HYDROLOGIC ANALYSIS OF THE HIGH PLAINS AQUIFER SYSTEM IN BOX BUTTE COUNTY, NEBRASKA

By Robert A. Pettijohn and Hsiu-Hsiung Chen

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) METRIC UNITS

Multiply inch-pound units	By	To obtain SI units
acre	4,047	square meter
acre-foot	1,233	cubic meter
foot	0.3048	meter
cubic foot	0.02832	cubic meter
cubic foot per second	0.02832	cubic meter per second
foot per day	0.03048	meter per day
inch	25.40	millimeter
inch per hour	25.40	millimeter per hour
inch per year	25.40	millimeter per year
gallon per minute per foot	0.2070	liter per second per meter
mile	1.609	kilometer
square mile	2.590	square kilometer
foot per mile	0.1894	meter per kilometer

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ABSTRACT

Irrigation development in Box Butte County, an area of 1,067 square miles on a plain in northwestern Nebraska began about 40 years ago. Since then, pumpage of ground water has caused a steady decline of water levels in the High Plains aquifer system underlying the east-central part of the County. Comparison of maps of the potentiometric surfaces of the aquifer system in 1938 and 1980 indicates that water levels declined by more than 10 feet in an area of 336 square miles and by more than 30 feet in an area of 17 square miles.

Quantitative studies of field data for the aquifer system indicate that hydraulic conductivity ranges from 6 to 60 feet per day and exceeds 25 feet per day in 21 percent of the County; specific yield ranges from 12 to 21 percent and averages about 15 percent; saturated thickness varied in 1938 from 190 to 510 feet and averaged about 342 feet. Recharge to the aquifer system, which comes mainly from precipitation averaging 17.1 inches annually, varied from 0.06 to 4.33 inches annually and averaged about 1.6 inches. The estimated volume of water stored in the aquifer system in 1980 is 80.3 million acre-feet; of water recoverable in 1980, 34.4 million acre-feet; and of water pumped in 1980, 104,000 acre-feet.

Results of digital flow model simulation indicate that by 1992 the area of water-level decline of 10 feet or more will increase from 336 square miles (1981) to 630 square miles (1992), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 240 square miles (1992) if pumpage continues to increase at the maximum annual rate recorded from 1938 through 1981. However, if pumpage is held to the 1981 rate, the area of decline of 10 feet or more will increase from 336 square miles (1981) to 530 square miles (1992). The maximum projected declines in water levels for the period 1981 to 1992 are 29 feet if pumpage is continually increased at the maximum annual rate recorded and 13 feet if pumpage is not increased beyond 1981.

INTRODUCTION

The U.S. Geological Survey, in 1977, began a 5-year regional study of the High Plains aquifer system, which underlies 177,000 square miles in eight states (Gutentag and Weeks, 1980), including 64,770 square miles in Nebraska. Within the regional study were more intensive studies of ground water in local areas, such as Box Butte County, where pumping is gradually depleting the amount of water stored in the aquifer system.

Box Butte County is principally a farming and ranching area. Approximately 51 percent (345,000 acres) of its area is in cropland, 43 percent (296,700 acres) in pasture and rangeland, and 6 percent (41,200 acres) in woodlands, residential lands, and other lands (Nebraska Crop and Livestock Reporting Service, 1981). About 28 percent of the cropland is irrigated with ground water from the High Plains aquifer system.

The High Plains aquifer system is defined as all sedimentary rocks from the water table down to the top of the Brule Formation of the White River Group. Thus the aquifer system is comprised of alluvium of Quaternary age and the Ogallala Formation, the Sheep Creek Formation, the Marsland Formation, the Harrison Sandstone, the Monroe Creek Sandstone, and the Gering Sandstone, all of Tertiary age. The Brule Formation, a relatively impermeable siltstone of several hundred feet in thickness and underlying the entire county, has not been reported as a source of water for Box Butte County, even though fractures in the Brule provide water in sufficient quantities for domestic and stock uses in areas southwest of Box Butte County (Wenzel and others, 1946, Smith and Souders, 1971, Smith and Souders, 1975).

The development of ground water for irrigation from the aquifer system began in about 1936 (Cady and Scherer, 1946), and by 1940 there were 16 registered irrigation wells in the county. Irrigation was prompted by the need to decrease the risks associated with dryland agriculture and by the ready availability of ground water. It was accelerated by the recent advent of the center-pivot irrigation distribution system. Drilling of irrigation wells continued steadily, and by January 1, 1980, there were 723 registered wells in the county.

Because of increasingly large withdrawals of ground water for irrigation, by 1980 the water levels in the aquifer system declined as much as 50 feet from predevelopment levels and continue to decline over much of the county. Because the economy of the county is largely dependent on the continued production of food through irrigation farming, the continued availability of ground water is of immediate concern to State and local water-planning agencies.

Purposes and Scope

The purposes of this study are: (1) to describe the High Plains aquifer system in Box Butte County; (2) to describe the changes in water levels that have taken place in the system; and (3) to project, by model simulation, changes in water levels that will occur under several assumed management schemes for future irrigation development.

This study is concerned principally with changes in water levels in the county and the climatic, geologic, and hydrologic framework within which these changes occur. A history of water-level changes since 1938 has been developed through detailed analysis of more than four decades of water-level measurements. Existing information has been interpreted to provide quantitative values for the hydrologic parameters that influence water levels, such as permeability of soils overlying the aquifer system and hydraulic conductivity and specific yield of the aquifer system itself. New data obtained for this study are limited mostly to pumpage. Projections of water-level changes are made using a digital model that simulates responses to stresses on the aquifer system.

Location and Physical Setting

Box Butte County is in northwestern Nebraska (fig. 1) and has an area of 1,067 square miles. It is situated on a plain called the "Box Butte Table", the surface of which is rolling to rough, due to dissection by small ephemeral streams. The tableland slopes easterly from an altitude of 4,600 feet on the Sioux - Box Butte County line west of Hemingford to 3,800 feet at the northeast corner of the county. The topography varies from steeply sloped escarpment in the northwest and sand dunes in the southeast to broad valleys in the lower reaches of the streams and depressions in the south-central area.

The two major streams in the county are the Niobrara River and Snake Creek. Snake Creek, which originates in Sioux County to the west, flows as a perennial stream to Kilpatrick Lake and then as an ephemeral stream to near an area of sand dunes southeast of Alliance, where it disappears. It and several other ephemeral streams drain approximately the southern three-fourths of the county. The Niobrara River, which is a perennial stream that crosses the northwest corner of the county, and its tributaries drains approximately the northern one-fourth of the county.

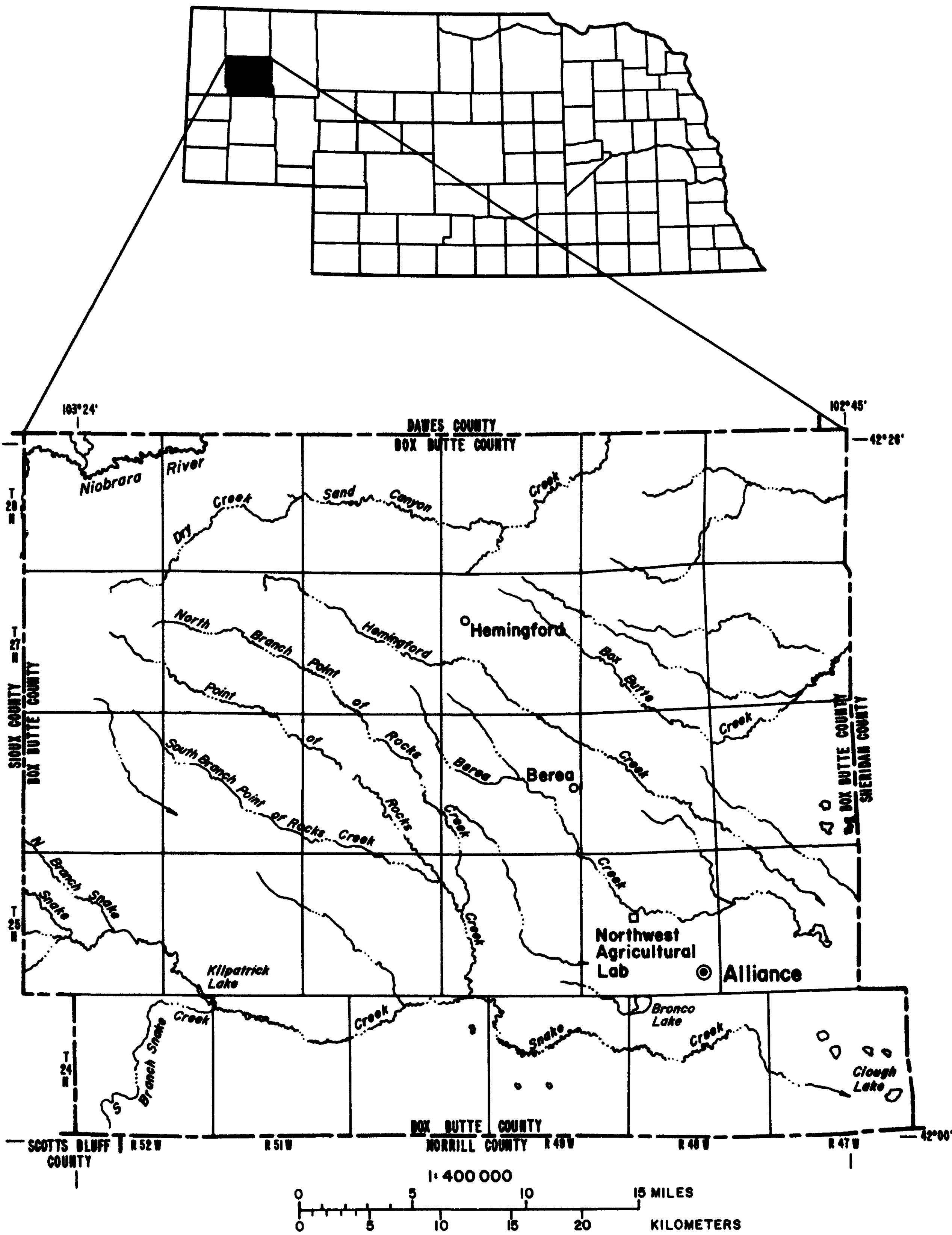


Figure 1.--Study area.

Methods of Investigation

Data compiled and analyzed in this investigation were collected during the past 40 years by personnel from Federal, State, and local agencies. The data include periodic measurements of water levels, test-hole logs, weather information, geologic descriptions, physical and hydrologic properties of aquifer material, crop acreage, number of irrigation wells constructed annually, average annual water use by crops and water-quality analyses.

A large percentage of the data compiled and analyzed came from previous reports and from files of Federal, State, and local agencies. The remaining data were collected in the field during the first 3 years of the 5-year regional study.

A digital, soil-moisture budget model, which incorporates hydro-meteorological, soil, vegetation, and topographic data was used to estimate the long-term average net recharge to the aquifer from precipitation. The mathematical equation describing the computation of storage in the model is written:

$$S_i = S_{i-1} + \frac{1}{\Delta Z}(I - ET) \quad (1)$$

where

S_i is dimensionless storage at time period i;

S_{i-1} is dimensionless storage at time period i-1;

ΔZ is thickness of the zone affected by evapotranspiration, L;

I is infiltration, L; and

ET is evapotranspiration, L.

Storage in the soil profile under both dryland and irrigated conditions was computed monthly using the above equation and a Fortran IV computer model (Lappala, 1978, p. 94). The initial moisture stored in root zone (S_{i-1}) was assumed at 50 percent of the moisture-holding capacity for irrigated land and 25 percent for nonirrigated land (Lappala, 1978, p. 98). When storage (S_i) computed by the above equation exceeds field capacity of the soil, deep percolation equal to the excess is simulated. It is assumed that long-term deep percolation through the unsaturated zone is equal to the long-term recharge to the saturated zone.

Infiltration (I) for the above equation was obtained from four rainfall-runoff curves that were developed by the Agricultural Research Service at Rosemont, Nebr. (Lappala, 1978, p. 95), from soil, vegetation, and topographic data.

Evapotranspiration (ET), the largest component of discharge from the soil zone, was estimated for a native grass and various crops by multiplying the monthly crop coefficient by potential ET. Potential ET was computed using the Jensen-Haise empirical formula (Jensen and Haise, 1963; Jensen, 1974). Crop coefficients were obtained from Stegman and others (1977), from Papton and others (1981), and through written communications (Blaine Blad, Department of Agricultural Engineering, University of Nebraska, and W. K. Lauenroth, Natural Resource Ecology Laboratory, Colorado State University).

A digital ground-water flow model was developed to simulate the aquifer system's response prior to major ground-water development for irrigation (steady-state simulation). The model was then tested and modified by simulating the aquifer system's response to ground-water development (transient simulation). Six pumping periods were simulated to match the historical data for 1950, 1960, 1965, 1970, 1975, and 1980. Following these simulations, the model was used to predict the response of water levels in the aquifer system to various management alternatives.

Previous Ground-Water Investigations

A report by Cady and Scherer (1946) contains a detailed description and discussion of the geography, landforms, geology, and ground-water hydrology of the county. A supplement to that report by Nace (1953) discusses the special problems observed in the construction, development, and use of irrigation wells and the subsequent effects on the water table and ground-water storage. A report by Bradley (1956) presents a general review of the ground-water resources of the upper Niobrara River basin. A Masters thesis by Waddington (1971) presents the results from a study in which an electric-analog model was used to predict the effects of pumping on the aquifer system.

A report by Souders and others (1980), which is more inclusive than the others listed, discusses the relationship between the geology and ground-water availability, evaluates the aquifer's water-bearing characteristics and storage, and describes movement of ground water in the county. Information and data from previous reports were evaluated and then incorporated with new data and information collected during their investigation. The new data, obtained through extensive examination of drill cuttings, logs, and field data, were used to designate rock strata into various hydrologic units. The hydrologic units were then evaluated in terms of their water-yielding capabilities.

Acknowledgments

The authors express appreciation to the residents of Box Butte County who gave information regarding their wells, cropping practices and acreage, and permitted the collection of pumpage data. Appreciation is extended to County officials, the Upper Niobrara-White Natural Resources District, and to representatives of State and Federal agencies who provided information and assistance.

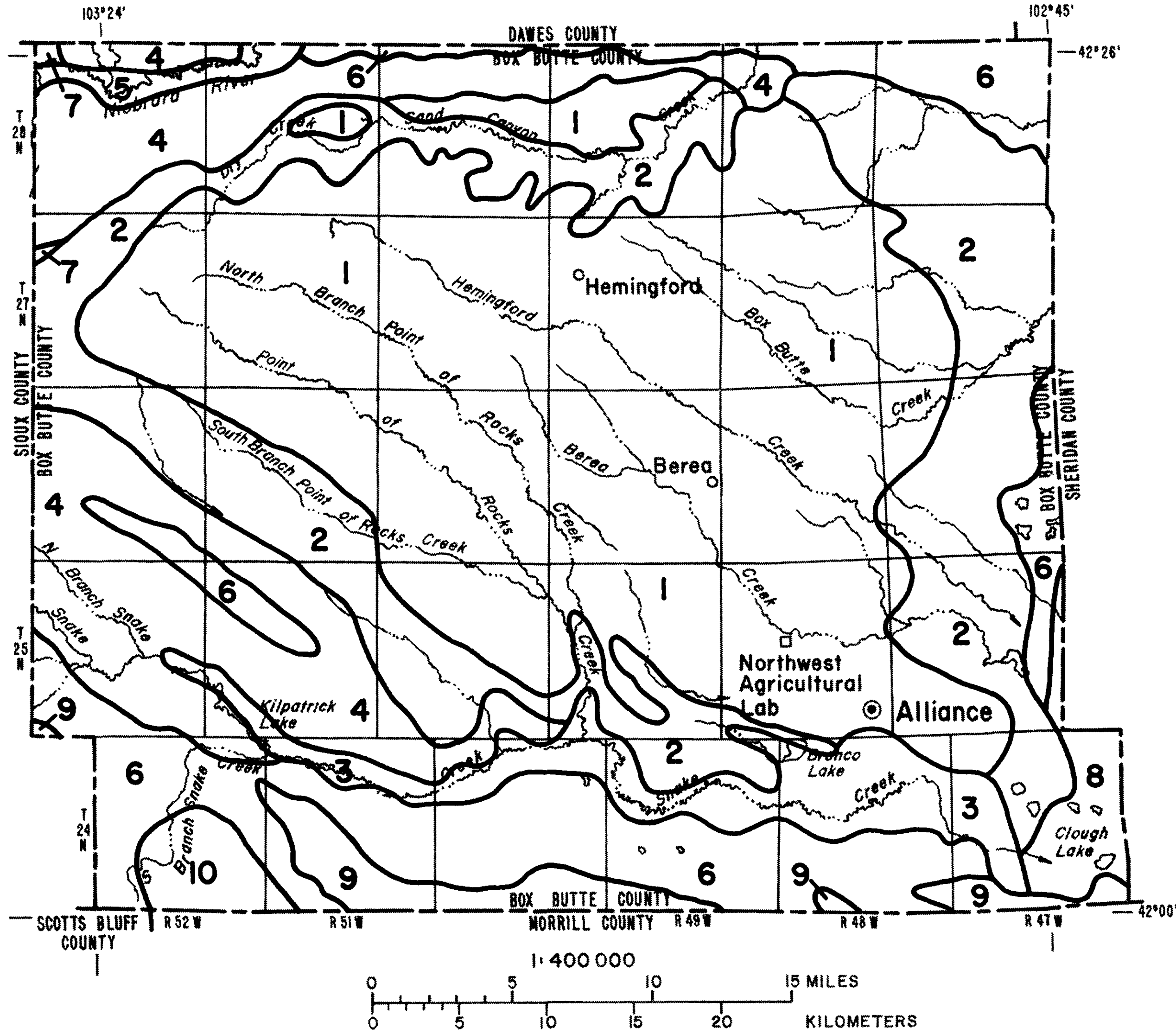
SOILS

The soils across the county range from silty clay loams on the uplands to sandy soils on some of the bottomlands and the sandhills. More than 60 percent of the county, principally the central part, is covered by silty to silty clay loam soils that have permeabilities of about 1.35 inches per hour (Dugan, in press) (fig. 2). The water-holding capacity of these soils is about 20 percent. Most of the silty soils are intensively cultivated. The remainder of the county is covered by loamy to sandy soils that have permeabilities ranging from 3.3 to 12.6 inches per hour (Dugan, in press). The water-holding capacity of these soils ranges from 8 to 16 percent. Most of the sandy soils of the county are still in native grasses.

