KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 80-6

HYDROGEOLOGIC INVESTIGATIONS IN THE PAWNEE VALLEY, KANSAS

by

Marios Sophocleous

Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726

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Hydrogeologic Investigations in the Pawnee Valley, Kansas

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ABSTRACT

The use of groundwater increased rapidly in the Pawnee Valley during the last two decades, causing groundwater levels to decline and streamflow to diminish. Because of the severity of groundwater declines, Groundwater Management District No. 5 declared a moratorium on new drilling in that area, pending public hearings on the matter. For this reason, the Kansas Geological Survey was asked to undertake a short-term investigation of the alluvial aquifer in the Pawnee Valley and to evaluate the impact of present and future groundwater withdrawals in the region.

The topics covered in this report include the availability of groundwater in the Pawnee Valley; documentation of the depleting water resource of the area; calculation of a preliminary hydrologic budget for the area with emphasis on the groundwater component of the budget; and the adaptation, calibration, and application of a mathematical model that adequately simulates the operation of the hydrogeologic system for the purpose of evaluating several schemes for managing the groundwater resource. Two different estimates of regional groundwater recharge in the area based on interpretation of streamflow records at the discharge end of the flow system and on the use of a modulated soil-moisture budget based on hydrometeorological and soil data, indicated that the average natural recharge is approximately 0.5 inches per year. On the other hand, it was found that the amount of appropriated groundwater in the area exceeded the natural recharge figure more than 11 times.

Digital simulations of the aquifer system indicated that, even without any additional development or with very wet periods, water-

level declines will continue indefinitely, since groundwater withdrawals in the Pawnee Valley are of such magnitude. One option put forth for consideration is to prolong the life of the groundwater resource through the application of all the following recommendations: concerted efforts to reduce water wasting and to increase efficiency of water use; implementation of a 40% saturated-thickness depletion allowance for the next several years; imposition of a freeze on the number of irrigation wells to the present levels; and engagement in an artificial-recharge program.

INTRODUCTION

Use of groundwater increased rapidly in Pawnee Valley during the past several years, causing water levels to decline and streamflows to diminish. For this reason, the Kansas Geological Survey was asked to undertake a short-term investigation of the alluvial aquifer in the Pawnee Valley and to evaluate the impact of present and future ground-water withdrawals in the region.

Two groundwater management districts have jurisdiction over the Pawnee Valley. The Pawnee County portion of the Pawnee Valley is under the jurisdiction of Groundwater Management District No. 5, while the Hodgeman County portion is under the jurisdiction of Groundwater Management District No. 3. Because of the severity of groundwater declines in the Pawnee Valley, the Chief Engineer of the Water Resources Division, Kansas State Board of Agriculture declared, in 1978, a moratorium on new drilling in the Pawnee County portion of Pawnee Valley pending public hearings on the matter.

This report describes the hydrogeologic system of the surficial materials along the Pawnee Valley; changes to that system caused by agricultural development over the period from 1945-47 to the present; the development of a preliminary water balance for the region; and the adaptation and use of mathematical models to assess the effects of present and future development of irrigation wells.

Data for this study were obtained from a variety of published reports and unpublished material on file at the Kansas Geological Survey or provided by the groundwater management districts involved. Because of time and financial constraints, use is made of readily available data only; no extensive field or laboratory investigations were conducted for this study. However, extensive water-level surveys of Pawnee Valley were conducted for this study during June 1979 and January 1980.

This study will be presented in two parts. The first part will deal with the hydrogeologic system and historic changes in it; the second part will deal with numerical simulation of that system, which will encompass automated parameter adjustment routines, predictive runs, and management models.

OBJECTIVES

The main objectives of this study include:

1) Determination of the occurrence and availability of groundwater in the area;

2) Calculation of a preliminary hydrologic budget for the area with emphasis on the groundwater component of the budget;

3) Adaptation, calibration, and application of mathematical models that adequately simulate the operation of the hydrogeologic system for the purpose of evaluating the effects of present and future development on the groundwater supply under various management schemes.

