimated by comparing simulated water levels in the aquifer during the years 2010 and 2030 for each of the scenarios to water levels in the aquifer in 1989.

All model parameters were the same for each scenario except for the pumpage and recharge values used. It was assumed for both scenarios that no additional well development occurs during the period of the simulation (June 1989 through May 2030).

Consumptive-Irrigation-Requirement Scenario

The first pumping scenario examined long-term effects on ground-water levels and streamflows if pumpage for 1989–2030 for each model cell was equal to the average CIR used during the model-calibration period (1952–89) and recharge was equal to the recharge for the same period. Simulated changes in water levels from 1989 to 2010 and 2030, resulting from long-term pumping at this rate, are shown in figures 29 and 30, respectively. The maximum simulated declines for both time periods occurred in northwestern Chase County. The hydrographs shown in figures 26, 27, and 28 illustrate the steady water-level declines simulated as a result of this scenario. The simulated saturated thickness of the High Plains



EXPLANATION

—*-20*— **Line of equal projected water-level change—**
Negative (-) value indicates water-level decline.
Interval 10 feet

Figure 29. Projected water-level changes in the High Plains aquifer, 1989–2010, using consumptive-irrigation-requirement pumping scenario.

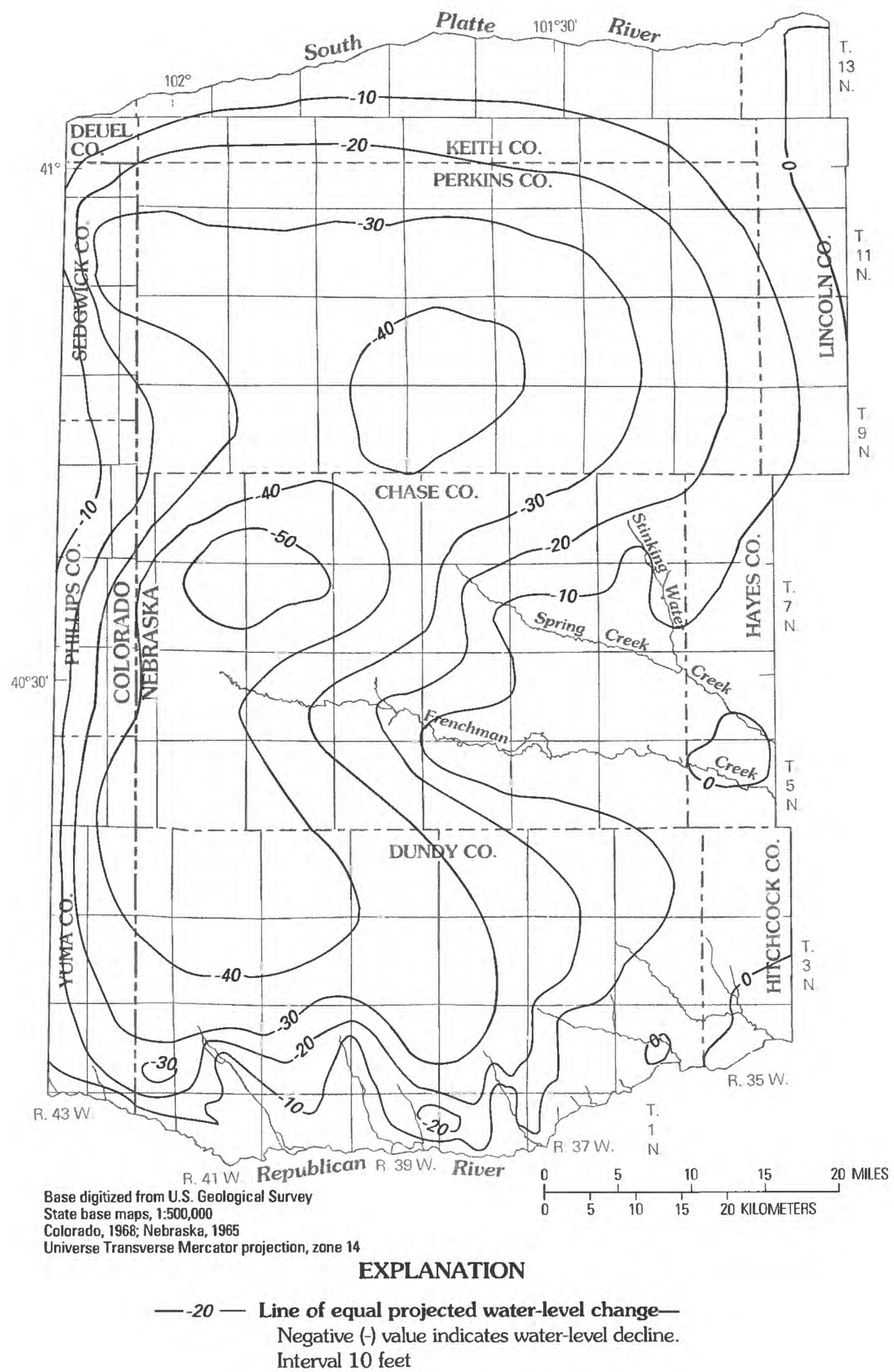


Figure 30. Projected water-level changes in the High Plains aquifer, 1989–2030, using consumptive-irrigation-requirement pumping scenario.

aquifer in 2030 resulting from this scenario is shown in figure 31. The simulated effects of this pumping scenario on streamflow at selected sites are listed in table 14. For example, the simulated stream-flow in Frenchman Creek near Imperial at the end of May 1989 was 32.6 cubic feet per second (table 14), whereas the simulated streamflow at the same location on May 31, 2030, was only 10.2 cubic feet per second (table 14).

"13-Inch" Scenario