GEOLOGY

Eolian deposits of Quaternary age cover the uplands, the terraces, and the dune areas of the county. However, of deposits of Quaternary age, it is only the alluvial deposits along the Niobrara River and Snake Creek that yield sufficient water for stock and domestic use. These alluvial deposits are composed of fine-grained sand intermixed with smaller amounts of coarse-grained material.

Deposits of Tertiary age that underlie Box Butte County are the principal water-bearing formations of the High Plains aquifer system in this area (fig. 3). These deposits are calcareous sands and silts, and belong to the Gering Sandstone, the Monroe Creek Sandstone, the Harrison Sandstone, the Marsland Formation, the Sheep Creek Formation, and the Ogallala Formation (Cady and Scherer, 1946). The base of the Tertiary



EXPLANATION

Number on map	Soil association represented	Average permeability: 60-inch soil profile (inch per hour)	Average permeability: Least permeable horizon (inch per hour)	Average available water capacity (inch per inch)	Average maximum soil slope (percent)	Depth to seasonal high water table (feet)
1	Alliance-Rosebud-Keith	1.36	1.21	0.21	9	> 15
2	Norrest-Canyon-Creighton	1.35	1.29	.19	20	> 15
3	Janise-Lisco	3.72	1.75	.16	2	5
4	Sarben-Busher-Valent	3.62	3.62	.17	21	> 15
5	Las Animas-Lisco	8.85	3.01	.13	2	5
6	Valent-Dailey	7.28	3.52	.14	12	> 15
7	Busher-Valent-Tassel	6.68	4.78	.14	12	> 15
8	Valentine-Elsmere	12.65	12.21	.08	10	10
9	Valentine-Thurman	11.85	10.38	.09	26	> 15
10	Creighton-Oglala-Canyon	3.3	3.27	.16	7	> 15

Figure 2.--Distribution and hydrologic properties of soils overlying the aquifer system.

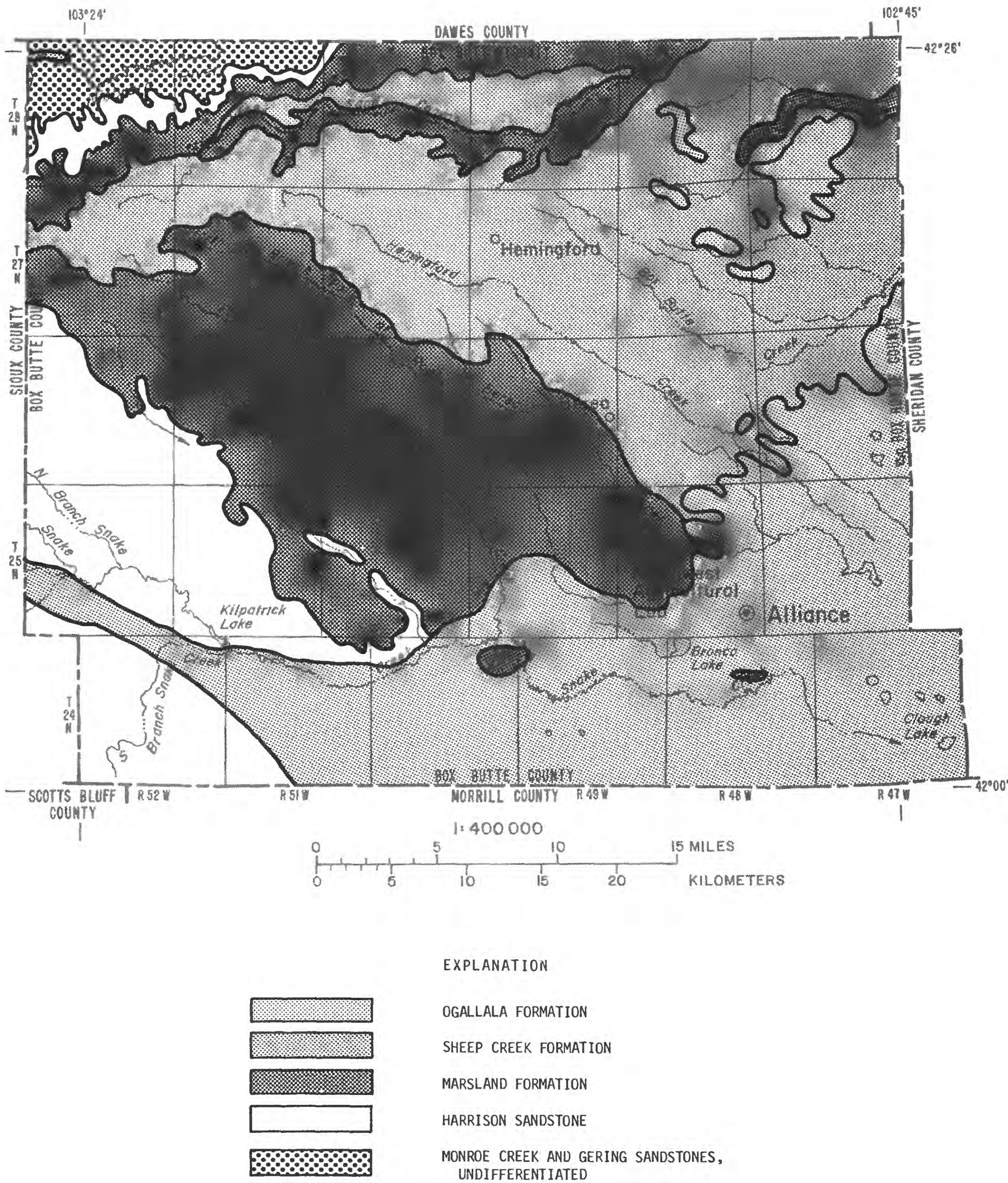


Figure 3.--Principal geologic units of Tertiary age comprising the aquifer system.

water-bearing formations, which is also designated in this report as the base of the High Plains aquifer system, is the Brule Formation of the White River Group.

Changes in nomenclature of rock strata, which have appeared recently in some State reports, have not yet been accepted by the Geologic Names Committee of the U.S. Geological Survey and consequently are not used in this report. For example, in the report by Souders and others, 1980, some new or revised nomenclature is used. They have separated the rock strata into hydrologic units and state that "A hydrologic unit consists of materials of generally similar water-bearing characteristics. The upper and lower limits of hydrologic units used in this report, with one possible exception, conform to boundaries of established members, formations, groups, or systems." They discuss both geology and hydrology in terms of the hydrologic units designated and present a table showing their revised nomenclature along with a discussion of the relationship between the revised and the established nomenclature. Therefore, the established nomenclature used in this report can be correlated with the revised nomenclature used in their report.

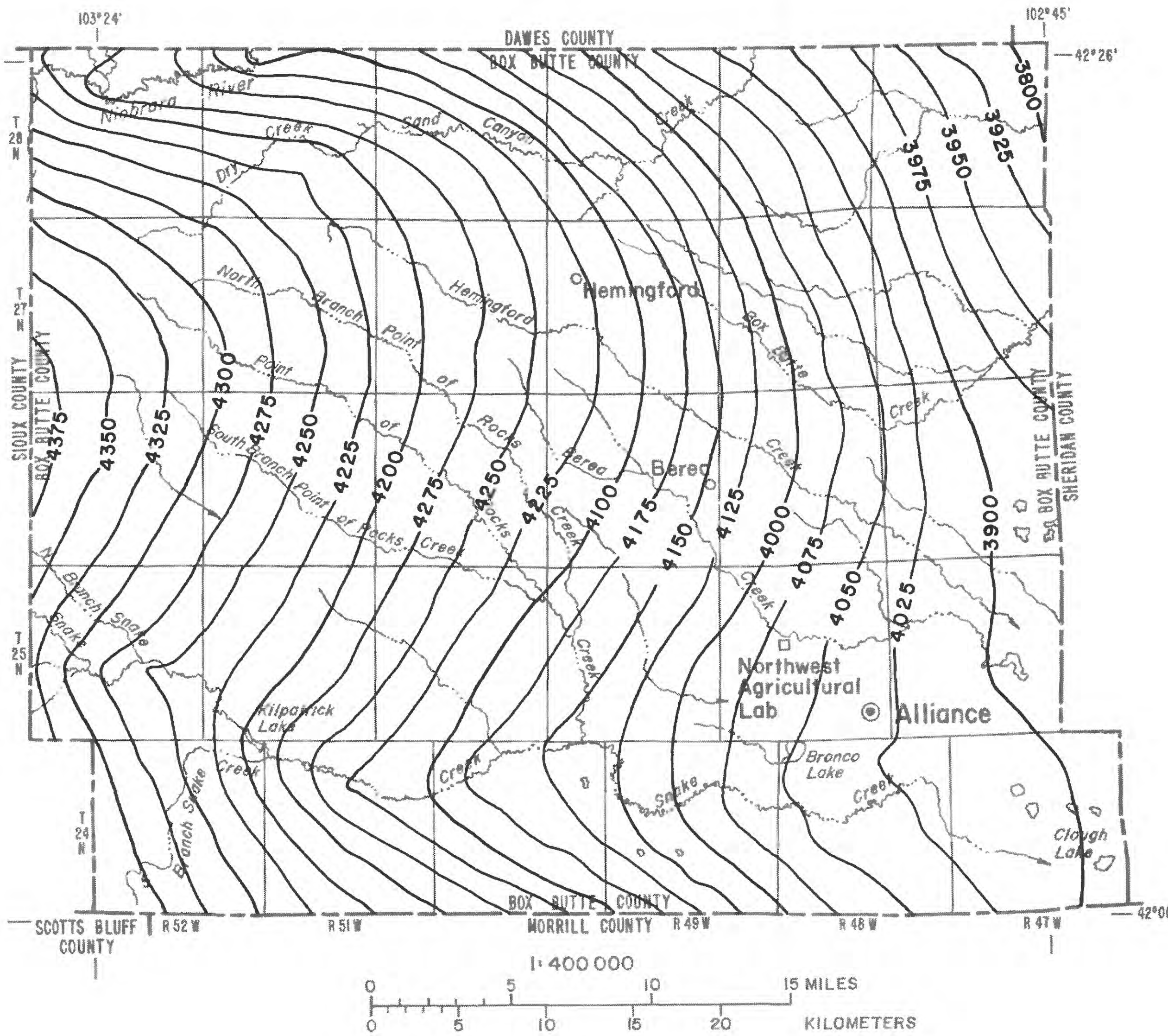
For further description of the geology and discussion of formation thickness and location in Box Butte County, the reader is referred to reports by Cady and Scherer (1946), Condra and Reed (1943), Lugn (1939), as well as to the above cited report of Souders and others (1980).

HYDROLOGY

This analysis of the hydrology of the aquifer system in Box Butte County is concerned primarily with the movement of water from the time it reaches the aquifer until it is discharged into rivers or returned to the atmosphere. Such an analysis involves the measurement of the movement of water at several stages of its course. A discussion of measurements or estimates made for this analysis are presented in this section of the report.

Potentiometric Surface

Water-table conditions generally prevail throughout the aquifer system, although water may be confined locally in small areas. Perched ground water has been reported in the north-central and northeastern parts of the county (Souders and others, 1980). To establish the configuration of the potentiometric surface prior to ground-water development, water-level data for 1938, taken from reports by Cady and Scherer (1946) and Souders and others (1980), were plotted on a county base map. Lines were drawn to connect points of equal altitude to form the potentiometric-surface map shown in figure 4. Similar maps were made from water-level measurements obtained in 1950, 1960, 1965, 1970, 1975, and 1980.



EXPLANATION

—— 4000 —— WATER-TABLE CONTOUR--Shows altitude of water table in 1938. Contour interval, 25 feet. Datum is NGVD of 1929

Figure 4.--Poteniometric surface of aquifer system prior to major ground-water development.

The altitude of the potentiometric surface in 1938 ranged from 4,380 feet at the west edge of the county to 3,780 feet at the northeast corner. The average gradient is to the east at about 15 feet per mile.

Water levels have been declining steadily in the county since about 1950 because of ground-water development for irrigation. They have declined 10 feet or more in an area comprising 215,000 acres (336 square miles) or 31 percent of the county, an area 2.2 times larger than all the irrigated acreage in the county and have declined 30 feet or more in an area of 10,900 acres (17 square miles) (fig. 5). A maximum decline of 50 feet was recorded in a well 3 mi north of Alliance (Johnson and Pederson, 1981, p. 48).

Hydraulic Conductivity

Hydraulic conductivity of the aquifer is a measure of the ability of the aquifer to transmit water and is dependent largely on the nature of the pore space in the aquifer deposits. Because pore space is a function of particle-size distribution, hydraulic conductivity was estimated primarily from size distribution of the particles comprising the deposits. This was accomplished by assigning a hydraulic-conductivity value to each lithologically distinct layer of saturated material between the potentiometric surface and the base of the aquifer as shown on the test-drilling logs. These assigned hydraulic-conductivity values were taken from a table that relates grain-size distribution and hydraulic conductivity (Lappala, 1978, p. 70). The hydraulic-conductivity values assigned to the individual layers were then weighted by the thickness of the layers, and a weighted-average hydraulic conductivity was computed for the entire thickness of the aquifer. The computations were made by the digital computer.

For areas where hydraulic conductivity could not be estimated by the method just described, supplemental estimates were made from specific capacity data of irrigation wells registered with the Nebraska Department of Water Resources. Only wells that penetrated the entire thickness of the aquifer were used to compute the estimate. The empirical formula modified from Logan (1964) is:

$$K = \frac{S_c}{7.48\ b} \times 2,250 \qquad (2)$$

where K is hydraulic conductivity, in feet per day,

S_c is specific capacity, in gallons per minute per foot,

b is aquifer thickness, in feet,

7.48 is factor to convert gallons per minute to cubic feet per day.

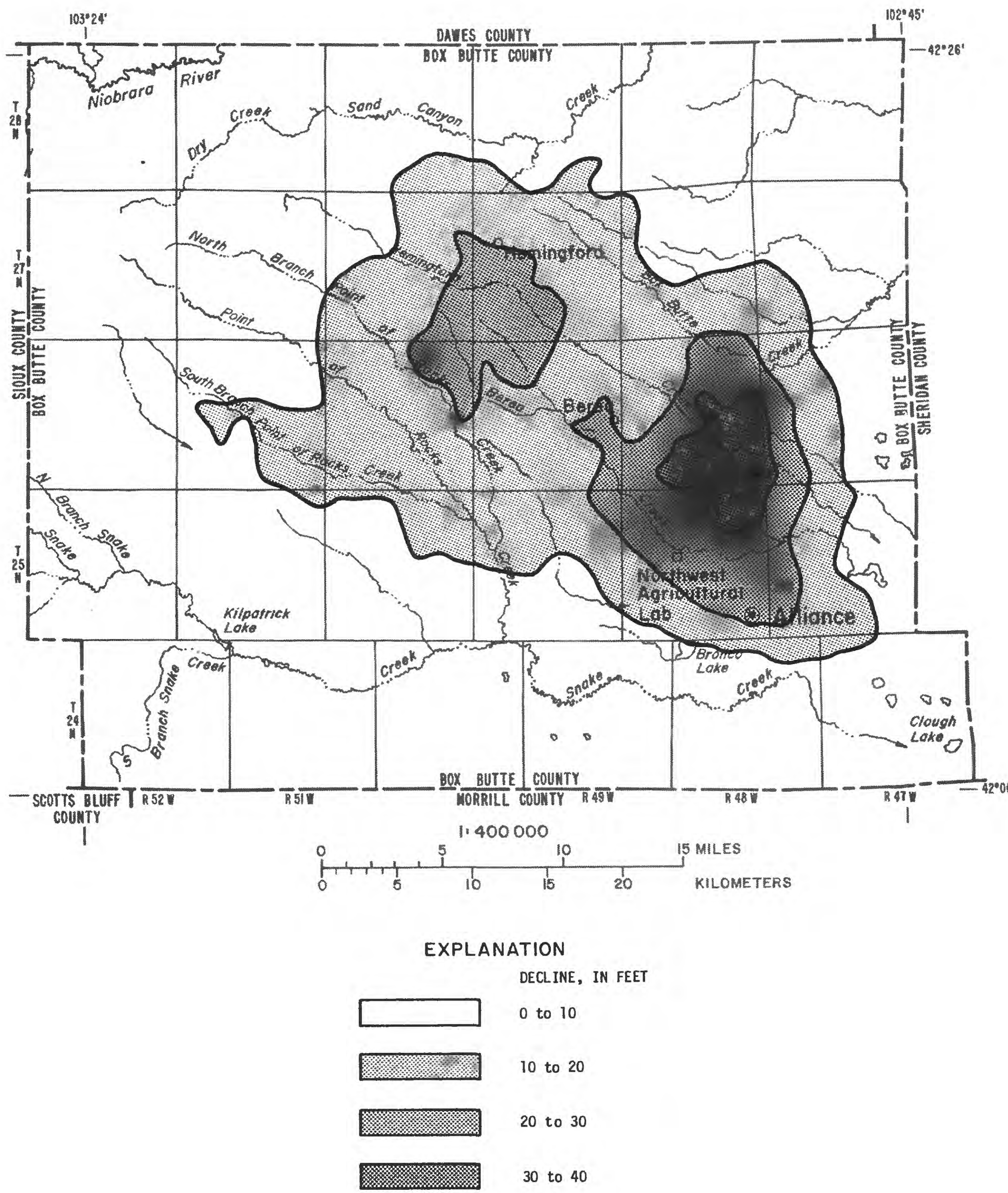


Figure 5.--Decline in ground-water levels from predevelopment to fall 1980.