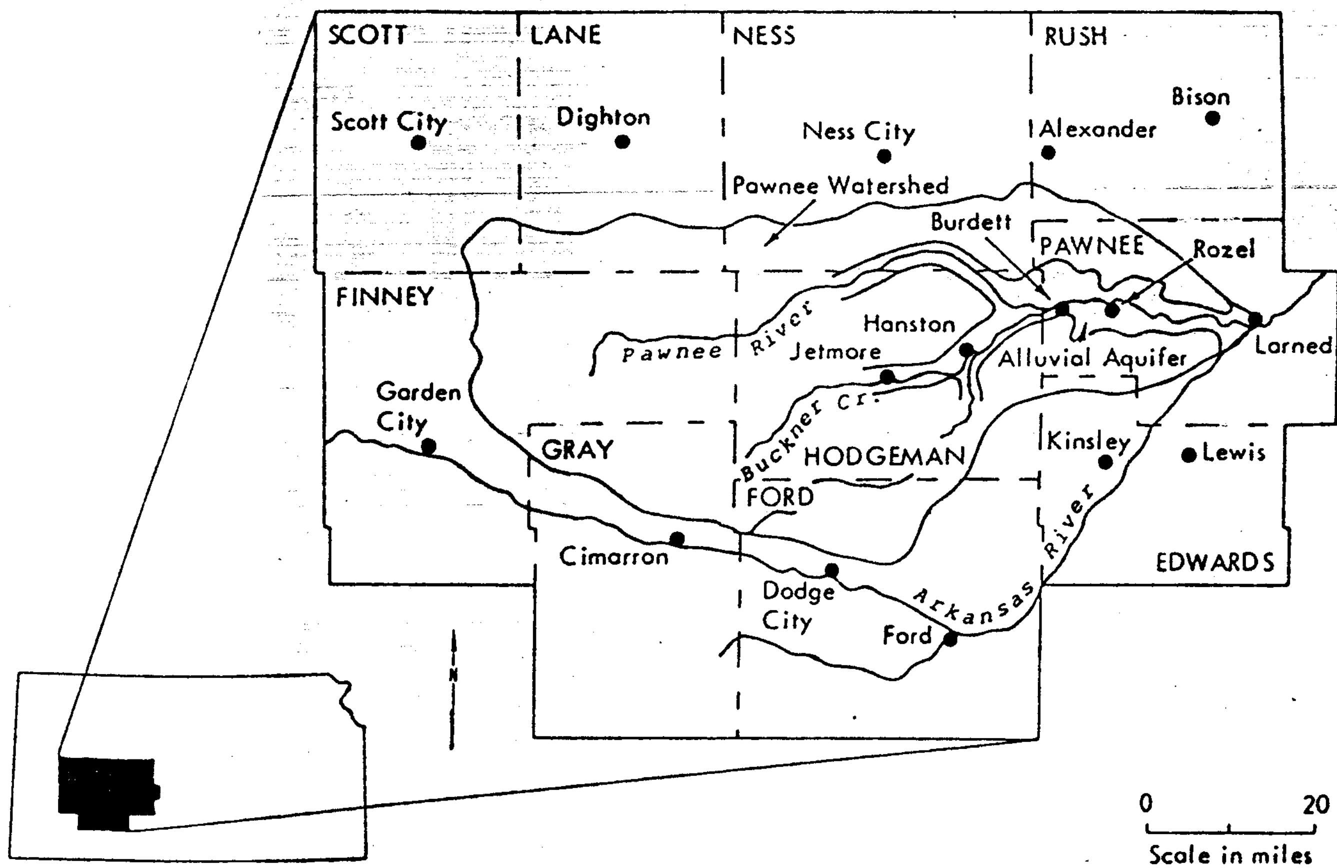


Figure 1. Area and location map.

LOCATION AND EXTENT OF THE STUDY AREA

The area studied in this report, in general terms, consists of the combined Pawnee River and Buckner Creek Watersheds, referred to as the Pawnee Watershed, approximately 2,735 square miles (Fig. 1). Particular emphasis is put on the area comprising the alluvial aquifer of the Pawnee Valley, which is located in Pawnee, Hodgeman, and Ness counties. It includes the Pawnee River Valley and the main tributaries of the Pawnee River, Buckner Creek, and Sawlog Creek.

WELL-NUMBERING SYSTEM

The well numbers in this report give locations according to the Bureau of Land Management's system of land subdivision. The first number indicates the township; the second number indicates the range west of the sixth principal meridian; and the third number indicates the section, followed by letters that indicate the subdivision of the section in which the well is located. The first letter denotes the quarter section or 160-acre tract; the second letter, the quarter-quarter section or 40-acre tract; and the third letter, when used, the quarter-quarter-quarter section or 10-acre tract. The 160-acre, 40-acre, and 10-acre tracts are designated a, b, c, and d, in a counterclockwise direction beginning in the northeastern quadrant. As an example, well 23-23W-21 aac is in the SW¼NE¼NE¼ sec. 21, T.23 S., R.23 W. (Fig. 2).