The second pumping scenario examined long-term effects on water levels using a single, constant withdrawal rate instead of the variable CIR-based withdrawal rate in the first scenario. The second scenario predicted the effects of the pumpage and application of 13 inches of water to irrigated fields during the irrigation season (June–August) of each year. Several other similar scenarios were simulated with different application rates. The results of these other similar scenarios are not presented here for brevity. The recharge to nonirrigated lands in nonirrigation periods was not considered in any of these constant withdrawal rate scenarios because it greatly simplified the model preparation to run these scenarios and did not significantly influence the simulation results for these scenarios. Under the 13-inch scenario, maximum water-level declines by the years 2010 (fig. 32) and 2030 (fig. 33) were about 40 and 90 feet, respectively, in northwestern Chase County. The simulated saturated thickness of the High Plains aquifer in 2030 resulting from this scenario is shown in figure 34. The flow in Frenchman Creek near Imperial on May 31, 2030, was predicted to be only 1.6 cubic feet per second (table 14).

LIMITATIONS OF THE MODEL

This ground-water-flow model was developed to evaluate regional management scenarios. Because of the scale of the model, estimates of water-level and streamflow changes are regional in scope. Therefore, the model should not be used to simulate aquifer responses at individual wells.

The model was designed to handle ground-water-flow simulation problems. It is not an optimization model. The model may be used to simulate the response of the ground-water system to specific pumping scenarios, but it is unable to estimate directly the pumping scenario required to cause a specific response within the system.

This model was specifically designed to simulate the ground-water flow in the Upper Republican NRD. In areas outside the Upper Republican NRD to the east and west, boundary conditions might affect the accuracy of the simulation results.