The number "2,250" in the above formula is a constant estimated from range of 2,000 (Pederson, 1979) to 2,400 (Cardwell and Jenkins, 1963).

The weighted hydraulic conductivities for 58 test-drilling sites plus 56 supplemental sites were plotted on a county base map, and lines of equal conductivity were drawn to delimit the ranges shown on figure 6. The hydraulic conductivities range from 6 to 60 feet per day and exceed 25 feet per day in 21 percent of the county.

The riverbed leakage coefficient (K_v) of the Niobrara River was computed using the following linear leakage equation adapted from Rushton and Tomlinson (1979):

$$Q = K_v \cdot HDIFF \quad \text{or}$$

$$K_v = \frac{Q}{HDIFF} \tag{3}$$

where Q is leakage, in cubic feet per day per unit length (reach) of river;

K_v is riverbed leakage coefficient, in feet per day;

HDIFF is head in aquifer minus head in river, in feet.

Leakage (Q) values for each reach of the river are based on data collected in April 1980 during a seepage study and were obtained by subtracting the rate of flow at the upstream site of the reach from that at the downstream site. The total head difference (HDIFF) between the upstream site and the downstream site was obtained by (1) computing the difference in altitude between the water level in the aquifer and the water level in the river for each river node, (2) computing the average altitude difference for the river reach, and (3) multiplying that average by the length of the river reach. Because the river area was less than the node area, the leakage coefficient obtained was multiplied by the ratio of river area to node area to compensate for the difference.

The estimated riverbed leakage coefficient of the Niobrara River ranges from 0.14 to 4.8 feet per day.

Specific Yield

Specific yield of the aquifer is a measure of the ability of the aquifer to yield water by gravity and was estimated from information in about 58 test-drilling logs. A specific-yield value was assigned to each lithologically distinct layer of material between the potentiometric

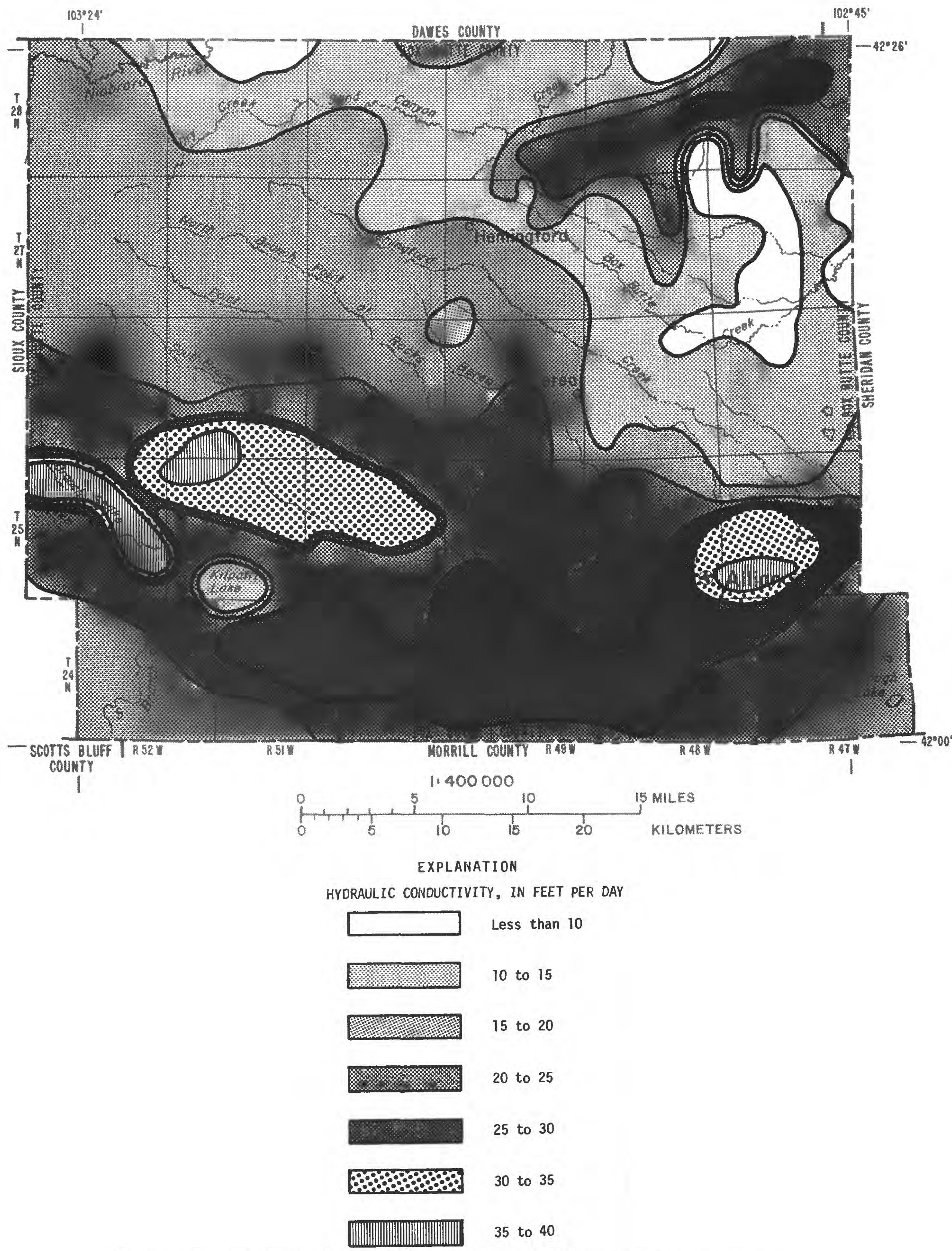


Figure 6.--Hydraulic conductivity of the aquifer system.

surface and the base of the aquifer for each driller's log. This specific-yield value was assigned to the individual layer of material according to particle-size distribution from a table of values modified from Johnson (1967). The specific yields assigned for the individual layers were then weighted by the thickness of the layers and a weighted-average specific yield was computed for the entire thickness of the aquifer.

The weighted specific yields for each of the driller's logs were plotted on a county base map, and lines of equal specific yield were drawn to delimit the ranges shown on figure 7. Weighted specific yields ranged from 12 to 21 percent and averaged 15 percent. The volume of water recoverable from the aquifer system in 1980 is estimated to have been 34.4 million acre-feet, based on volume of saturated material and average specific yield. However, because of cost and limits of existing technology, this entire amount could not actually be recovered.

Base of Aquifer System

The altitude of the base of the aquifer system was determined by identifying the top of the Brule Formation of the White River Group and recording the altitude at which it occurs in 58 test-hole logs. The recorded altitude of the top of the Brule Formation for each log was plotted on a county base map, and lines of equal altitude were connected to form the configuration of the base of the aquifer (fig. 8). The Brule Formation, which consists mostly of clays, silts, and channel sandstones beneath Box Butte County (Lugn, 1939) and for which no reports of fractures exist, is assumed to have minimal hydraulic conductivity.

The altitude of the base of the aquifer system ranges from about 4,150 feet along the western edge of the county to about 3,350 feet at the northeast corner. The average gradient is to the east at about 20 feet per mile.

Saturated Thickness

The saturated thickness of the aquifer system in 1938 ranged from about 190 to 510 feet and averaged 342 feet (fig. 9). The saturated thickness decreased from about 360 feet in 1938 to 343 feet in 1980 in an observation well 5 miles south of Hemingford, and from about 440 feet in 1938 to 391 feet in 1980 in an observation well 3 miles north of Alliance. The percentage decrease in saturated thickness from 1938 to 1980 in terms of the area in the county is shown by the following table:

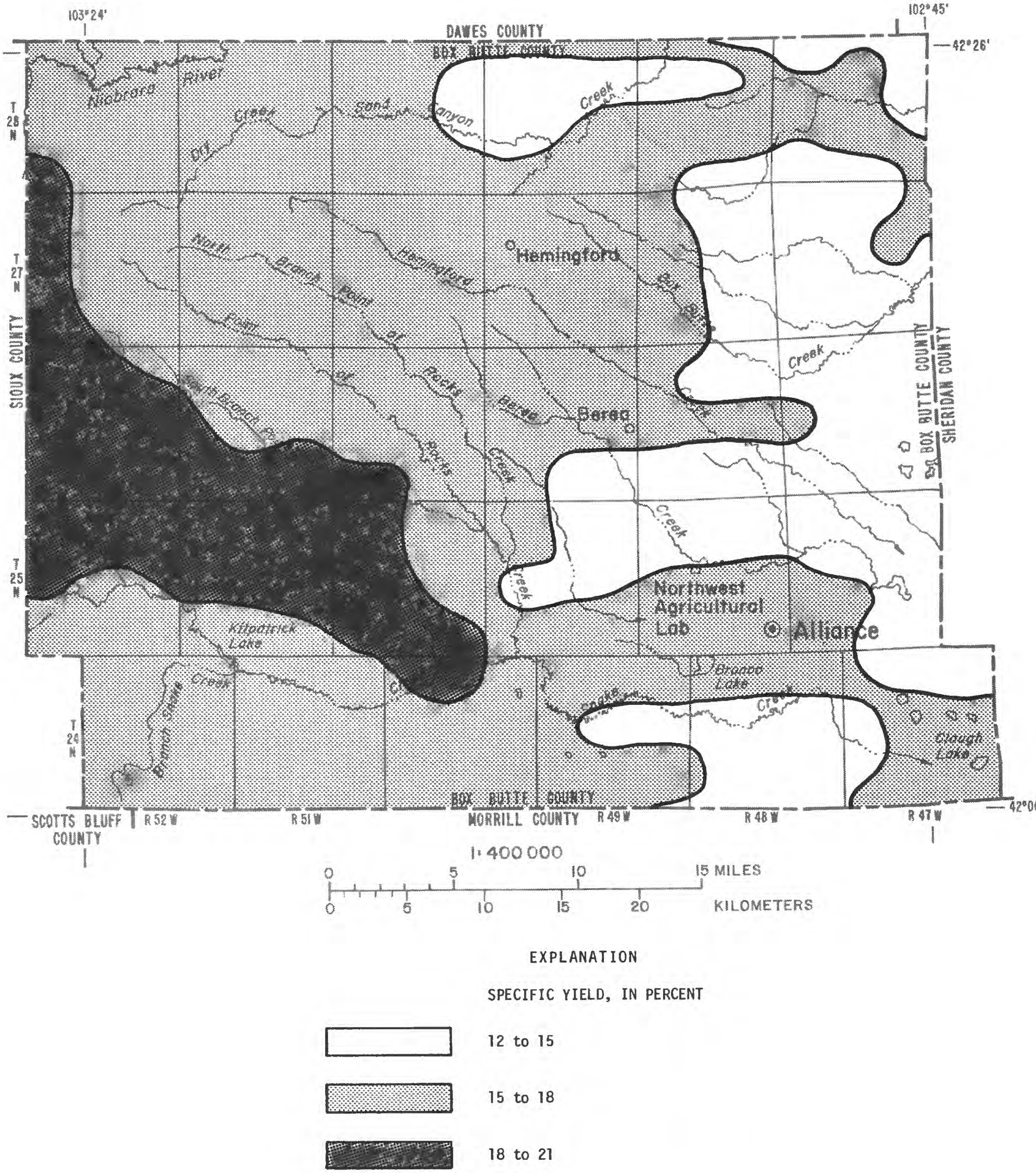
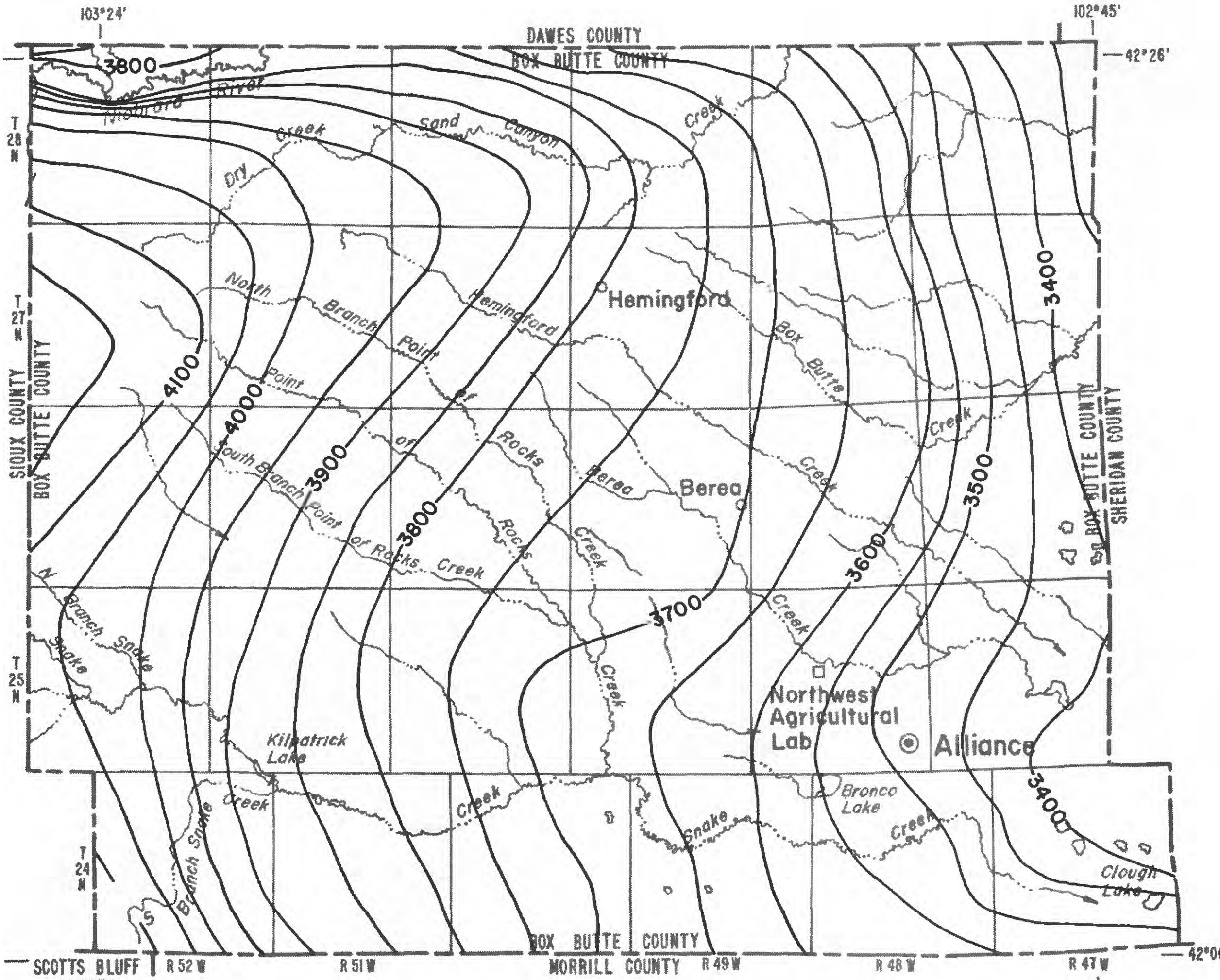


Figure 7.--Specific yield of the aquifer system.



1:400 000

0 5 10 15 MILES

0 5 10 15 20 KILOMETERS

EXPLANATION

—3800— BASE OF AQUIFER CONTOUR--Shows altitude of base of aquifer system. Interval, 50 feet. Datum is NGVD of 1929

Figure 8.--Altitude and configuration of base of aquifer system.