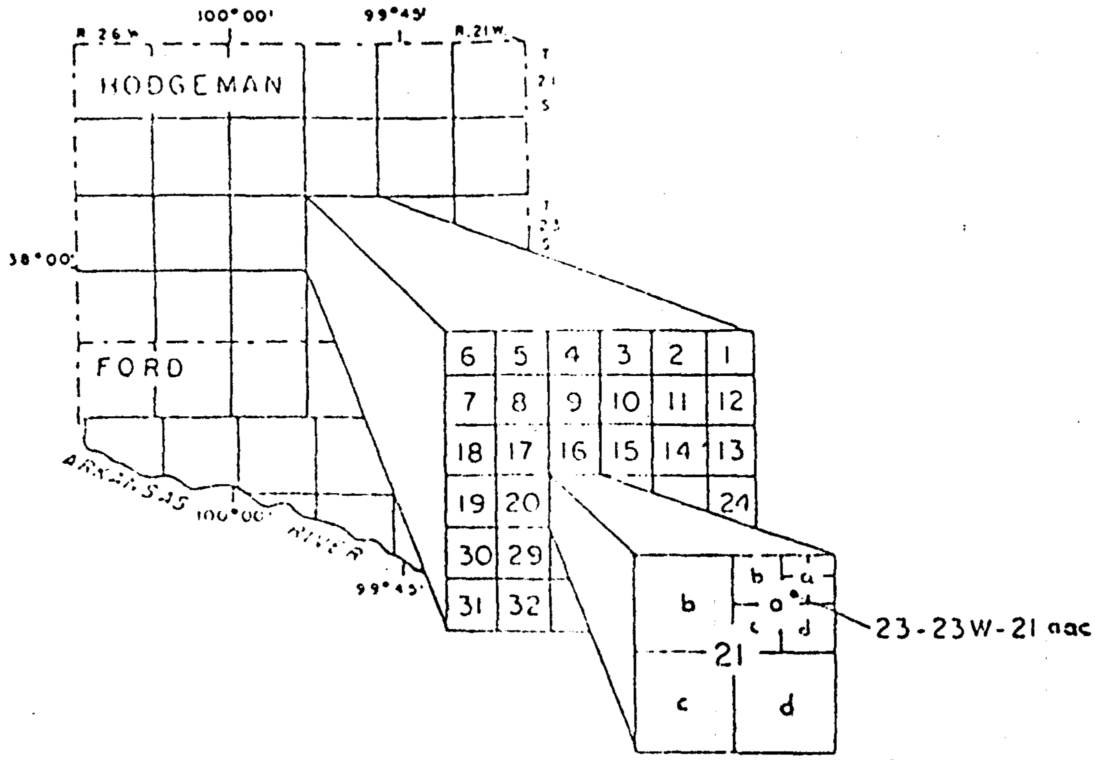


Figure 2. Well numbering system.

TOPOGRAPHY, DRAINAGE, AND LAND USE

The study area lies in the High Plains subsection of the Great Plains physiographic province. The principal topographic features of the area are flat bottomlands and terraces. Altitudes range from approximately 2,900 feet near the westernmost edge of the watershed to approximately 2,000 feet near the easternmost end of the watershed near Larned (Fig. 3).

The watershed area is drained by the Pawnee River and its many tributaries. The Pawnee River originates in Finney County and joins the Arkansas River at Larned in Pawnee County. Its largest tributary, Buckner Creek, originates in the northeastern part of Gray County and joins the Pawnee River near the northeast corner of Hodgeman County. The largest tributary of Buckner Creek is Sawlog Creek, which originates in the northwest corner of Ford County and joins Buckner Creek at Hanston in Hodgeman County (Fig. 3). The drainage pattern of the Pawnee Valley Watershed is dendritic (characterized by irregular branching of tributary streams in many directions). Such a pattern usually develops in areas where structural control, such as faults and folds, is missing and where the underlying rock units are nearly horizontal; both of these characteristics are prevalent in the study area.

The land is used for agricultural purposes under both dryland and irrigation conditions. The major crops in the area are wheat, sorghum, alfalfa hay, and corn. The increase in irrigated acreage is shown in Figures 4 and 5 for the entire Pawnee and Hodgeman counties, where a dramatic increase since the mid-60's is clearly evident. During the