SUMMARY

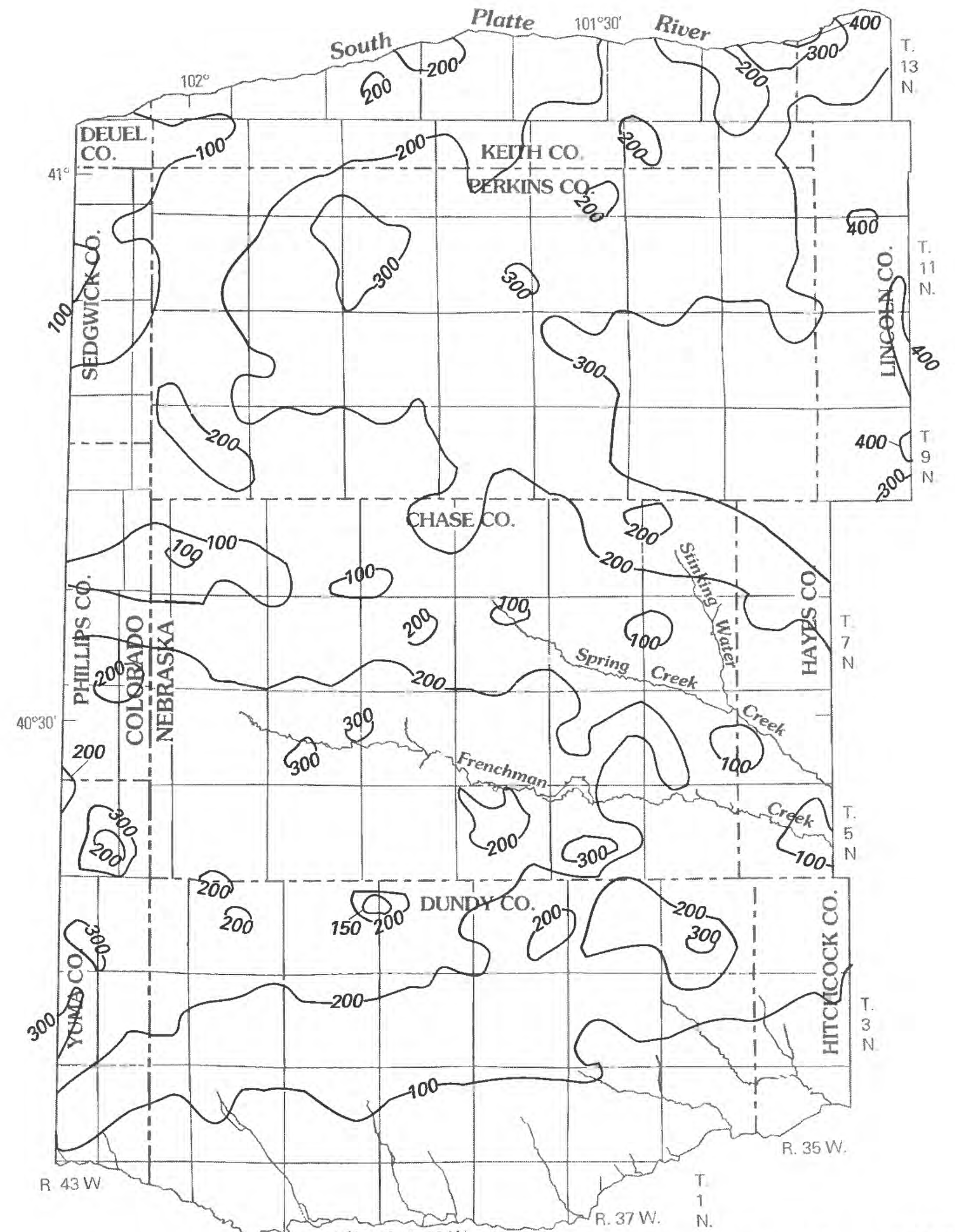
Concern over declining water levels in the High Plains aquifer in the Upper Republican NRD and the decreasing accuracy of an existing ground-water-flow model of the Upper Republican NRD prompted the USGS, as part of continuing cooperative studies with the NRD and the Nebraska Natural Resources Commission, to update this model. The updated model used more recent data and modeling techniques to more accurately simulate ground-water flow in the study area.

The principal aquifer in the study area is the High Plains aquifer. It is confined below by the relatively impermeable White River Group or Pierre Shale. The hydraulic conductivity of the aquifer used in the model ranged from 20 to 155 feet per day, and the specific yield used in the model ranged from 0.09 to 0.22.

A digital model was developed for the study area using the modular, three-dimensional, finite-difference, ground-water-flow model MODFLOW. The aquifer was represented as a single-layer, regularly spaced grid of 79 rows and 54 columns. Each row and column of the model represented a 1-mile-wide strip of aquifer.