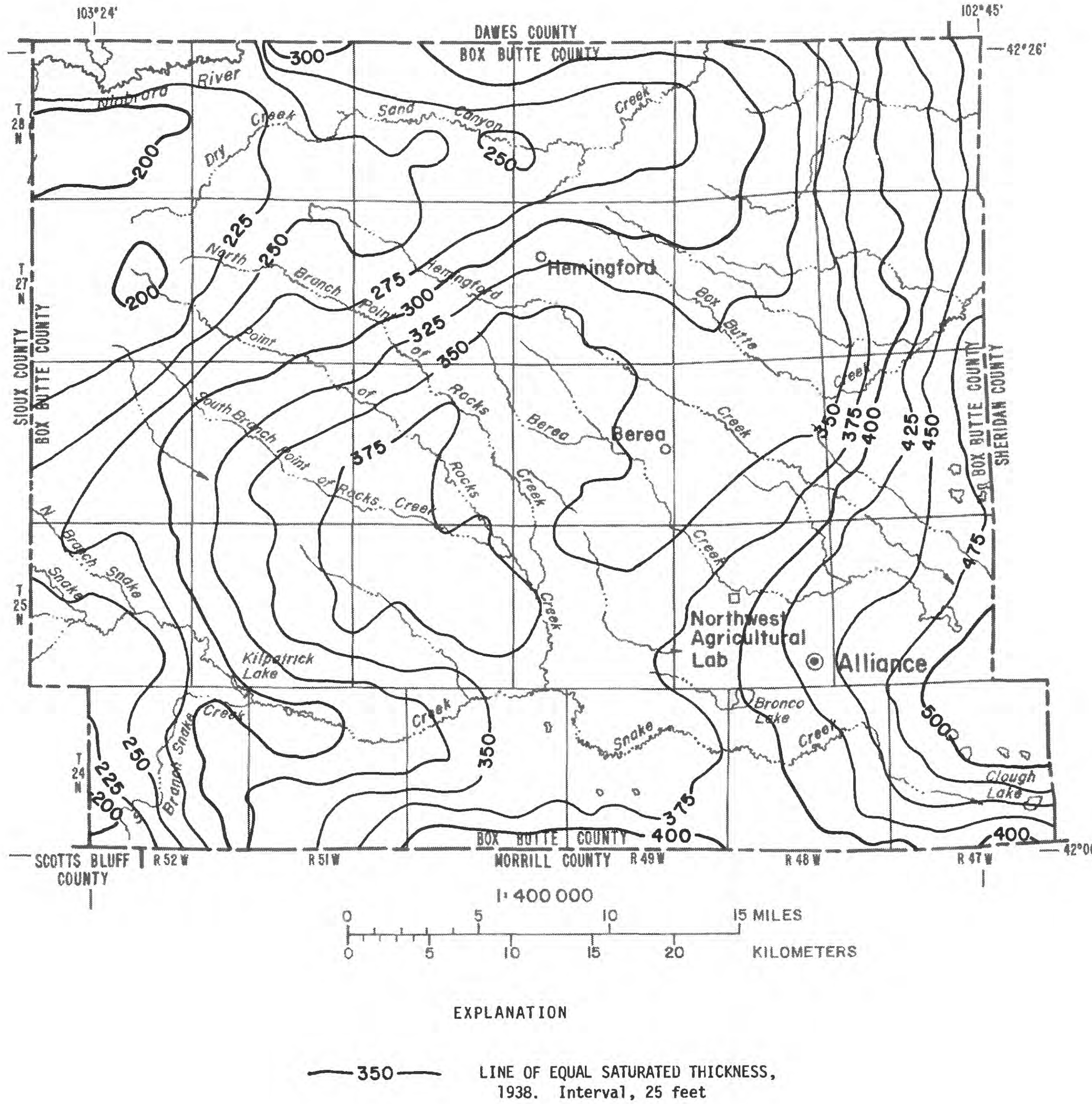


Figure 9.--Saturated thickness of aquifer system prior to major ground-water development.

Table 1.--Percentage decrease in saturated thickness in terms of area

Percentage decrease in saturated thickness	County area	
	Square miles	Percent
0 to 1	587	55
1 to 3	218	21
3 to 6	152	14
6 to 9	110	10
Totals	1,067	100

The percent decrease in terms of the volume of water stored in the aquifer system in the county was computed to be about 1.7. This is a reduction in aquifer storage from 81.7 million acre-feet in 1938 to 80.3 million acre-feet in 1980. The porosity value used in computing aquifer storage was 35 percent (Morris and Johnson, 1967).

Recharge

The aquifer system is recharged naturally by infiltration from precipitation and ephemeral streams that cross the area. Some recharge comes from subsurface inflow from areas to the west and south. Precipitation on the land surface provides most of the recharge to the aquifer system. Average annual precipitation is 17.3 inches at Alliance, 15.7 inches at Northwest Agricultural Laboratory, and 18.3 inches at Hemingford (National Oceanic and Atmospheric Administration, Nebraska), which is an overall average of 17.1 inches. Long-term average recharge from precipitation to the aquifer system was estimated from climatic records of the three stations and the soil-moisture budget model described previously. The recharge values from model computation for the three stations are given in table 2 and range from 0.06 to 4.33 inches per year and average about 1.6. Differences in recharge values for the three climatological stations are due to differences in precipitation and evapotranspiration. Souders and others (1980) estimated recharge to range from 0.7 to 6.0 inches per year.

The amount of precipitation that recharges the aquifer is dependent upon a number of factors, the most important of which are permeability of soil, slope of land, vegetative cover, time of year of precipitation, and intensity and duration of precipitation. The wide range in recharge to the aquifer is attributed primarily to changes in soil permeability across the county.

Table 2.--Estimated average annual recharge from precipitation through different soils used for different purposes

D = Depth of root zone, in inches

Number of the soil associa-tions on figure 2	Recharge, in inches per year								
	Native grasses		Row crop D = 36		Small grain D = 30		Summer fallow	Alfalfa D = 60	Pasture D = 30
	D = 16	D = 23	Irri-gated	Non-irri-gated	Irri-gated	Non-irri-gated			
(Computed using 50 years of climatic data for Alliance)									
1, 2	1.96	1.36	1.22	0.90	0.97	0.45	0.63	0.40	0.68
3, 10	2.25	1.65	1.51	1.01	1.21	.77	.85	.47	.55
4,5,6,7	2.71	2.04	1.60	1.07	1.41	.78	1.06	.41	.83
8, 9	3.67	3.02	2.34	2.01	2.00	1.41	1.82	.19	1.24
(Computed using 32 years of climatic data for the Northwest Agricultural Laboratory)									
1,2	1.52	1.05	.90	.68	.82	.32	.45	.30	.48
3, 10	1.76	1.27	1.09	.81	1.04	.42	.52	.35	.38
4,5,6,7	2.17	1.61	1.02	.61	1.32	.61	.78	.30	.62
8, 9	3.12	2.48	1.67	1.30	1.72	1.10	1.37	.06	.97
(Computed using 17 years of climatic data for Hemingford)									
1, 2	2.28	1.43	2.07	1.14	1.64	.63	1.00	.45	1.29
3, 10	2.64	1.92	2.48	1.51	1.94	.89	1.29	.53	1.30
4,5,6,7	3.24	2.40	2.76	1.83	2.37	1.35	1.86	.46	1.76
8, 9	4.33	3.60	3.82	3.35	3.14	2.31	2.96	.28	2.71

Areal distribution of recharge to the aquifer system from precipitation that was used in modeling steady-state conditions is shown in figure 10 and is based on the estimated average recharge rates for Alliance and Hemingford in table 2. Recharge values for Hemingford were used for the northern half and those for Alliance were used for the southern half of the county. The values were adjusted for distance east or west of these two stations to account for changes in precipitation. For transient conditions, the average recharge rates from the steady-state model were adjusted for each pumping interval to account for changes in land use and cropping pattern within each node.

Recharge from subsurface inflow into the County was estimated at 44,000 acre-feet in 1975 (Souders and others, 1980). Subsurface inflow, which occurs primarily along the Sioux and Morrill County borders on the west and south, respectively, has had minimal change due to ground-water development. Recharge from ephemeral streams is considered negligible. On the other hand, recharge from seepage of irrigation water from wells is estimated to be 10 to 15 percent of the water pumped.

Discharge

Water is discharged from the aquifer system by evaporation, transpiration, subsurface underflow, streams, and wells. Because it is often difficult to separate evaporation and transpiration losses from ground water, they are usually combined and measured, or calculated, as one quantity and referred to as evapotranspiration (Q_{et}). Evapotranspiration losses from ground water decrease as depth to water increases and become negligible in Box Butte County at depths of 12 feet or more, because water loss by capillary movement is negligible and plant roots do not reach the saturated stratum to cause loss through transpiration by the plants. Consequently, the maximum Q_{et}, which was set equal to the lake evaporation rate of 42 inches (3.5 feet) per year (Meyers and Nordenson, 1962), occurs when water levels are at ground surface and decreases linearly with increasing depth to 12 feet, where it ceases. The following equation was used to compute the annual Q_{et}:

$$Q_{et} = 3.5 - \frac{3.5}{12} X \qquad X \leq 12$$

$$Q_{et} = 0 \qquad X > 12 \tag{4}$$

where Q_{et} is annual evapotranspiration from aquifer, in feet,

X is depth to water, in feet.

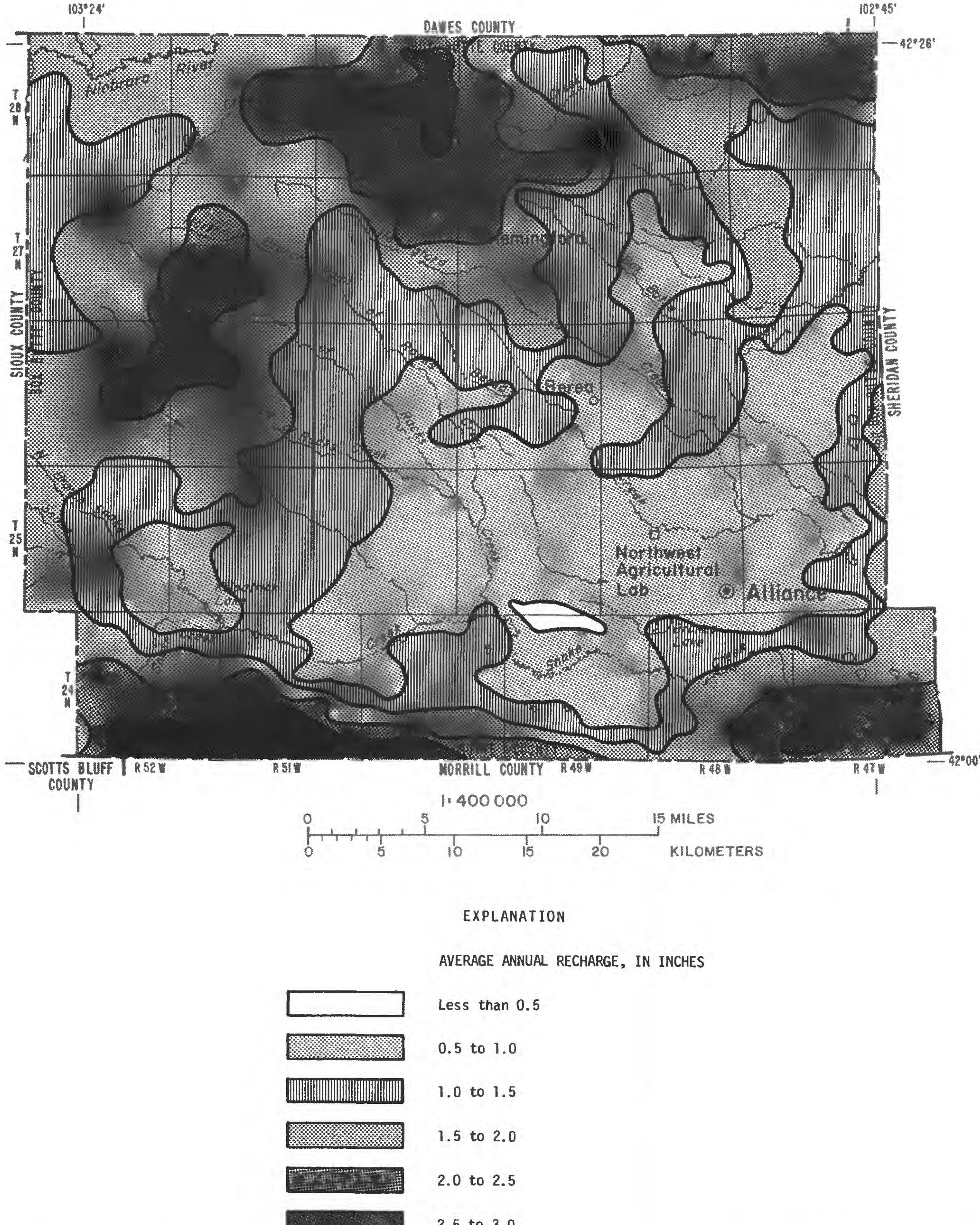


Figure 10.--Average annual recharge to the aquifer system from precipitation prior to major ground-water development.

Areas discharging ground water by evapotranspiration occur in the Niobrara River valley, the lake area in the eastern part of the county, and in an area that widens considerably from west to east along the Snake River valley. Souders and others (1980) estimated discharge of ground water by evapotranspiration prior to ground-water development at 153,000 acre-feet annually from these areas.

The discharge of ground water from the county as subsurface underflow occurs along the Dawes and Sheridan County borders. It was estimated that in 1938, 21,000 acre-feet could be attributed to underflow leaving the county (Souders and others, 1980). This was about one-half of the underflow entering the county. Comparison of predevelopment and 1980 water-table maps indicated that underflow has remained much the same.

The discharge of ground water to streams that flow out of the county occurs along the Niobrara River and Box Butte Creek. Seepage measurements made during April 1980 indicate that the discharge of ground water to the Niobrara River in the reach from 5 miles west of the Sioux-Box Butte County line to 4 miles east of Dawes-Sheridan County line was approximately 52.4 cubic feet per second (18,970 acre-feet per year). It is estimated that 26.2 cubic feet per second or one-half of the discharge comes from south of the river in Box Butte County. Discharge from ground water to Box Butte Creek from the area upstream to the measuring site 2 miles east of Box Butte-Sheridan County line was approximately 7.8 cubic feet per second (5,650 acre-feet per year).

Discharge of ground water by wells for irrigation has increased from an estimated 1,200 acre-feet in 1938 to 104,000 acre-feet in 1980. This increase is due to an increase in the number of irrigation wells from 8 in 1938 to 723 on January 1, 1980.

The average well density in the county increased from about 3 wells per township in 1950 to 24 wells in 1980. The estimated volume of aquifer material dewatered in the county by ground-water pumpage between predevelopment (1938) and 1980 is 3.9 million acre-feet. This represents a county-wide 1.7 percent change in volume of saturated material. Because this change in volume occurred primarily in the area of pumpage, or in less than one-half of the county, the percent change in volume in the area of pumpage was 3.4.

Although most of the wells are in the southeastern part of the county, wells also are now being drilled in other parts of the county due to the advent of the center-pivot distribution system, a system which functions economically over rolling land and sandy soils. Center-pivot wells increased from 50 in 1972 to 428 on January 1, 1980. The distribution over the land surface of the estimated quantity of pumpage from the underlying aquifer system in 1980 is shown in figure 11. This figure was constructed using information on well density and on application rate for each type of distribution system. Well-density data were obtained from the 1980 well-registration file. Application rates were estimated from data collected for 44 randomly selected wells in an inventory taken in 1981 by the Conservation and Survey Division, University of Nebraska, of water used for irrigation. The method is described by Heimes and Luckey (1980), and the estimates are shown in table 3.

Table 3.--Annual rates of withdrawal, per well, of ground water for irrigation in Box Butte County

Type of irrigation system	Average acres irrigated per well	Average quantity applied per acre (inches)	Withdrawal rate (ft^3/s)	
			Gross	Net[1/]
Center pivot	130	11.49	0.172	0.155
Gravity, or other	110	16.78	.213	.181

1/ Assuming 10 percent of the gross irrigation withdrawals are returned to the ground-water system from center-pivot systems and 15 percent from gravity or other systems (Souders and others, 1980; and Darrell Watts, Agricultural Engineering Department, University of Nebraska, personal commun., 1981).

Chemical Quality of Ground Water

The water in the aquifer system is hard, is of the calcium-magnesium bicarbonate type, and has only minor amounts of sulfate, chloride, and other constituents. The water quality was evaluated from chemical analyses listed in Cady and Scherer (1946, p. 82) and in Nace (1953, p. 12), and from seven analyses in the District's file.

The concentrations of major dissolved constituents in most of the water analyzed were within recommended limits for public drinking water supplies (U.S. Environmental Protection Agency, 1975). Concentrations of constituents that exceeded the recommended limits in one or more of the water samples were fluoride (2.0 mg/L), iron (0.5 mg/L), nitrate (20 mg/L), and sulfate (274 mg/L). Two of the water samples had dissolved solids exceeding 500 milligrams per liter (mg/L), and all water samples had hardness properties judged as hard to very hard.

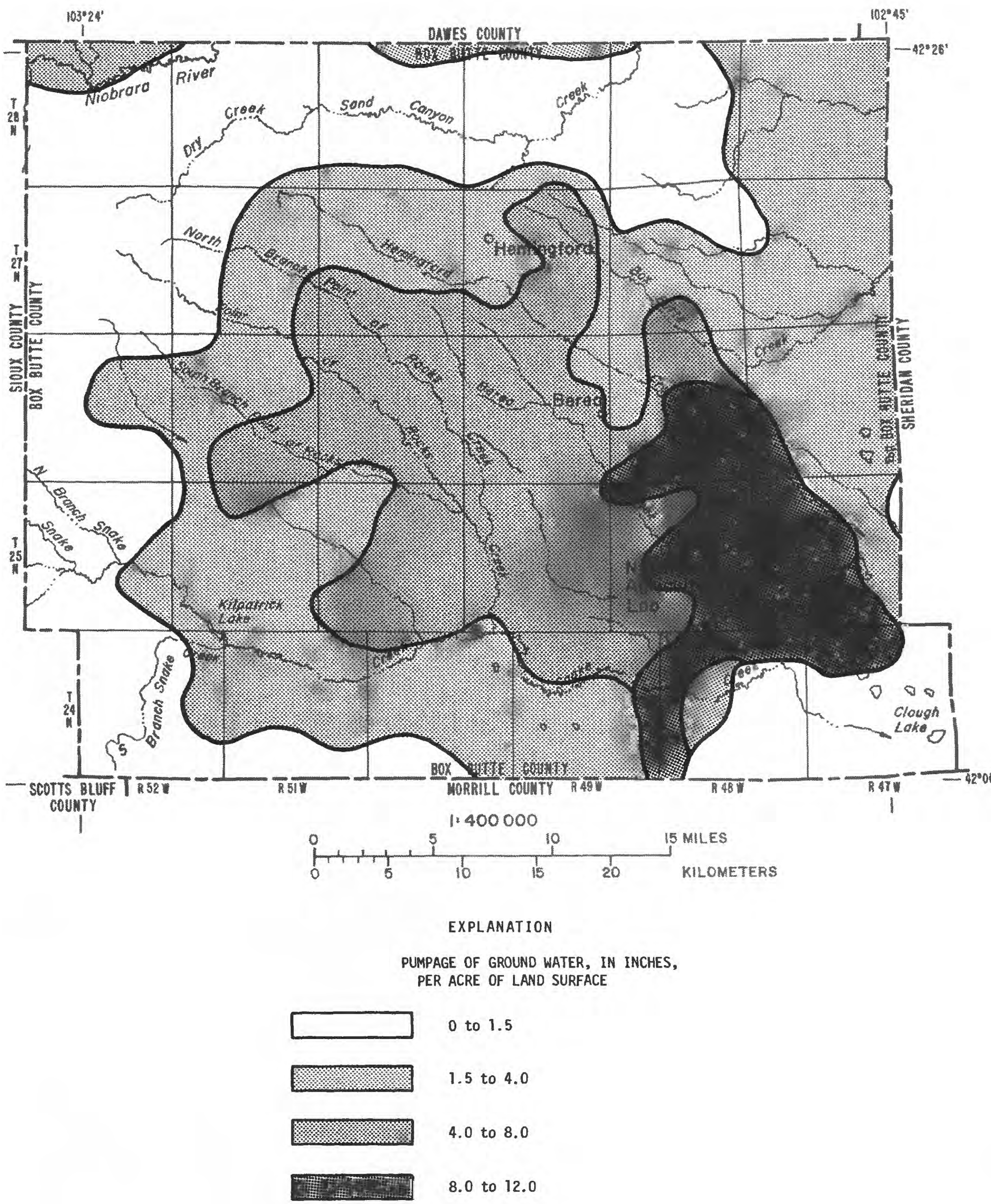


Figure 11.--Distribution of quantity of pumpage from the aquifer system, 1980.