Topography and Drainage of the Pawnee Watershed

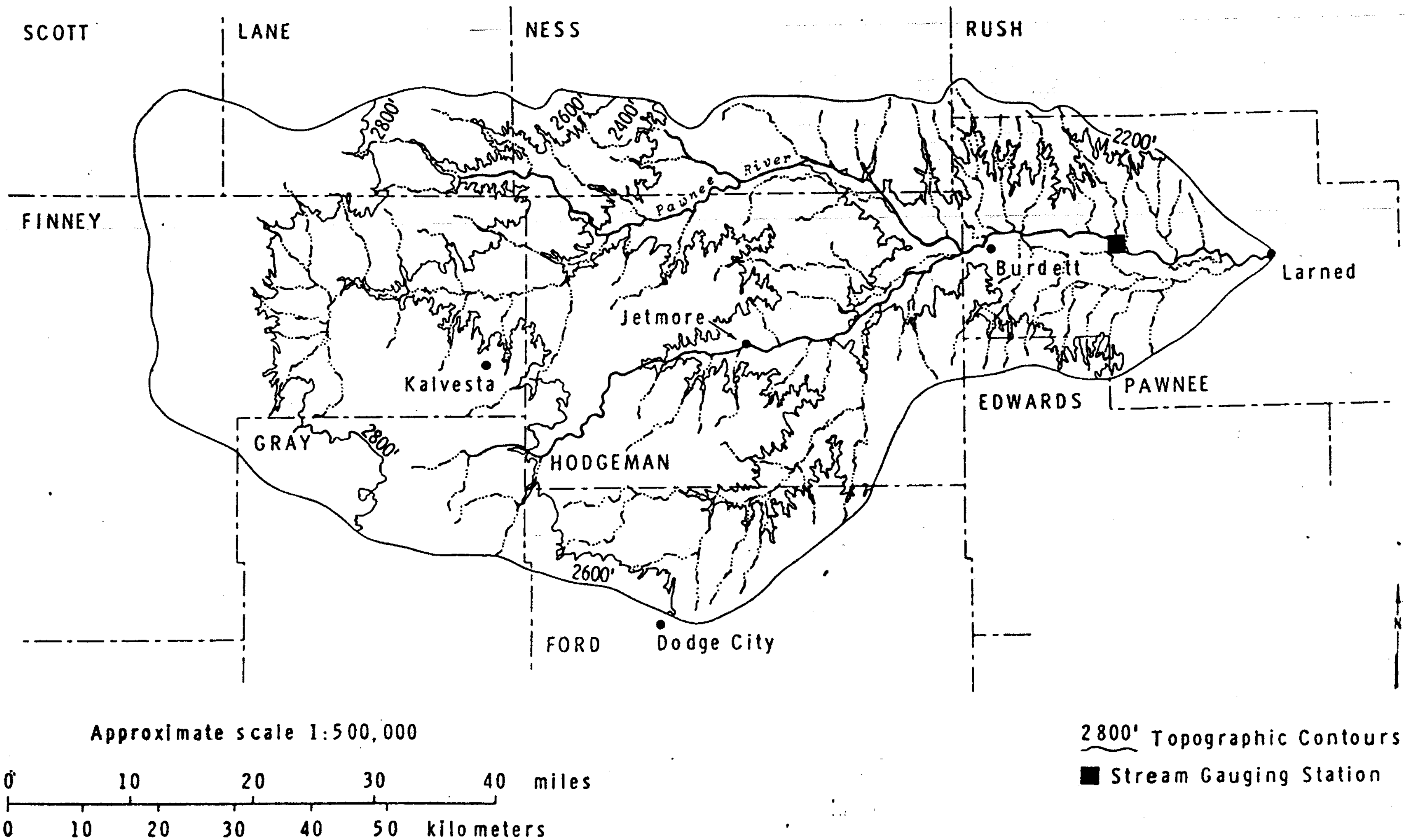
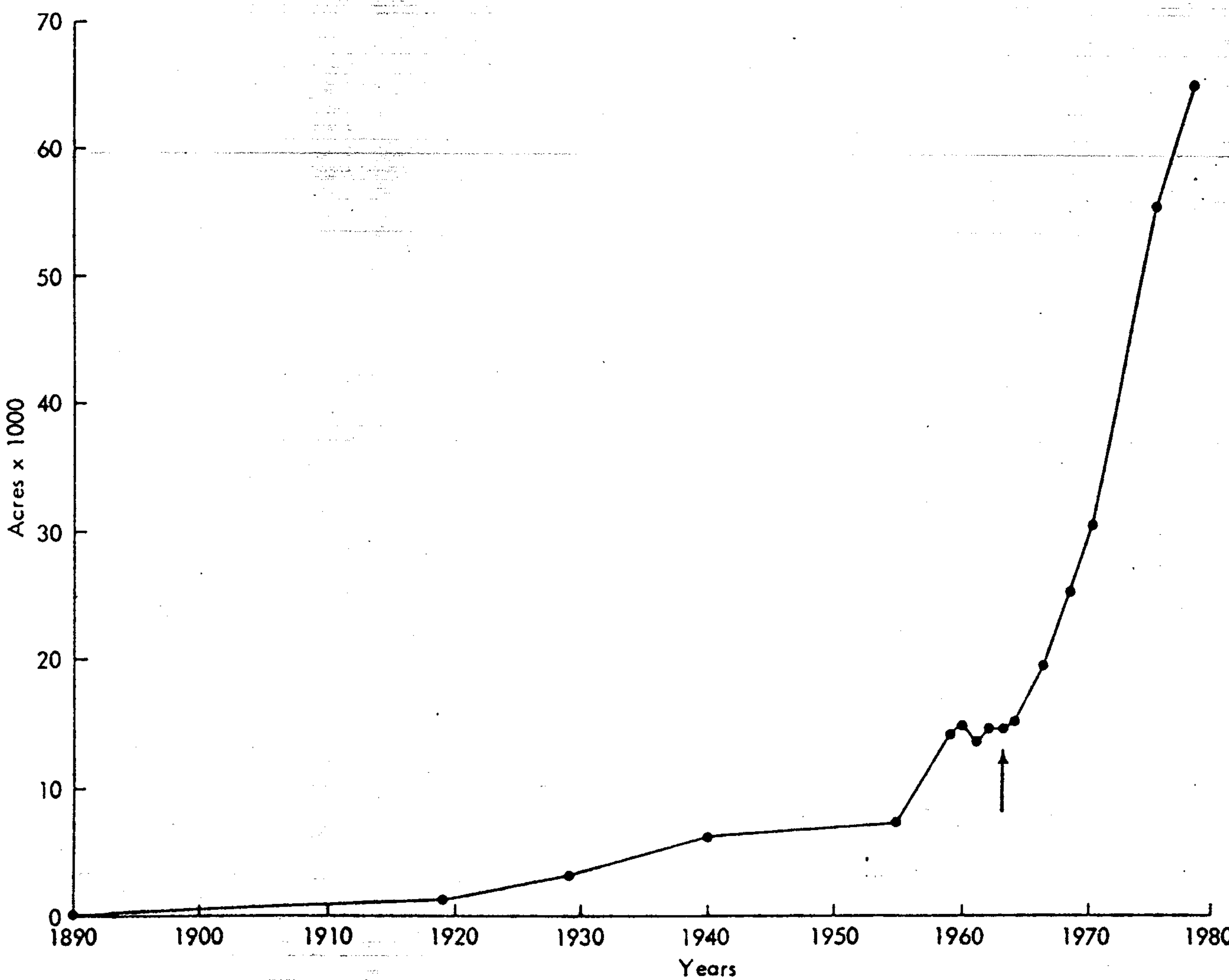