Boundaries for the model were the South Platte, Republican, and North Fork of the Republican Rivers along the northern and southern edges of the model. These boundaries were designated by constant-head cells. General-head boundaries were used along the western and eastern edges of the study area in the absence of natural boundaries. The bottom of the aquifer was modeled as a no-flow boundary because of the generally impervious nature of the underlying rocks.

Recharge and pumpage were estimated based on soil, climate, and land-use characteristics using two previously documented computer programs, the potential evapotranspiration (PET) program and the soil-water program. Pumpage stresses were included in the model using the well package in MODFLOW, and



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

—*300*— **Line of equal projected saturated thickness—**
Interval 100 feet

Figure 31. Projected saturated thickness of the High Plains aquifer in 2030 using consumptive-irrigation-requirement pumping scenario.

Table 14. Comparison of streamflows simulated for 1989 and projected for 2010 and 2030 using the consumptive-irrigation-requirement and 13-inch scenarios at selected seepage-measurement sites in the study area

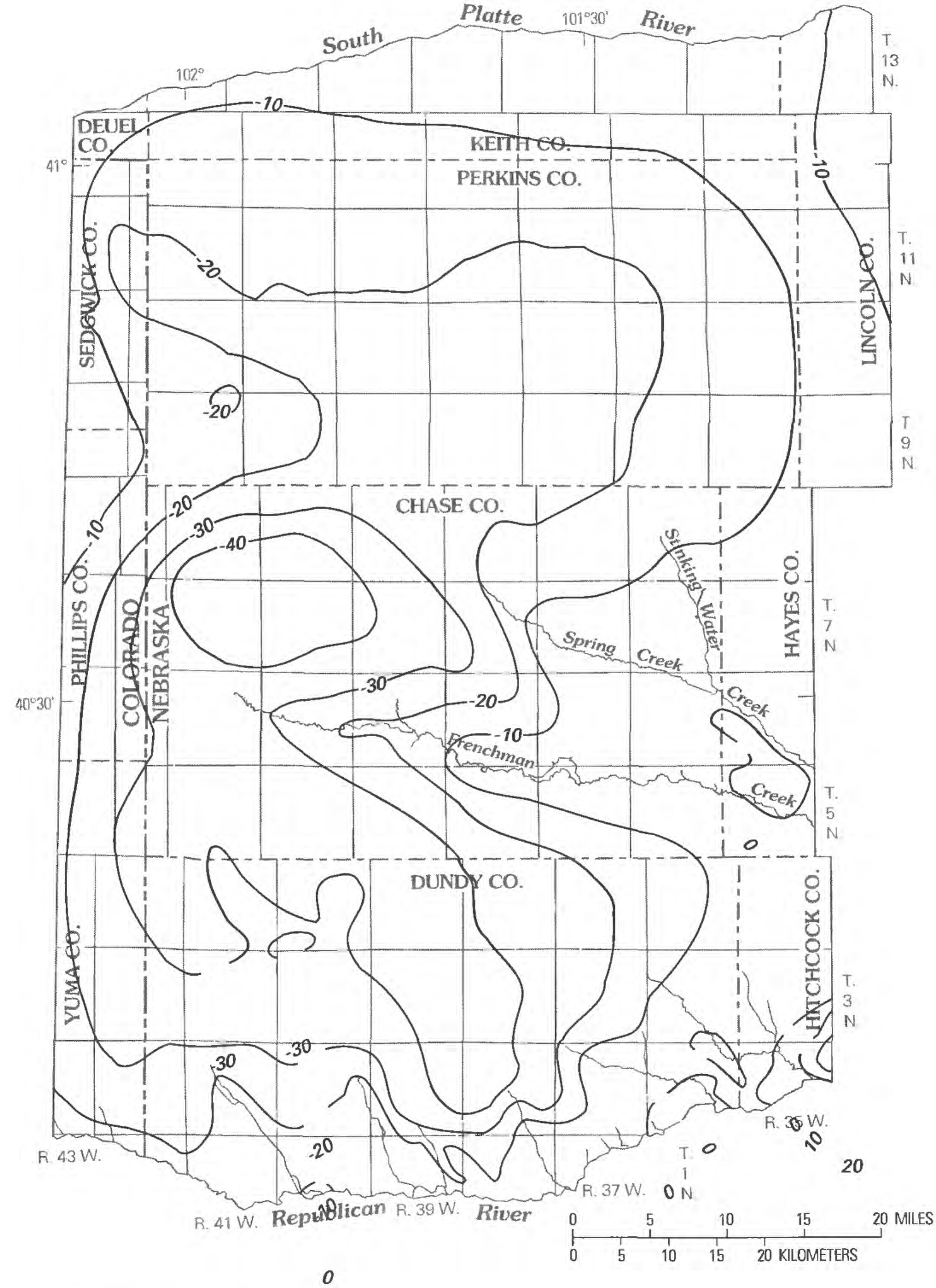
[values are given in cubic feet per second; CIR, consumptive irrigation requirement]