The sodium and salinity hazard of the water for irrigation for 13 samples is shown on figure 12. The figure shows that the sodium hazard involved in using the water for irrigation is low. The salinity hazard of 12 of the samples is medium, and that of 1 of the samples is high. Water with low sodium can be used on almost all soils with little danger of exchangeable sodium accumulating in the soils in harmful amounts. Water of medium salinity can be used satisfactorily for irrigation of all but extremely salt-sensitive plants, provided soil drainage is adequate. Water having a high salinity hazard is best used only on soils having at least moderate permeability.

APPLICATION OF DIGITAL SIMULATION MODEL

Mathematical Model

A simulation model is a simplification or generalization of a complex physical system and its processes. Most aquifer systems are extremely complicated, and available data are not sufficient to describe them mathematically in sufficient detail; thus simplifications are necessary. These simplifications take the form of a set of assumptions that provide a basis for model selection or construction and aid in model calibration.

The two-dimensional finite-difference ground-water flow model described by Trescott and others (1976) was used to simulate the ground-water flow in the Box Butte County area. The strongly implicit procedure was used to solve the ground-water flow equations for the hydraulic head (potentiometric surface) values.

The equation describing two-dimensional flow of ground water in a water-table aquifer may be written as:

$$\frac{\partial}{\partial x}\left(Kxx\, b\, \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kyy\, b\, \frac{\partial h}{\partial y}\right) = Sy\, \frac{\partial h}{\partial t} + W\,(x,y,t) \qquad (5)$$

where

Kxx, Kyy are the principal components of the hydraulic conductivity tensor (Lt^{-1}) in the x and y Cartesian coordinate directions;

b is saturated thickness (L);

h is hydraulic head (L);

Sy is specific yield (dimensionless);

t is time (t); and

W(x,y,t) is volume flux per unit area (Lt^{-1}).

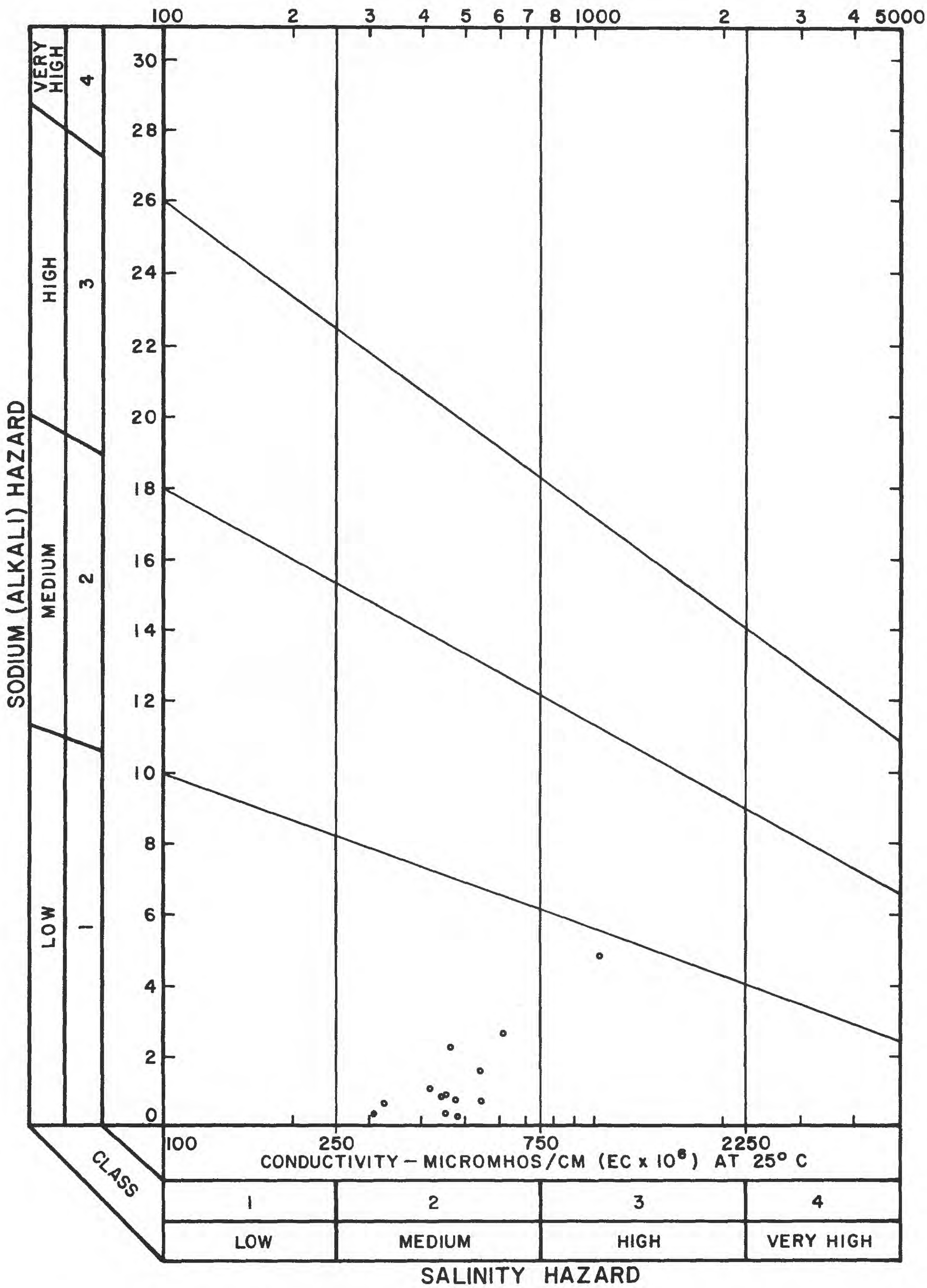


Figure 12.--Classification for irrigation of ground water from the aquifer system.

This finite-difference model simulates ground-water flow in a single layer aquifer system that can be described in two dimensions. Qualifying assumptions made in the model analysis to enable usage of the Trescott model are as follows:

1. All saturated rock above the Brule Formation of the White River Group is treated as a single aquifer.

2. Ground water moves horizontally in the High Plains aquifer system in a single-layer, heterogeneous, isotropic medium.

3. Water moves vertically into or out of the High Plains aquifer system through the overlying unsaturated zone. No leakage occurs through the lower confining layer.

4. Regionally, the vertical-flow velocity within the aquifer is negligible in comparison to the horizontal-flow velocity; thus, flow is considered to be two-dimensional.

5. Aquifer parameters are averaged for each cell in the model.

6. Aquifer system is treated wholly as an unconfined aquifer.

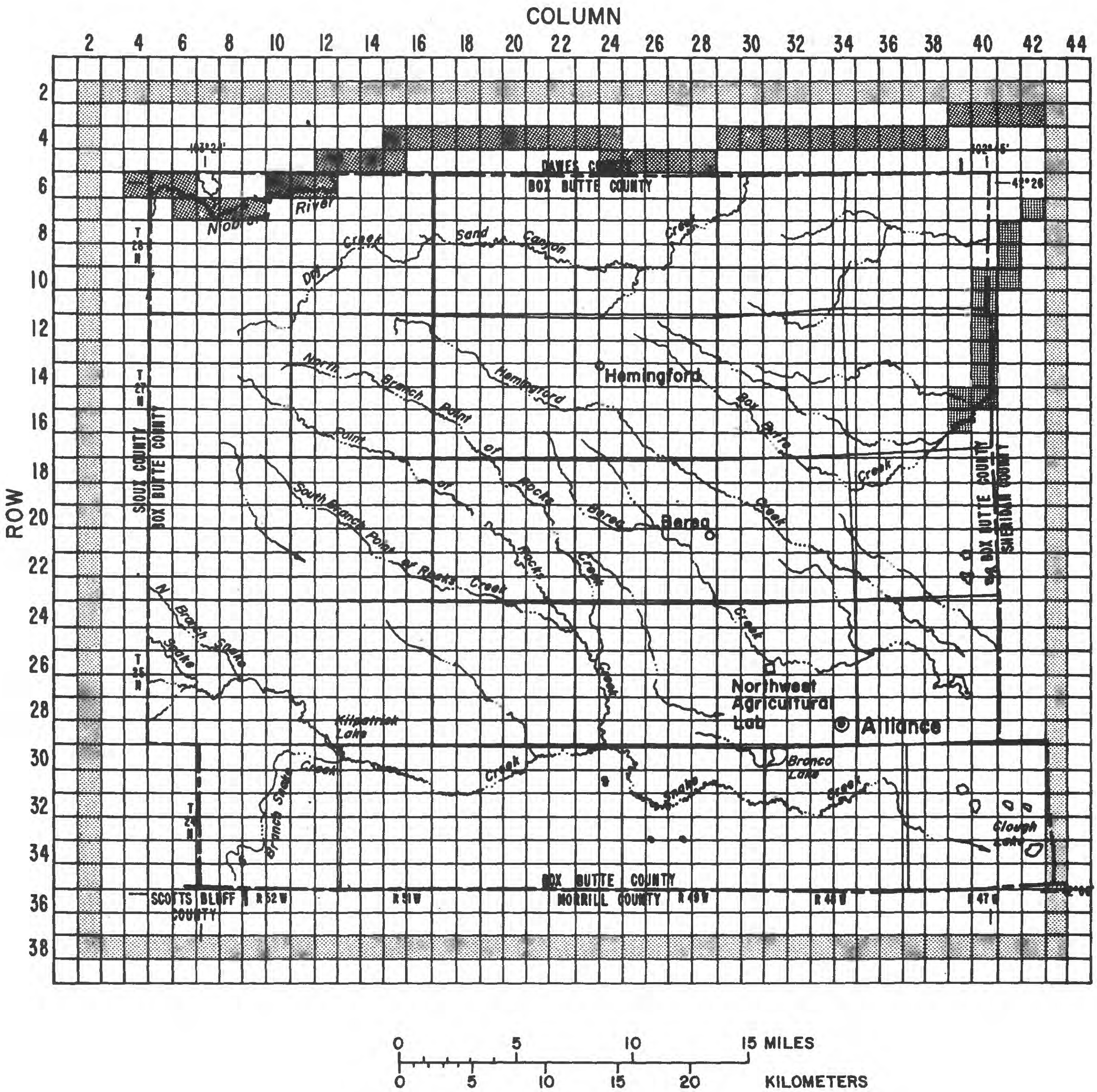
7. Reported perched ground water is temporary and will not affect model calibration; therefore, it is not included in the input to the model.

Modeled Area and Boundary Conditions

The boundaries of the modeled area extend several miles beyond the borders of the county and far enough from simulated pumping areas so that they would not be significantly affected by pumping stresses (fig. 13). The area modeled exceeds 1,700 square miles.

The modeled area was subdivided into cells of 1 square mile forming a finite-difference grid having 39 rows and 44 columns. By convention, nodes are located at the centers of the cells of the grid. All aquifer properties and stresses were defined at the nodes.

The nodes along the boundaries were modeled as constant heads, because it was believed that underflow into or out of the study area was sufficient to maintain the head in the aquifer system at nearly a constant altitude. Although pumpage occurs near the eastern boundary of the modeled area, the proximity of numerous lakes provide an abundant source of water for maintaining constant heads. Heads at river nodes, which



EXPLANATION

FINITE-DIFFERENCE CELL

CELL REPRESENTING CONSTANT-HEAD BOUNDARY

CELL REPRESENTING STREAMS HYDRAULICALLY CONNECTED TO AQUIFER

Figure 13.--Finite-difference grid used in simulation model.

represent the boundary between the Niobrara River and the aquifer system, were adjusted downward for leakage from the aquifer (gaining stream) or adjusted upward for leakage to the aquifer (losing stream), in order to match the gain or loss in streamflow determined by seepage measurements made in 1980. Heads at river nodes were not adjusted if no leakage occurred between the stream and the aquifer system. Snake Creek above Kilpatrick Lake was not simulated because the flow, although perennial, was assumed to be too small to significantly affect the model. The base of the aquifer system, which is the top of the Brule Formation of the White River Group, has very low hydraulic conductivity compared to that of overlying deposits and is represented in the model as a no-flow boundary.

Input Data to Model

The data needed in modeling the aquifer system are hydraulic conductivity, specific yield, altitude of base of aquifer, stresses on the aquifer system (all recharges and discharges to system), and hydraulic head or potentiometric surface. Data are prepared for modeling in the form of arrays, which are arrangements of specific values for each node in figure 13. The potentiometric surface arrays needed in the respective simulation were prepared from potentiometric surface maps for the respective years of 1938, 1950, 1960, 1965, 1970, 1975, and 1980. The arrays of hydraulic conductivity, specific yield, and base of aquifer altitudes were prepared from the maps of the respective parameters discussed and presented in the section on hydrology.

Natural discharge was assumed to be to streams and to evapotranspiration. Discharge to streams was estimated from seepage measurements and was adjusted in the model by varying the leakage coefficient of the streambed. The quantity discharged by evapotranspiration was estimated from lake evaporation and vegetation characteristics at the ground surface and was decreased in the model as depths to water increased. Discharge by underflow from the study area was accounted for by constant heads, as described under the section on Boundary Conditions.

Natural recharge was assumed to occur only by underflow and infiltration of precipitation. Recharge by underflow to the study area was accounted for by constant heads as described earlier. The quantity recharged through infiltration was estimated across the study area from the amount of precipitation, evapotranspiration, vegetation, slope, and soil permeability.

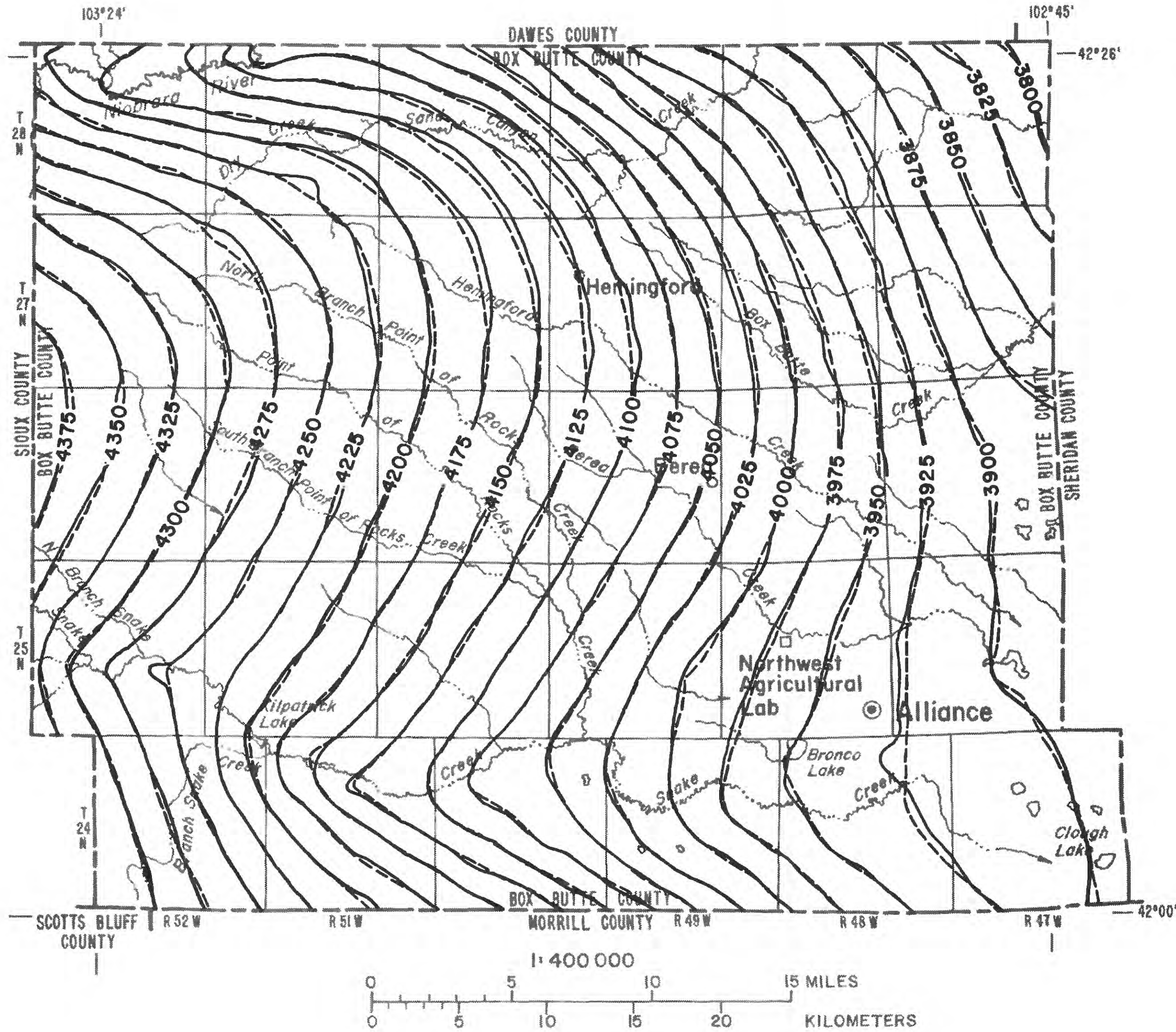
Model Calibration and Verification

Prior to 1938 and the development of ground water for irrigation, the ground-water system in Box Butte County is assumed to have been in equilibrium, that is to say, in a steady-state condition. Natural recharge equaled natural discharge; and water levels, while varying seasonally, changed little over long periods of time. A digital model was developed and calibrated to represent steady-state conditions in order to evaluate the conceptual model of the ground-water system.