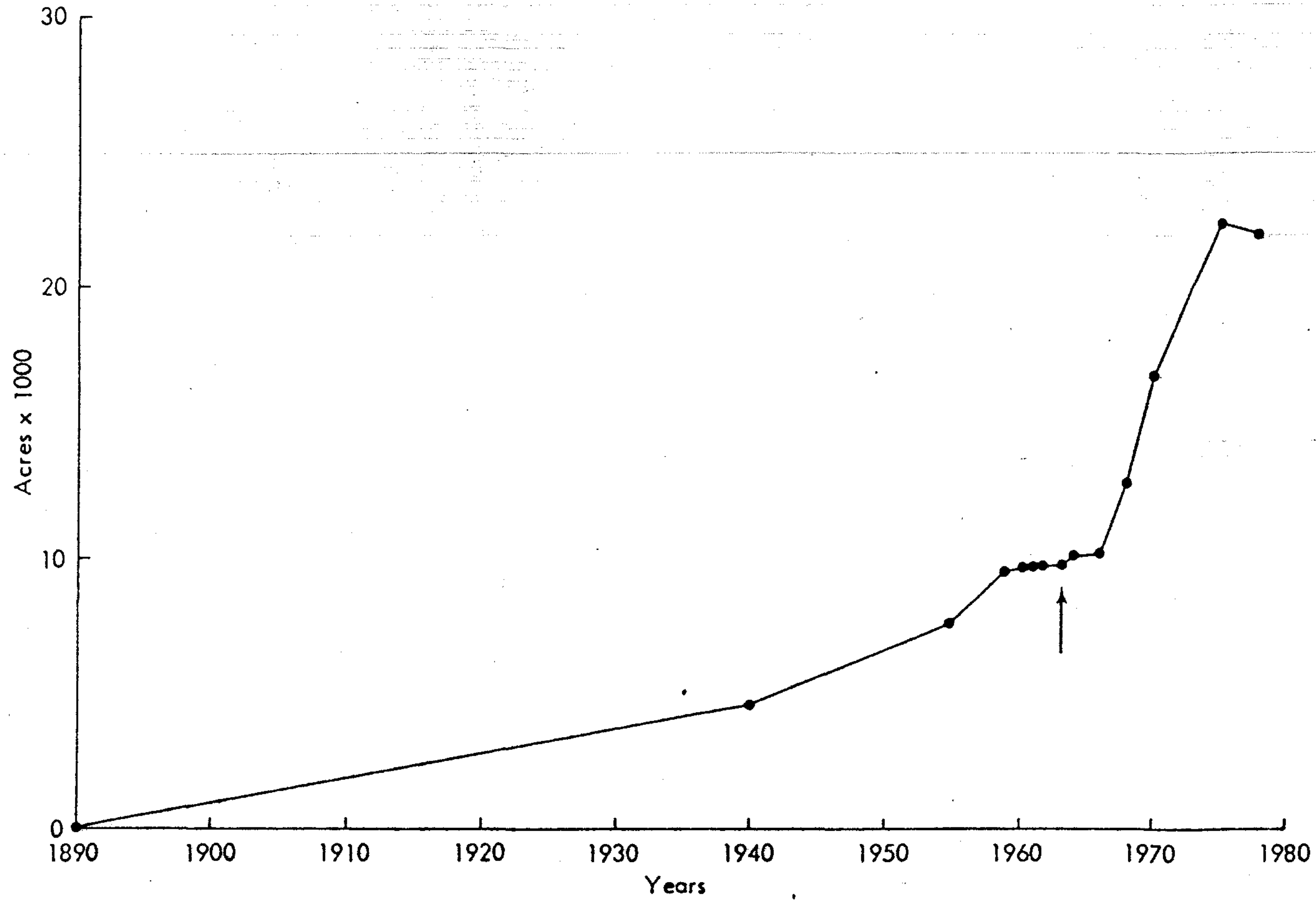
Figure 3

Figure 4
IRRIGATED ACREAGE, PAWNEE COUNTY



Source of Data: Division of Extension, Extension Agricultural Engineering, Kansas State University.

Figure 5
IRRIGATED ACREAGE, HODGEMAN COUNTY



Source of Data: Division of Extension, Extension Agricultural Engineering, Kansas State University.

forties, irrigated acreage represented approximately 1.3 percent of the total acreage in Pawnee County and 0.8 percent of Hodgeman County. In 1978, the irrigated acreage comprised approximately 13.4 percent of the total acreage in Pawnee County, a tenfold increase, and 4.0 percent of Hodgeman County, a fivefold increase.

The major source of irrigation water in Pawnee Valley is groundwater; therefore, the increase in irrigated acreage has had a significant effect on that source. The historic growth of well registration in the entire Pawnee and Hodgeman counties is shown in Figures 6 and 7. In Pawnee County, growth is exponential, closely matching that of the irrigated acreage growth. A similar growth, but of a smaller scale, is also observed in Hodgeman County.