Seepage-measurement site and streamflow-gaging station number (fig. 14)	Cell (row, column) (fig. 15)	Simulated flow, May 31, 1989 (table 12)	Projected flows			
			CIR scenario		13-inch scenario	
			May 31, 2010	May 31, 2030	May 31, 2010	May 31, 2030
Stinking Water Creek (above Spring Creek)	(44, 43)	3.9	2.4	1.7	2.7	1.9
Spring Creek	(45, 42)	12.2	6.4	4.0	4.8	3.0
Stinking Water Creek near Wauneta (includes Spring Creek in Chase County)	(50, 49)	32.2	15.0	14.8	15.2	14.9
Frenchman Creek near Imperial (6831500)	(51, 31)	32.6	15.7	10.2	8.6	1.6
Buffalo Creek near Haigler (6823500)	(78, 17)	11.8	7.3	5.5	7.5	5.1
Rock Creek at Parks (682400)	(78, 24)	11.4	8.0	5.4	6.5	4.2
Horse Creek near Parks	(78, 26)	.59	.12	0	0	0
Spring Creek near Benkelman	(78, 34)	.19	0	0	0	0
Indian Creek near Max	(72, 43)	10.1	8.3	6.8	7.3	5.1
Muddy Creek near Republican River	(70, 50)	6.6	6.6	5.4	6.6	5.0

recharge was applied using the recharge package in MODFLOW. Stream-aquifer interaction was simulated using a stream-routing package for MODFLOW.

The model was calibrated under steady-state conditions by adjusting input data including hydraulic conductivity, streamflows assigned to the upstream reach of each stream segment, and boundary head and conductance in general-head boundary cells. Calibration under transient conditions also included adjustment of specific yield, recharge, and pumpage values. A root mean square error of 8.8 feet was obtained for the transient calibration, indicating that the model was adequately simulating transient conditions. Sensitivity analysis indicated that the model was most sensitive to recharge and pumpage and least sensitive to hydraulic conductivity. Analysis of model results indicated that over the period from June 1, 1952, to May 31, 1989, the volume of water removed from storage was 6.25 10^6 acre-feet.

Possible long-term effects of two pumping scenarios were evaluated for 1989–2030. For the first scenario, pumpage was held constant at the rate necessary to supply a crop's consumptive irrigation requirement. Simulated water-level declines resulting from this scenario were greatest in northwestern Chase County. A second scenario held pumpage constant at the rate necessary to apply 13 inches of water to irrigated crops during the irrigation season. Simulated