With the increasing development of ground water for irrigation beginning in the late 1930's, the equilibrium of the ground-water system was upset because withdrawal of ground water from the aquifer resulted in the removal of water from aquifer storage. The rate of withdrawal has accelerated and water levels have declined as much as 50 feet. To predict the effects of continuing ground-water development on water levels, the steady-state model was modified into a transient ground-water flow model that could represent response to pumping during the period 1938 to 1980.

In the model representing steady-state conditions, the hydrologic parameters for which data values are needed are: measured water levels of 1938; hydraulic conductivity of the aquifer system and leakage coefficient of streambeds; altitude of the base of the aquifer; natural recharge; and natural discharge. In calibrating the model to steady-state conditions, initial values were assigned to each hydrologic parameter and initial model computations were made. Results of these computations were compared to measured results, adjustments were made in the values of selected parameters, and computations were made repeatedly until a "best fit" between computed and measured results was achieved.

In calibrating to steady-state conditions, adjustments of parameter values were limited to hydraulic conductivity of the ground-water system, leakage coefficient of the streambeds, and to recharge. Initial values assigned to natural recharge were adjusted systematically during the calibration process. The adjustments (described in the section on "Recharge") were principally to increase recharge to the northeast and decrease it to the southwest to account for variations of climatic factors. The magnitude of the changes made in hydraulic conductivity and recharge during calibration was an average absolute value of 2.89 feet per day and 0.068 inches, respectively, per node. The change made in the leakage coefficient of the streambed during calibration was both very small and for a small percentage of the area modeled. Consequently, the average magnitude of the small change was not determined. The degree to which the model was able to simulate steady-state conditions is shown on figure 14.



EXPLANATION

—4000— MEASURED WATER-LEVEL CONTOUR--Shows altitude of potentiometric surface in 1938. Contour interval, 25 feet. Datum is NGVD of 1929

--4000-- SIMULATED WATER-LEVEL CONTOUR--Shows computed altitude of potentiometric surface. Contour interval, 25 feet. Datum is NGVD of 1929

Figure 14.--Comparison of 1938 water-level contours developed from water levels simulated by the steady-state model to those developed from measured water levels.

In order to represent transient conditions in the model, data values are needed not only for the parameters mentioned in the previous paragraph, but also for specific yield and for any additional stresses on the aquifer. The main added stress on the aquifer system is pumpage for irrigation, which generally has increased each year. The pumpage was estimated by first determining the annual average volume of water pumped by a well for each type of distribution system (table 3). Then a weighted-average volume of water for each grid block was computed by multiplying the number of wells serving each type of distribution system in the block by the appropriate annual average volume. The weighted-average volume of water then was adjusted to account for seepage of pumped water back to the ground-water system.

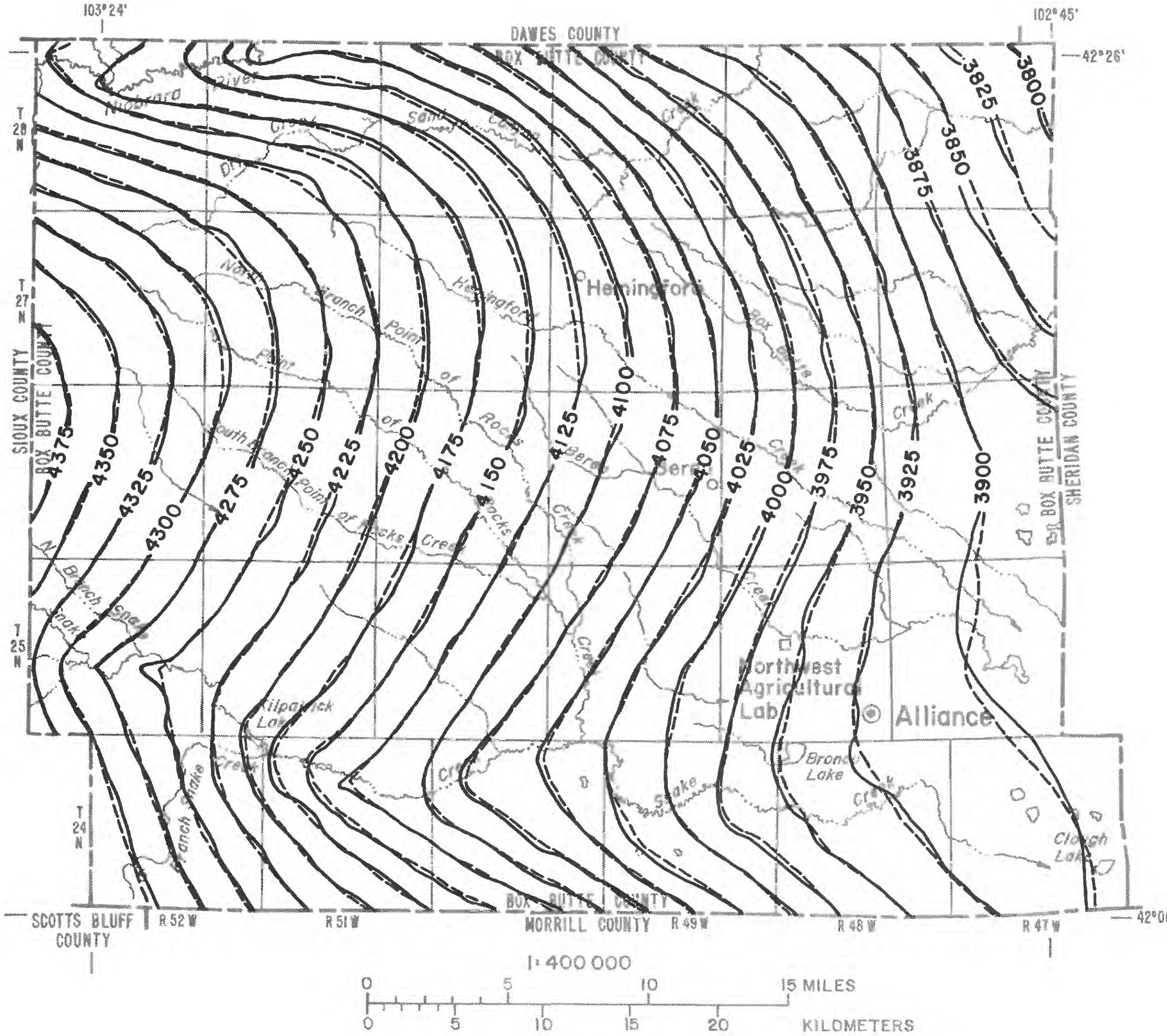
A secondary added stress on the system is recharge from precipitation, which was recomputed for 1950, 1960, and for every fifth year thereafter to 1980. This was necessary because each year some dryland was converted to irrigated land. As irrigated land has a higher average soil moisture than dryland, it allows more of the precipitation that falls on it to percolate to the water table.

Transient model simulations were calibrated for three pumping periods: 1939-40, 1941-50, and 1951-60. Heads from the steady-state model were used at the beginning of the first pumping period to simulate transient conditions. Heads for the beginning of all succeeding periods of transient simulation were those from the last pumping period of the previous simulation.

The parameters adjusted in calibrating the model to transient conditions were specific yield, recharge from precipitation due to change in land use, and discharge from wells. As in calibrating the model for the steady-state conditions, adjustments of parameter values and subsequent model computations were made repeatedly until a "best fit" was achieved between measured and computed data. A satisfactory fit was achieved as shown on figure 15.

The magnitude of the change made in specific yield during calibration was an average absolute value of 1.25 per node. The change in recharge due to land-use change and discharge from wells was made based on values presented in table 2 and table 3, respectively.

The calibration procedure aims to minimize differences between the computed and the measured potentiometric surface by adjusting the input data. The degree of allowable adjustment of any of the input parameters generally is directly proportional to the uncertainty of its value. For example, if test-hole logs and well logs are available to determine hydraulic conductivity and altitude of base of the aquifer, their values



EXPLANATION

—— 4000 —— MEASURED WATER-LEVEL CONTOUR--Shows altitude of potentiometric surface in 1960. Contour interval, 25 feet. Datum is NGVD of 1929

– – 4000 – – SIMULATED WATER-LEVEL CONTOUR--Shows computed altitude of potentiometric surface. Contour interval, 25 feet. Datum is NGVD of 1929

Figure 15.--Comparison of 1960 water-level contours developed from water levels simulated by the transient-state model to those developed from measured water levels.

may need very little adjusting. By contrast, natural discharge and recharge may be poorly known, so that it is necessary to estimate discharge by evapotranspiration using a technique illustrated by equation (4) and adjust recharge from precipitation over a range of estimated values.

The calibration procedure helps to improve our understanding of the aquifer. The model integrates the effects of all the factors that affect ground-water flow, and the computed water levels are a result of input data. Hence, whether any element of the conceptual model must be revised can be determined during simulation. Any adjustment of input data constitutes a modification of the model itself.

A simulation model of a ground-water system is commonly tested over periods of time by providing stress data, such as pumping, for one or more time periods and comparing simulated results from the calibrated transient model to one or more independent sets of measurements. Transient-model simulations were compared for four pumping periods: 1961-65, 1966-70, 1971-75, and 1976-80. Using the parameters, stresses, and boundary conditions previously described, the transient model was tested by generating annual water-level contours to match those measured between 1961 and 1980. The acceptability of the transient model was determined by comparing the best fit of the measured and calculated water-level contours as shown for the years 1970 and 1980 in figures 16 and 17, respectively.

The best fit of computed to measured water levels also was determined statistically from the root mean square (rms). A decrease in rms indicates an improvement in fit. The rms was computed using the following equation:

$$\text{rms} = \left[\frac{1}{n} \sum_{i=1}^{n} (h_i \quad h_i^o)^2 \right]^{1/2} \tag{6}$$

where

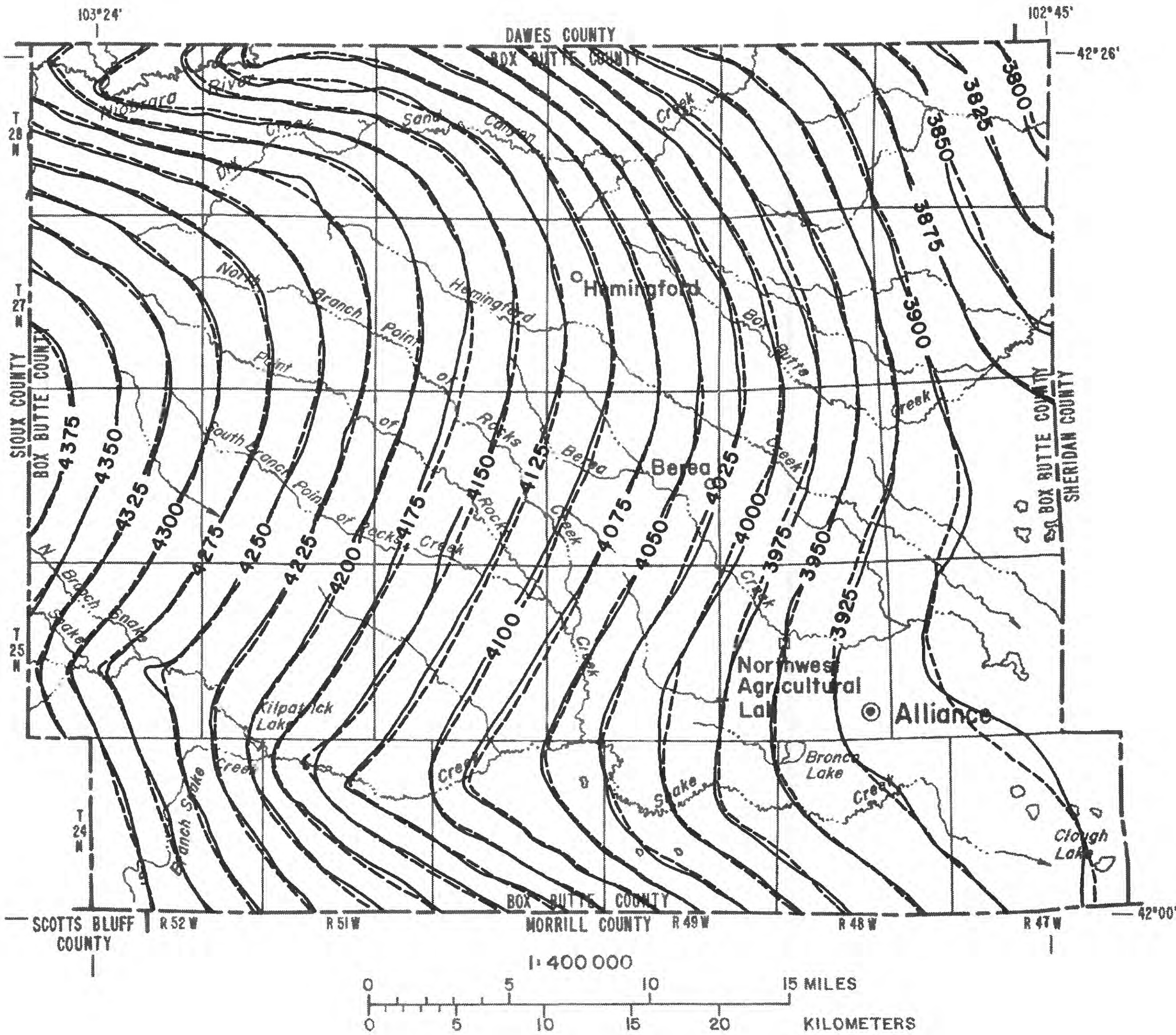
rms is root mean square of the difference between water levels computed by the model and measured water levels, in feet;

n is number of data nodes;

h_i is computed water level of the i^{th} node, in feet; and

h_i^o is measured water level of the i^{th} node, in feet.

Only those observation wells located on or near a contour line that passes through the center of the node were used to compute rms. The rms for the steady-state model, using 1938 data for 88 nodes, was 7.12 feet

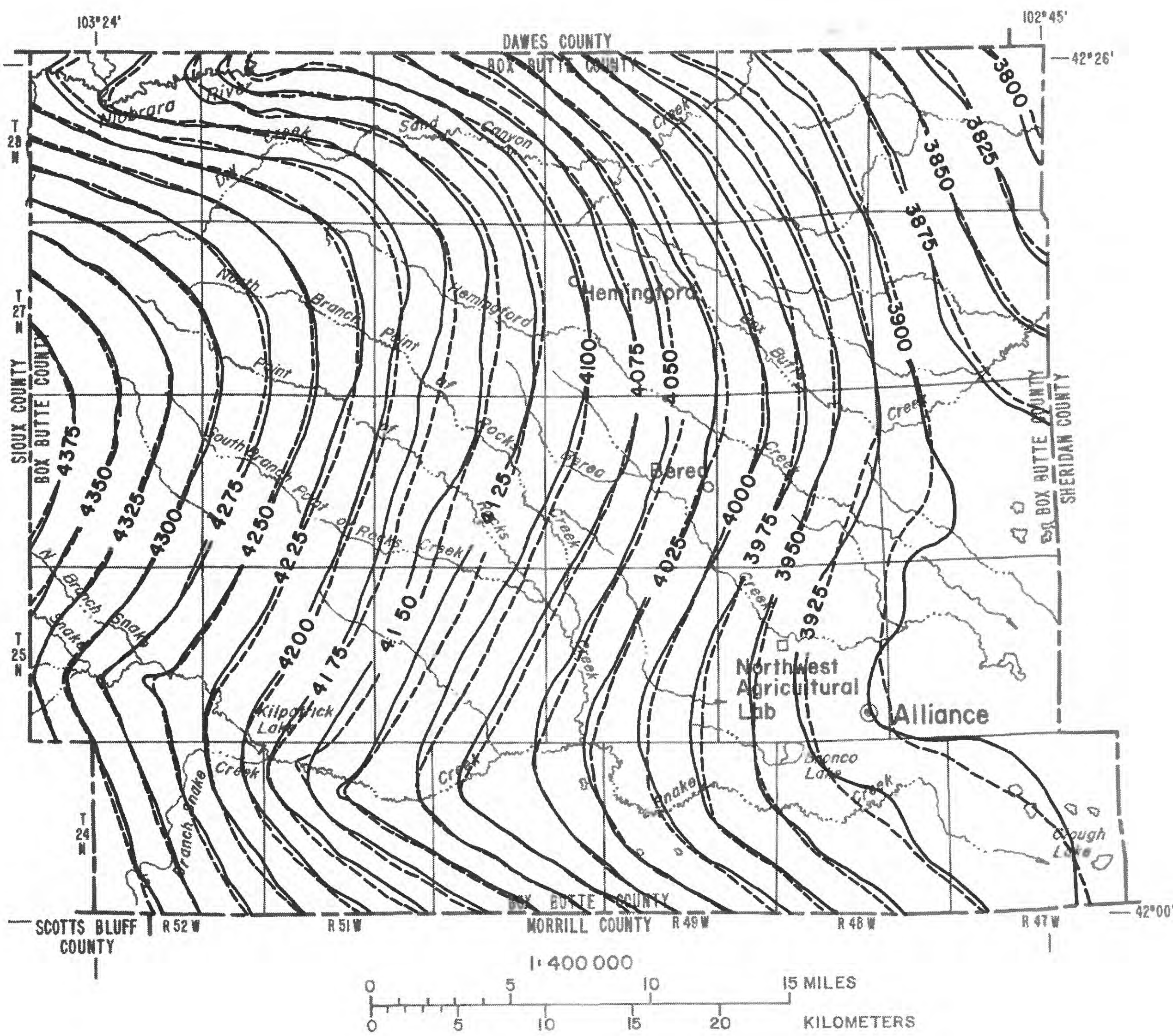


EXPLANATION

——4000—— MEASURED WATER-LEVEL CONTOUR--Shows altitude of potentiometric surface in 1970. Contour interval, 25 feet. Datum is NGVD of 1929

– – 4000 – – SIMULATED WATER-LEVEL CONTOUR--Shows computed altitude of potentiometric surface. Contour interval, 25 feet. Datum is NGVD of 1929

Figure 16.--Comparison of 1970 water-level contours developed from water levels simulated by the transient-state model to those developed from measured water levels.