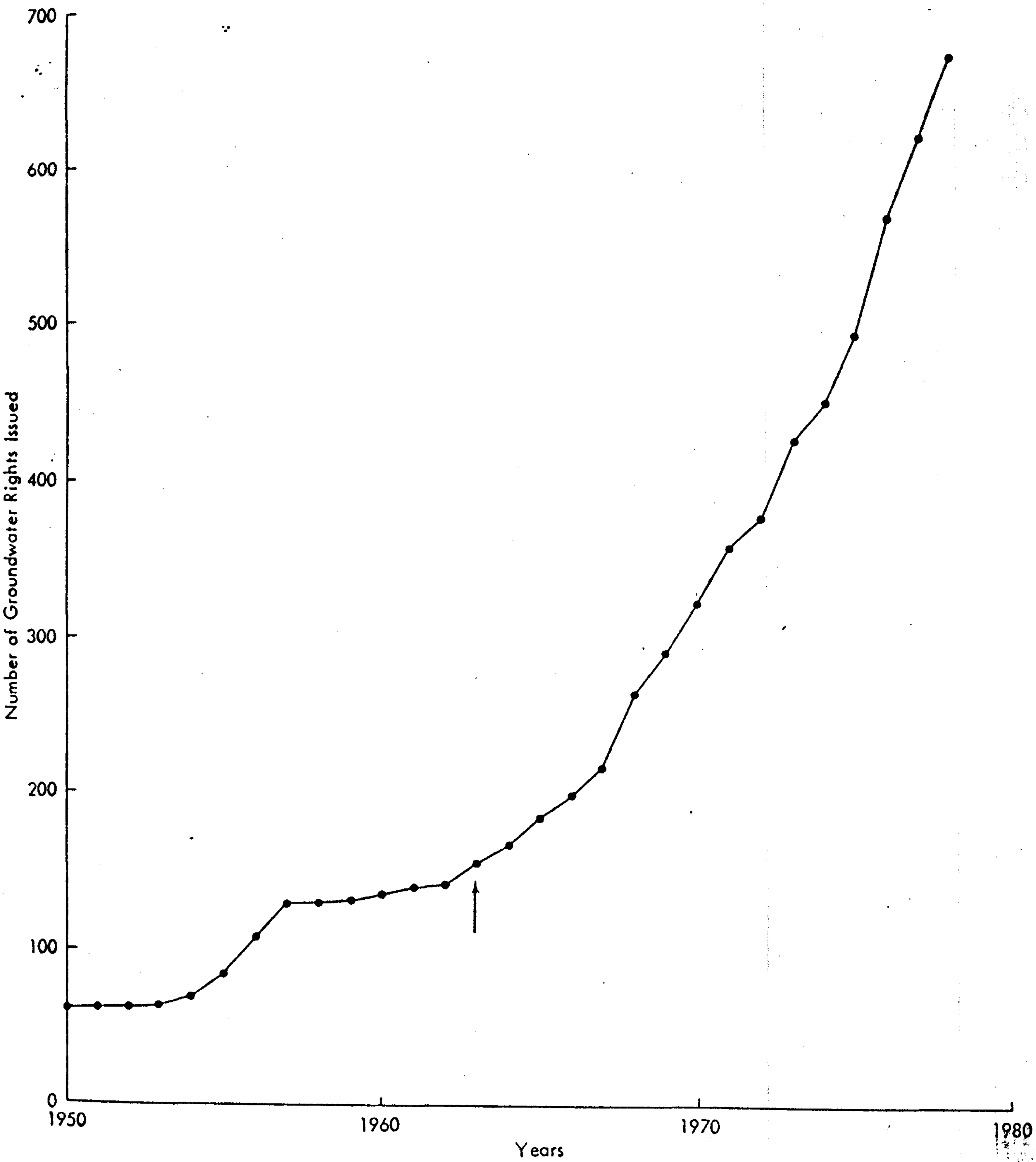
GEOLOGY AND SOILS

The geology of the area, as related to groundwater, is described by McLaughlin (1948) and Fishel (1952), and is summarized as follows.

The rocks that crop out in the Pawnee Valley are sedimentary and range in age from Cretaceous to Quaternary (Fig. 8). The oldest rocks exposed are Cretaceous and comprise the Dakota Formation, Graneros Shale, Greenhorn Limestone, and Carlile Shale. The Ogallala Formation of Tertiary age caps the upland area in much of Hodgeman County. The terrace deposits that cover large areas adjacent to the Pawnee River are believed to be Pleistocene in age, but may be Tertiary in part. The alluvium in the principal valleys is Pleistocene. Most upland surfaces are thinly mantled with eolian silt or loess.