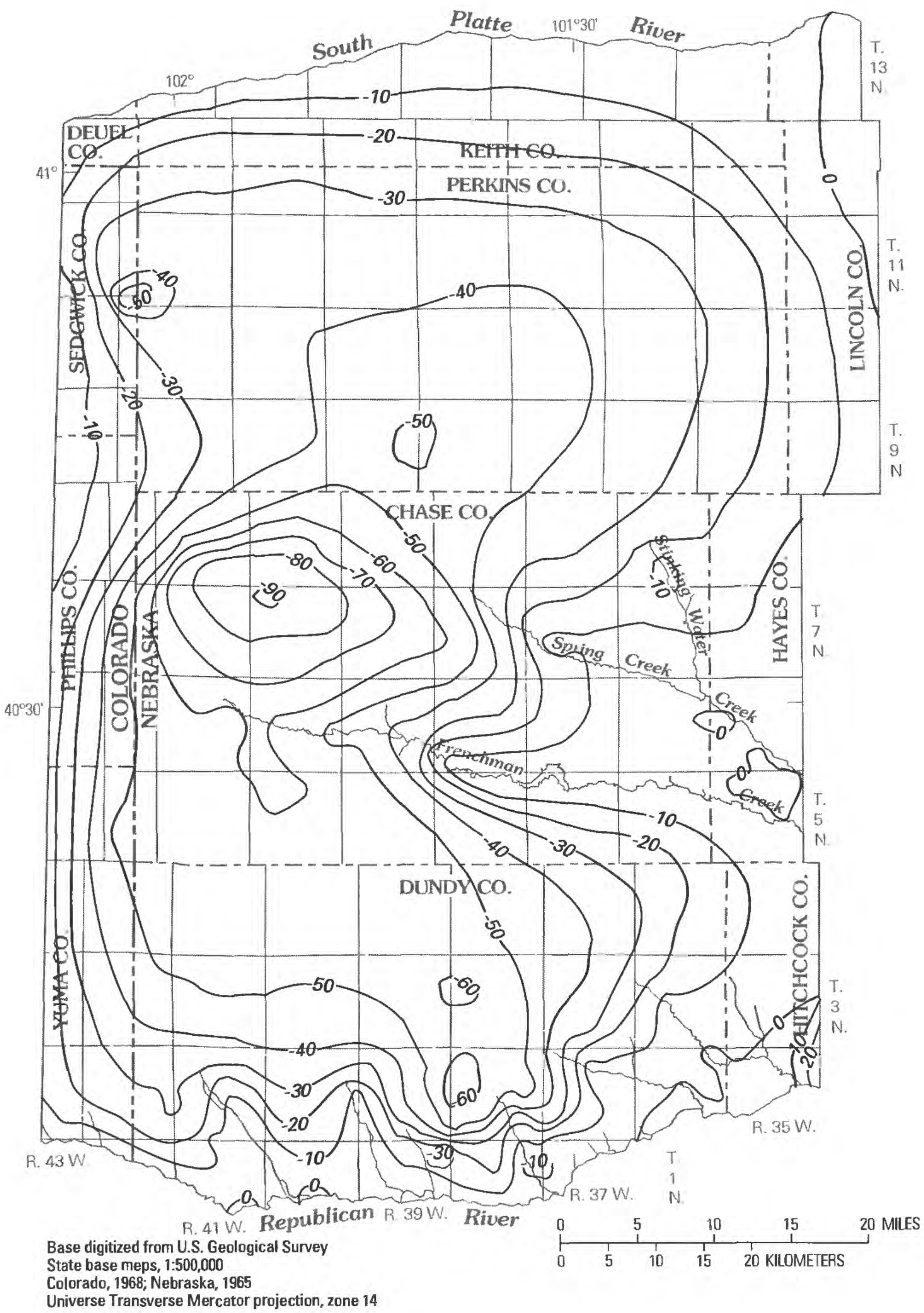


Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

EXPLANATION

-20 **Line of equal projected water-level change—**
Negative (-) value indicates water-level decline.
Positive value indicates water-level rise.
Interval 10 feet