EXPLANATION

—4000— MEASURED WATER-LEVEL CONTOUR--Shows altitude of potentiometric surface in 1980. Contour interval, 25 feet. Datum is NGVD of 1929

- -4000- - SIMULATED WATER-LEVEL CONTOUR--Shows computed altitude of potentiometric surface. Contour interval, 25 feet. Datum is NGVD of 1929

Figure 17.--Comparison of 1980 water-level contours developed from water levels simulated by the transient-state model to those developed from measured water levels.

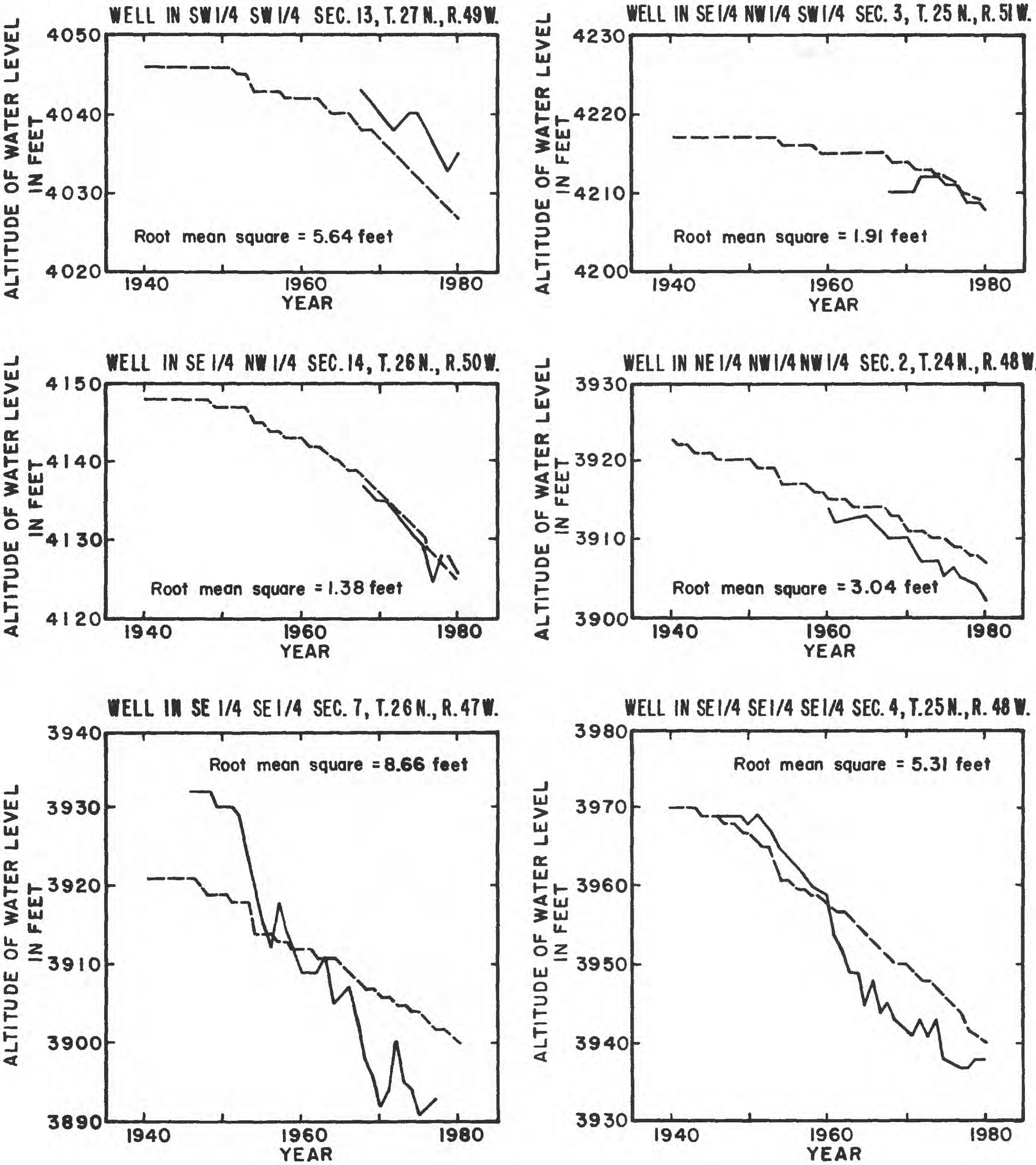
(fig. 14), which is the average difference between the measured and computed water levels for the 88 nodes. The rms for the transient model, using 1980 data for 33 nodes, was 9.03 feet (fig. 17), which is the average difference between the measured and computed water levels for the 33 nodes. The difference for both steady and transient-state computations is less than one-half the contour interval for the respective potentiometric surface maps.

How well the model simulated the general response of the aquifer system is shown in figures 15, 16, and 17 and by the computed rms. To verify how well the model simulates water levels in individual wells, simulated water levels are compared to measured water levels in six wells, each of which has been measured at least 10 years (fig. 18). The rms for the six wells ranged from 1.38 to 8.66 feet and averaged 4.32 feet, which is the average difference between measured and computed water levels for the six wells. This difference is less than 2 percent of the average saturated thickness in 1938.

The comparison of measured to computed water-level altitudes through the use of contour maps, graphs, and rms computations indicates that the transient model is adequate for projecting water-level changes likely to occur as the result of following various management alternatives.

Results of model computations are influenced to different degrees by changes in principal aquifer parameters. To determine the magnitude of the change in the computed water levels that would occur due to a change in one or more of the aquifer's parameters that make up the conceptual model, an analysis of the sensitivity of the hydrologic model was made. This analysis provides data by which the effect of error in measurements or estimations of parameter values on the model-computed data may be assessed.

Results of the sensitivity analysis of the transient-slate model (table 4) indicate the variation in average and maximum computed water levels when hydraulic conductivity, specific yield, or recharge are increased by either 25 or 50 percent. For example, the average change in computed water levels is 7.3 feet when specific yield is increased by 50 percent, but is 11 feet when hydraulic conductivity is increased either 25 or 50 percent. Maximum change in water levels is 45 feet for a 25 percent increase in hydraulic conductivity and is 48 feet for a 25 percent increase in recharge. These results indicate that the model is only slightly sensitive to increases in the above parameters when the average water-level change for the whole county is being computed, but that it can be very sensitive when water levels for small areas are being computed.



EXPLANATION

-------- MODEL-SIMULATED WATER LEVEL

———— MEASURED WATER LEVEL

Figure 18.--Comparison of model-simulated and measured water levels in individual wells.

Decreases in hydraulic conductivity and recharge parameter values showed results similar to those for increases. However, when specific yield was decreased 50 percent, an average water-level change of 21.7 feet resulted. This indicates that the model became increasingly sensitive as specific yield decreased in magnitude and, thus, to change in pumpage.

Data in table 4 indicate that the model-computed results would be only slightly affected by errors in the parameters of as much as 25 percent if the model is computing change for the entire county, but might be highly affected if the model is computing change for small areas within the county.

Table 4.--Sensitivity of the transient model to changes in hydrologic parameters

Parameter	Change in potentiometric surface, absolute value in feet							
	Parameter decreased by				Parameter increased by			
	50 percent		25 percent		25 percent		50 percent	
	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
Hydraulic conductivity	11.1	72	11.0	56	11.0	45	11.0	43
Specific yield	21.7	90	14.6	63	8.8	39	7.3	32
Recharge	11.4	48	11.2	48	10.8	48	10.7	47

Model Projections

Following calibration and verification of the transient-state model, several different management alternatives were simulated to estimate future water-level trends with changes in simulated pumpage and recharge.

A series of simulation computations were made using the projected pumpage for 1980 through 1991 and 1980 through 2002 and noting the effect this pumpage has on spring water levels for the periods 1981 through 1992 and 1981 through 2003. Projected pumpage was varied to estimate the range of water-level decline that wouid occur in the county during those periods. The alternative-management plans explored were:

(1) to increase pumpage from 1980 through 1991 at the 1975 rate, which is the maximum annual rate recorded in the county from 1938 through 1981; (2) to increase pumpage from 1980 through 1991 at the average annual rate recorded for the period 1961 through 1981, which is about 45 percent of the maximum annual rate for plan (1); and (3) to continue pumpage at the 1981 rate from 1980 through 1991 and from 1980 through 2002.

The procedure used to distribute increases in pumpage called for in plans (1) and (2) was designed on the assumption that all pumping increases would be from new irrigation wells supplying center-pivot distribution systems on existing nonirrigated cropland, and that each well would supply water for a quarter section of land. The number of quarter sections of nonirrigated cropland in each township was determined from a land-use map prepared during an inventory taken in 1981 of water used for irrigation. The totals of such quarter sections in each township were then summed to get the total number of quarter sections not irrigated in the county. The increase in the number of quarter sections to be irrigated in each township per year was computed from the ratio of the nonirrigated quarter sections in the township to those in the entire county multiplied by the planned annual county increase. For example, if nonirrigated cropland in a township was 40 quarter sections, the nonirrigated cropland in the county totaled 1,600 quarter sections, and the planned county annual increase was 80 quarter sections, the annual increase in the number of irrigated quarter sections for that township was two. The two quarter sections were then selected randomly within the township. This procedure was followed for each year in management plans (1) and (2).

Plan (1) is a management alternative to continually increase crop production by increasing pumpage to the maximum annual rate recorded from 1938 through 1981. The increased pumpage would be from new wells drilled on cropland that previously had not been irrigated. The projections from this plan indicate that for the period 1981 to 1992, water levels will decline as much as 29 feet below the 1981 water level. The projections from this plan also show that the area of decline of 10 feet or more (fig. 19) will increase from 336 square miles (1981) to 630 square miles (1992), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 240 square miles (1992).

Plan (2) is a management alternative to moderate the annual increase in pumpage and still maintain a continuing increase in crop production. In this plan it is assumed that pumpage will continue to increase at the average annual rate recorded for the period 1961 through 1981, and that acres irrigated and wells installed will continue to increase. The

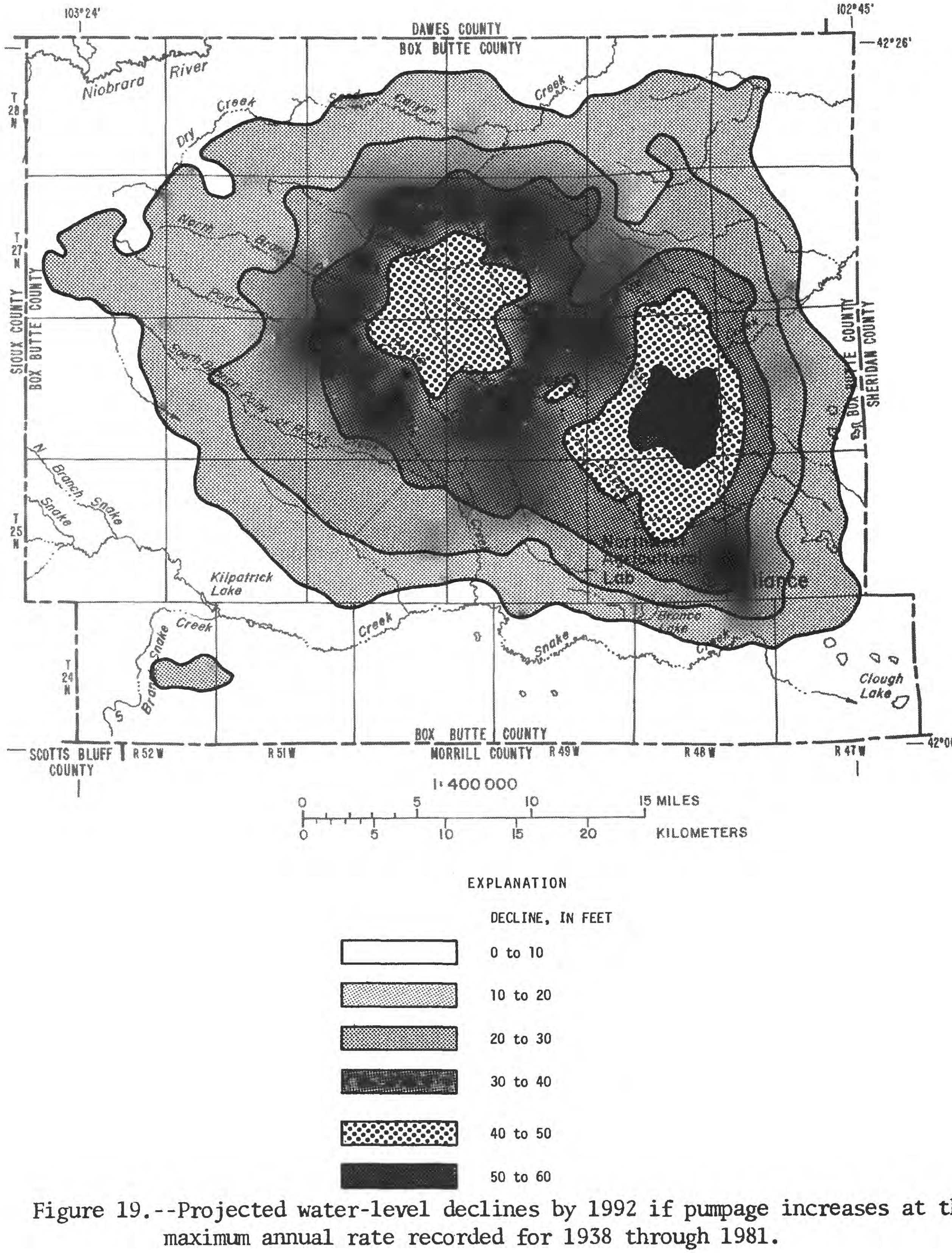


Figure 19.--Projected water-level declines by 1992 if pumpage increases at the maximum annual rate recorded for 1938 through 1981.

projection from this plan indicates that for the period 1981 to 1992, water levels will decline as much as 20 feet below the 1981 water level. The projections from this plan also show that the area of decline of 10 feet or more (fig. 20) will increase from 336 square miles (1981) to 565 square miles (1992), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 198 square miles (1992).

Plan (3) is a management alternative to maintain crop production and pumpage at the 1981 level. In this plan it is assumed that the number of acres irrigated and number of wells pumped would not increase above the 1981 level. The projection from the first part of this plan indicates that for the period 1981 to 1992, water levels will decline as much as 13 feet below the 1981 water level. The projections from this plan also show that the area of decline of 10 feet or more (fig. 21) will increase from 336 square miles (1981) to 530 square miles (1992), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 152 square miles (1992).

The second part of this plan assumes that pumpage will continue at the 1981 rate for 23 years and thus maintain crop production near the 1981 level to the year 2002. The projection from this plan indicates that for the period 1981 to 2003, water levels will decline as much as 24 feet below the 1981 water level. The projections from this plan also show that the area of decline of 10 feet or more (fig. 22) will increase from 336 square miles (1981) to 595 square miles (2003), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 320 square miles (2003).

Results of computations of mass balance of ground water in Box Butte County are given in table 5. The small differences, in percent, between inflow to the ground-water system and outflow from the system provide assurance that the model was performing all mathematical manipulations properly, and that the results for each component of inflow or outflow are reasonable. In the table, water removed from storage is treated as inflow. "Constant head" refers to the ground water that moves into or out of the county across a constant-head boundary. "Leakage" may be either inflow to the ground-water system from streams or outflow from the ground-water system to streams.

Results of mass-balance computations are given in the table for two historical periods of a decade each. Comparison of results for the two decades indicates that pumpage in the county increased eightfold between the 1940's and the 1970's from 9,338 to 78,266 acre-feet. Most of the water pumped came from storage. In the 1940's, 5,178 acre-feet was removed from storage each year; but in the 1970's, the amount removed from storage annually was 38,491 acre-feet.