Figure 6

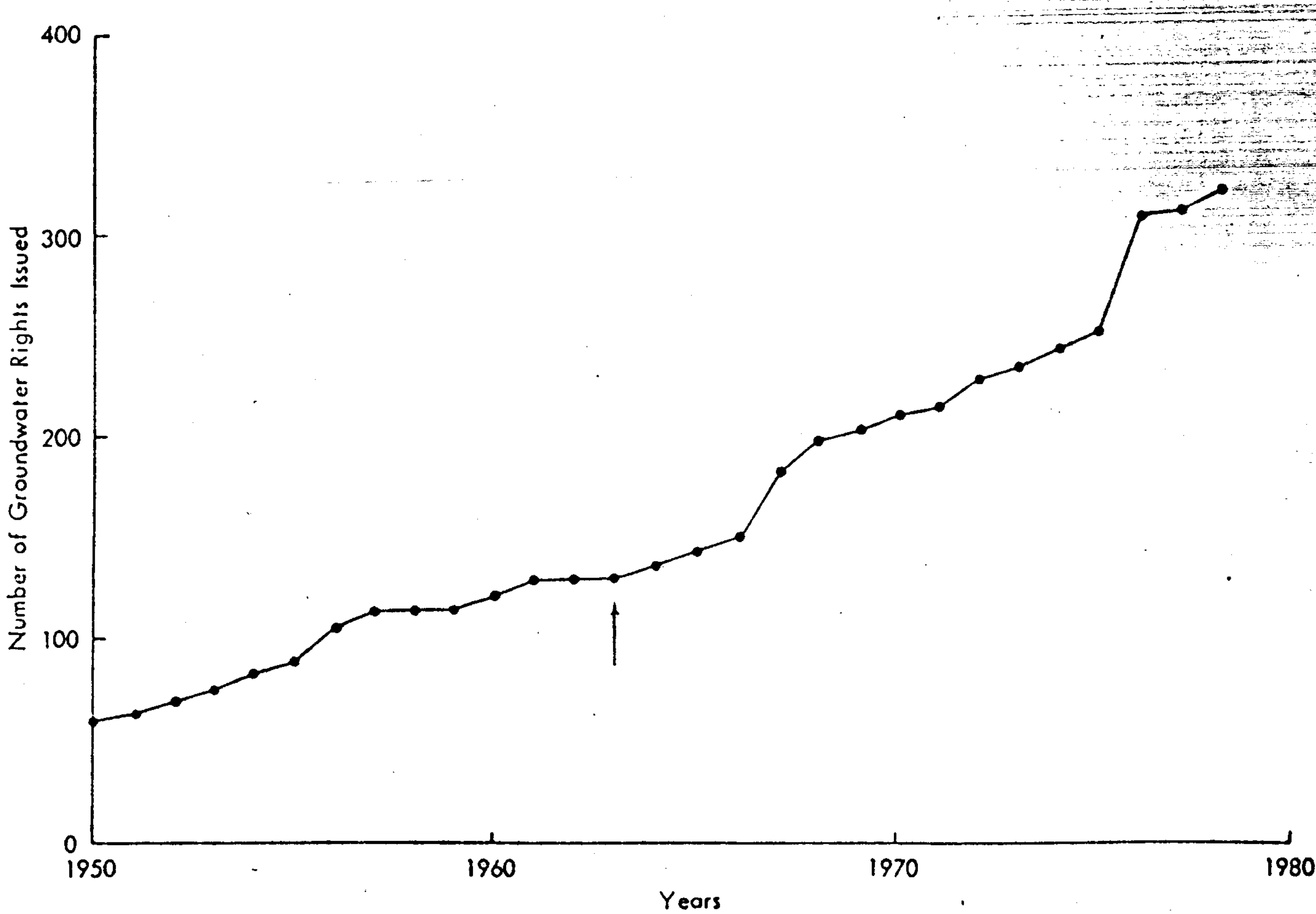
NUMBER OF GROUNDWATER RIGHTS ISSUED IN PAWNEE COUNTY FROM 1950 TO 1978



Source of Data: Division of Water Resources, Stafford Field Office.