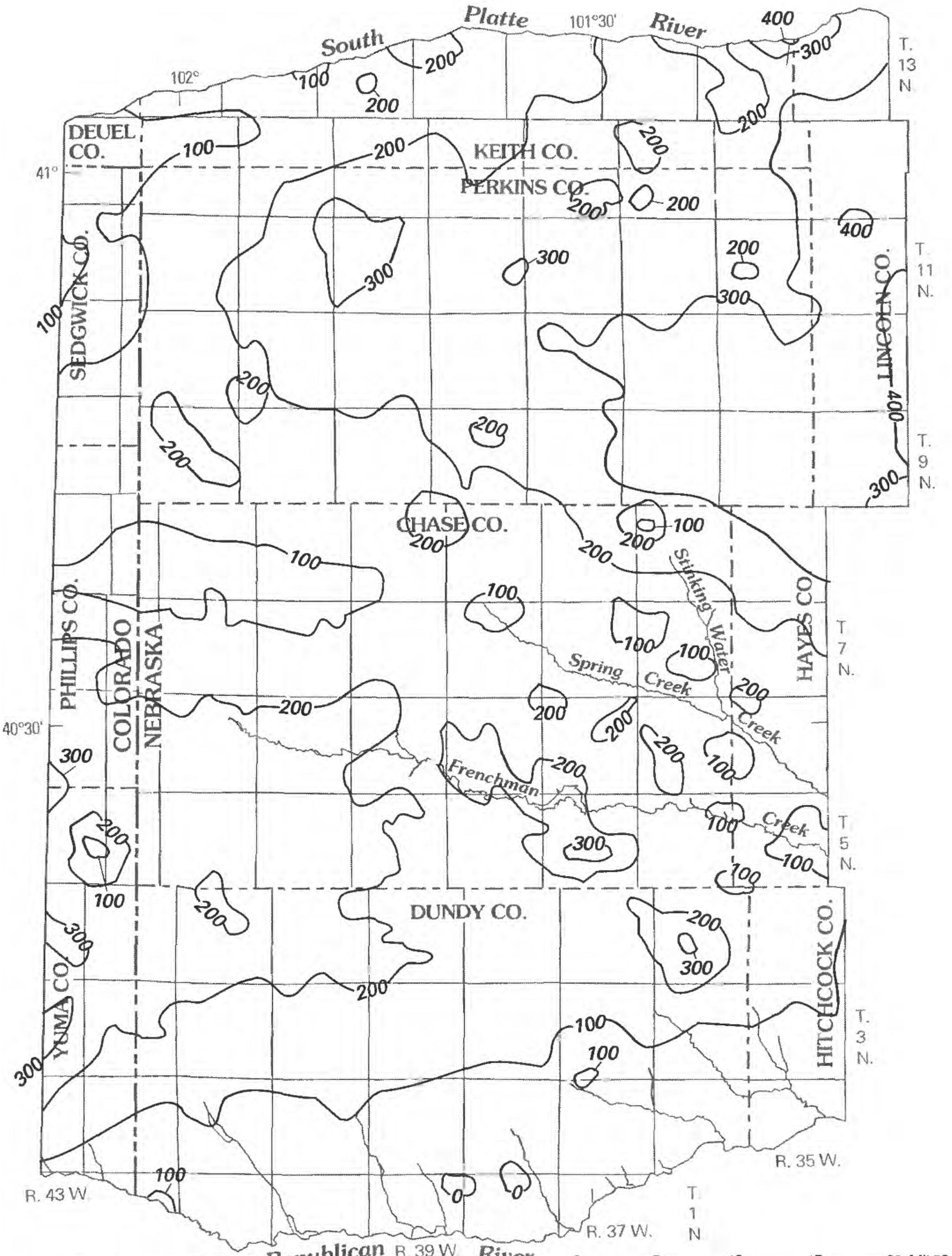
Figure 32. Projected water-level changes in the High Plains aquifer, 1989–2010, using 13-inch pumping scenario.



EXPLANATION

—— -20 —— **Line of equal projected water-level change—**
Negative (-) value indicates water-level decline.
Positive value indicates water-level rise.
Interval is 10 feet

Figure 33. Projected water-level changes in the High Plains aquifer, 1989–2030, using 13-inch pumping scenario.



Base digitized from U.S. Geological Survey
State base maps, 1:500,000
Colorado, 1968; Nebraska, 1965
Universe Transverse Mercator projection, zone 14

0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS

EXPLANATION

—300— **Line of equal projected saturated thickness—**Interval 100 feet

Figure 34. Projected saturated thickness of the High Plains aquifer in 2030 using 13-inch pumping scenario.

water-level declines resulting from this scenario were even larger than those for the first pumping scenario. Water levels would decline as much as 90 feet by 2030 in northwestern Chase County.

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