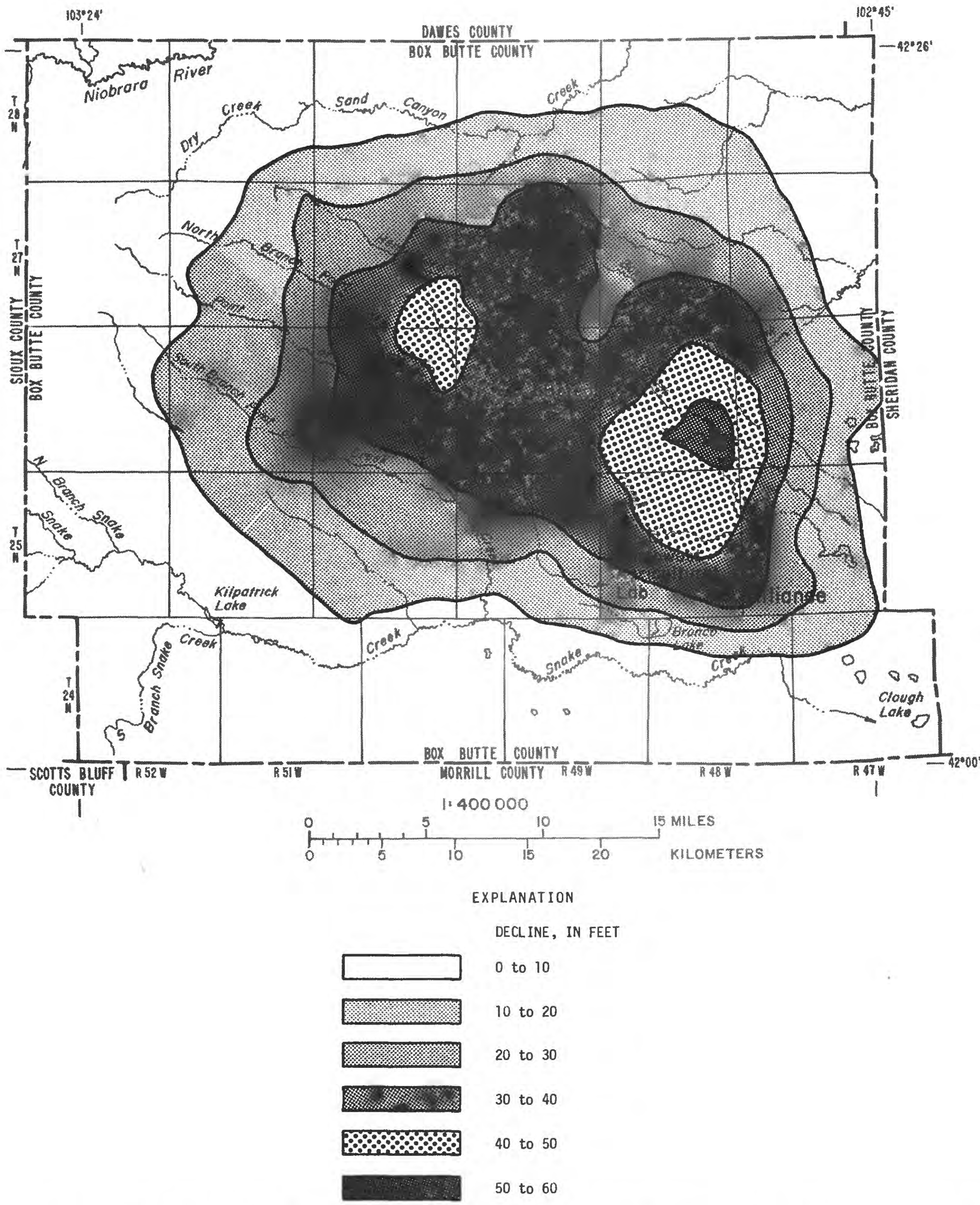


Figure 20.--Projected water-level declines by 1992 if pumpage increases at the average annual rate recorded for 1961 through 1981.

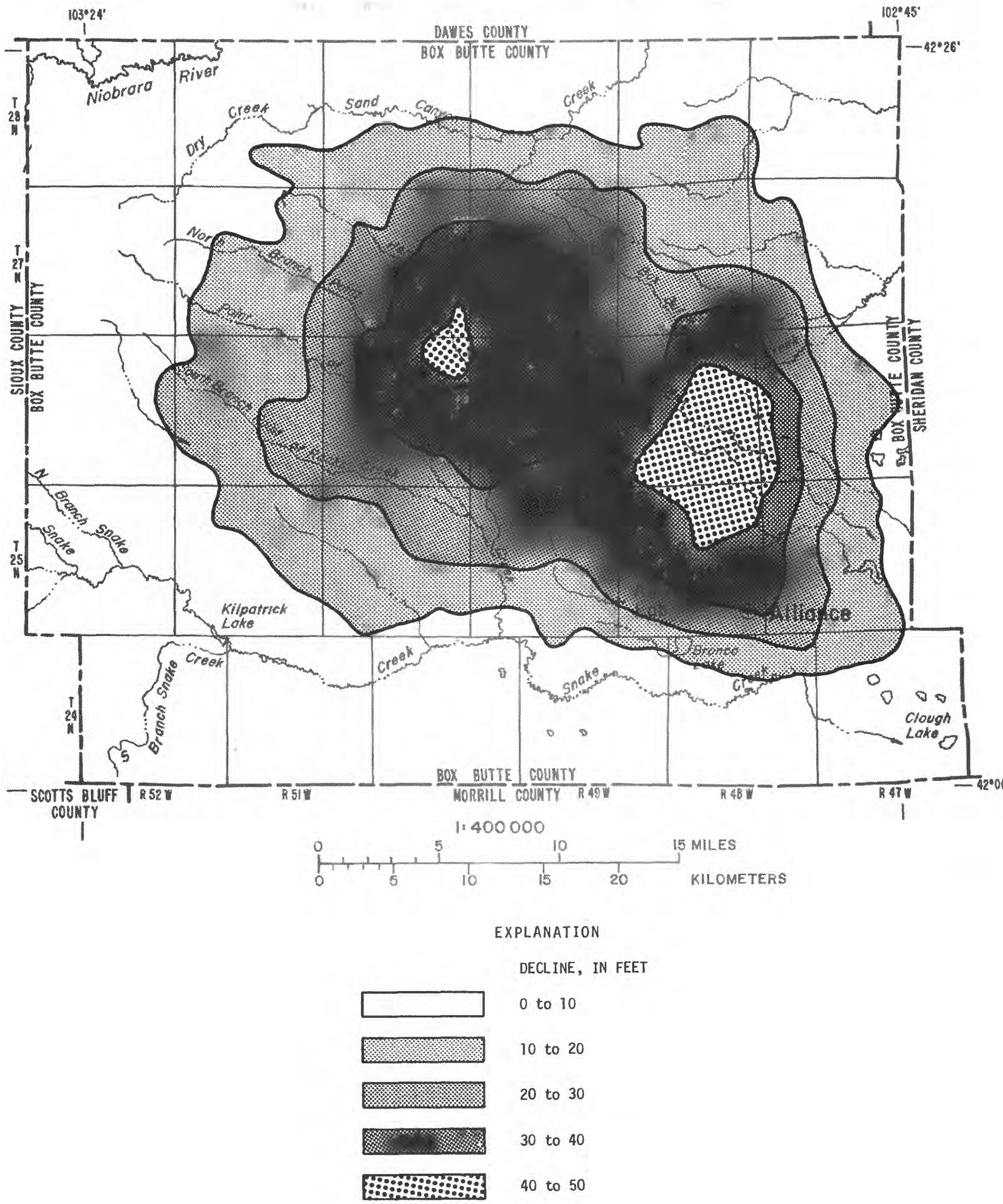


Figure 21.--Projected water-level declines by 1992 if pumpage remains at the annual rate recorded for 1981.

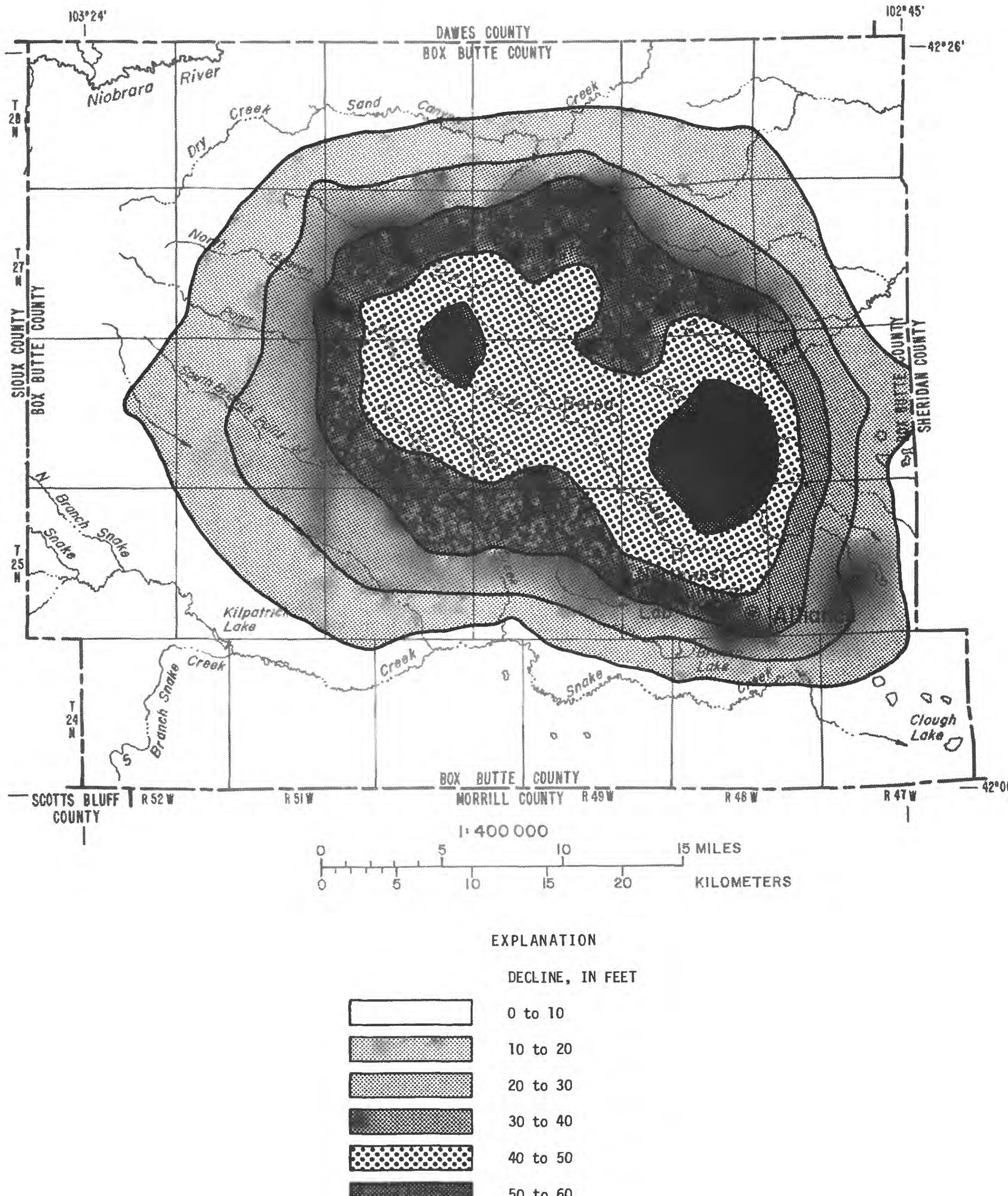


Figure 22.--Projected water-level declines by 2003 if pumpage remains at the annual rate recorded for 1981.

Table 5.--Average annual mass balance of ground water in Box Butte County model area

[Inflow and outflow in acre-feet per year]

Period or plan	Inflow					Outflow					Percent difference
	Removal from storage	Recharge	Constant head	Leakage	Total	Evapotranspiration	Constant head	Pumping	Leakage	Total	
					Historic balance						
1941-50	5,178	118,349	72,146	0	195,672	110,235	12,593	9,338	63,413	195,578	0.05
1971-80	38,491	121,189	73,346	272	233,357	90,521	11,622	78,266	52,906	233,315	.02
					Projected balance, 1981-92						
Plan 1	84,467	121,756	74,310	572	281,105	78,080	10,580	141,972	50,408	281,040	.03
Plan 2	65,861	121,933	74,209	455	263,459	78,912	10,637	122,930	50,914	263,393	.02
Plan 3	52,636	122,756	74,171	418	248,981	79,398	10,683	107,517	51,314	248,912	.03

Increased removal of water from storage caused small amounts of leakage to the ground-water system from streams during a few periods in the 1970's--something that did not happen in the 1940's, nor, in fact, in the 1950's or 1960's. Increased removal of water from storage, by lowering the potentiometric surface, caused outflow from the ground-water system through evapotranspiration to decrease significantly from 110,235 to 90,521 acre-feet. The 19,714 acre-foot difference between these two figures may be regarded as additional water being salvaged each year that would otherwise have been lost through evapotranspiration. In addition, recharge to the ground-water system increased due to a change from dryland to irrigated farming in much of the county.

Results of mass-balance computations are given in the table for each of the three alternative-management plans. Regardless of the plan considered, pumpage will be significantly higher in the 1981-92 period than during the 1970's. However, implementation of plan (1) will result in the greatest increase in pumpage, in removal of water from storage, and in leakage to the ground-water system from lakes and streams. Even though pumpage would increase to 141,972 acre-feet annually if plan (1) were followed, such an amount is small compared to the 34.4 million acre-feet estimated to be recoverable by pumping in the county in 1980.

SUMMARY AND CONCLUSIONS

A gradual depleting of the water stored in the aquifer system beneath the county has resulted in concern for the agricultural economy of the area by both State and local agencies. From 1938 to 1980, water levels declined more than 10 feet in an area of about 336 square miles in the east-central part of the county. These water-level declines represent a decrease in saturated thickness of from 1 to 9 percent. The saturated thickness of the aquifer throughout the county averages about 342 feet.

The estimated volume of ground water stored in the aquifer system in Box Butte County in 1980 was 80.3 million acre-feet, and the estimated volume recoverable was 34.4 million acre-feet. The estimated volume pumped in 1980 was 104,000 acre-feet.

Average annual precipitation in the county is 17.1 inches. The permeabilities of overlying soils range from 1.35 inches per hour for silty clay loam soils to 12.6 inches per hour for sandy soils. The resultant average annual recharge to the aquifer ranges from 0.06 to 4.33 inches and averages about 1.6 inches. Hydraulic conductivity of the aquifer system ranges from 6 to 60 feet per day and is more than 25 feet per day in 21 percent of the county. Weighted specific yield ranges from 12 to 21 percent and averages about 15 percent.

A digital model of the aquifer system underlying Box Butte County was developed to simulate steady-state conditions. Because the equilibrium of the ground-water system was upset by pumping after 1938, the steady-state model was modified into a transient-state model. This latter model was modified, based on the pumping history, and used to project changes in ground-water levels under three alternative-management plans.

Alternative-management plan (1) assumes that pumping will continue to increase at the maximum annual rate recorded from 1938 through 1981. Based on this assumption, the projections indicate that for the period 1981 to 1992, water levels will decline as much as 29 feet below the 1981 water level, that the area of decline of 10 feet or more will increase from 336 square miles (1981) to 630 square miles (1992), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 240 square miles (1992).

Alternative-management plan (2) assumes that pumpage will continue to increase at the average annual rate recorded for the period 1961 through 1981. Based on this assumption, the projection indicates that for the period 1981 to 1992, water levels will decline as much as 20 feet below the 1981 water level, that the area of decline of 10 feet or more will increase from 336 square miles (1981) to 565 square miles (1992), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 198 square miles (1992).

Alternative-management plan (3), first part, assumes that pumpage will continue at the 1981 rate. Based on this assumption, the projections indicate that for the period 1981 to 1992, water levels will decline as much as 13 feet below the 1981 water level, that the area of decline of 10 feet or more will increase from 336 square miles (1981) to 530 square miles (1992), and that the area of decline of 30 feet or more will increase from 17 square miles (1981) to 152 square miles (1992). The second part of the plan assumes that pumpage will continue at the 1981 rate to the year 2003. Based on this assumption, the projections indicate that for the period 1981 to 2003, water levels will decline as much as 24 feet below the 1981 water level, that the area of decline of 10 feet or more will increase to 595 square miles (2003), and that the area of decline of 30 feet or more will increase to 320 square miles (2003).

Computation of mass balance provides information on the accuracy of the technique for solving the finite-difference equations and a means of evaluating the modeling results. These computations indicate an eightfold increase in pumpage in the county from the decade of the 1940's to that of the 1970's and that most of the water pumped was removed from storage. In the 1970's, 19,714 acre-feet more water was salvaged annually from evapotranspiration than in the 1940's. Model projections for 1981-92 indicate that plan (1) will result in a greater increase in pumpage, in removal of water from storage, and in leakage to the ground-water system from lakes and streams. Even though pumpage would increase to 141,972 acre-feet annually if plan (1) were followed, this amount is small compared to the 34.4 million acre-feet estimated to be recoverable by pumping in the county in 1980.

Many hydrologic model studies are used to project water-level declines that result when pumpage is increased, decreased, or kept the same in the same general area. In this study, the projected pumpage was either kept the same or increased, and the increases were simulated by putting wells in cropland areas not previously irrigated. Consequently, because water-level decline was spread over a larger area, the projected rate of decline due to increased pumpage was reduced.

Spreading the increases in pumpage over previously nonirrigated areas appears to be consistent with prior irrigation development in the study area. Development, which first occurred near Alliance and then proceeded northwesterly, stabilized at about four wells per section. As development continues and this density of wells is achieved in new areas, water levels will continue to decline. Therefore, the hydrologic model presented in this study ought to be updated as new data become available and additional projections are needed.

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