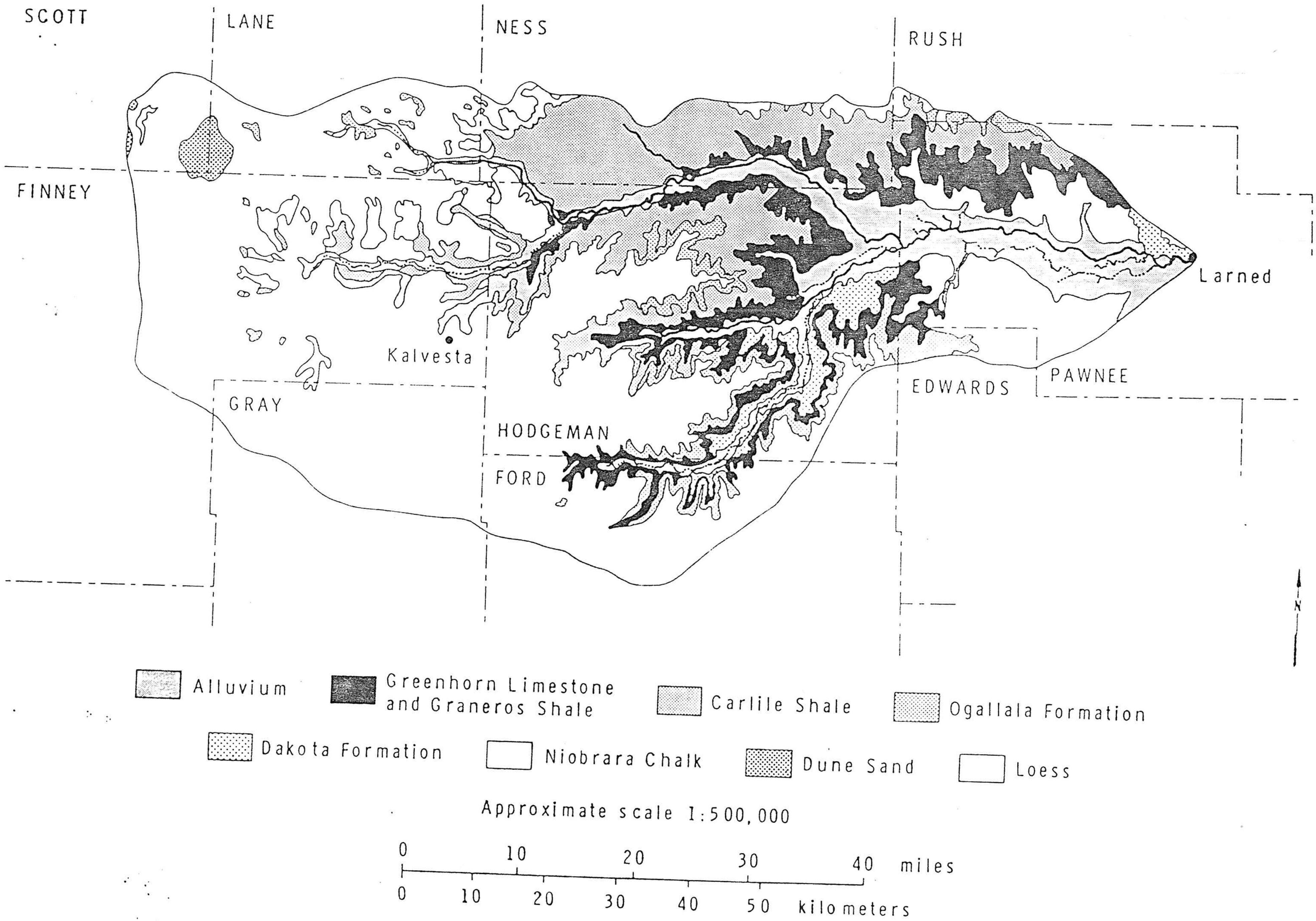
Figure 7

NUMBER OF GROUNDWATER RIGHTS ISSUED IN HODGEMAN COUNTY FROM 1950 TO 1978



Source of Data: Division of Water Resources, Stafford Field Office.

Figure 8 Geologic Formations of the Pawnee Watershed



A generalized stratigraphic section of the geologic formations of the study area, together with their physical and water-supply characteristics, is given in Table 1.

The consolidated rocks that underlie the unconsolidated Tertiary and Quarternary deposits are referred to as bedrock. These rocks are not considered to be major aquifers in the area but do supply water for some irrigation wells in the upland areas of the valley (Table 1). The principal water-bearing materials underlying the study area are the unconsolidated deposits of Quaternary age. The Tertiary age Ogallala Formation, although the principal aquifer in western Kansas, yields relatively small quantities of water in the Pawnee Valley Watershed because it is the eastern fringe of the Ogallala Formation and is highly dissected, thinned, and largely drained of water. The Quaternary system in the Pawnee Watershed consists of terrace deposits and alluvium (Table 1), which form the alluvial aquifer. The terrace deposits overlie the Cretaceous rocks on both sides of the Pawnee River throughout most of Pawnee County and extend into Ness and Hodgeman counties.

Inasmuch as the terrace deposits consist primarily of silt and clay and lesser amounts of sand and gravel, this formation yields generally moderate quantities of water to wells. However, in places where the deposits contain much sand and gravel, the beds yield adequate water for irrigation.

Alluvium underlies the bottomland of the Pawnee River and some of its larger tributaries. The alluvium of the Pawnee Valley is as wide as three miles in parts of the Pawnee Valley and two miles in Hodgeman and

TABLE 1

Generalized section of the geologic formations in Pawnee Valley, Kansas

System	Series	Subdivision	Thickness (feet)	Physical character	Water supply
Quaternary	Pleistocene	Loess	0-10	Silt, windblown, locally reworked and deposited by streams.	Most of deposits above water-table. Not known to yield water to wells.
		Alluvium	0-135	Coarse sand and gravel containing silt and clay. Sand and gravel generally overlain by 15 to 50 feet of silt and clay.	Yields large quantities of water to domestic, stock, and irrigation wells.
		Terrace deposits	0-150	Principally silt and clay but locally contains considerable sand and gravel.	Yields moderate supplies of water to domestic and stock wells and to a few irrigation wells.
Tertiary	Pliocene	Ogallala Formation	0-100	Consists mainly of silt, sand, and gravel containing caliche.	Yields fair amounts of water for stock and domestic wells in parts of Ness and Hodgeman Counties.
Cretaceous	Upper	Carlile Shale	0-100	Chalky shale containing thin beds of chalky limestone.	Yields small quantities of water to wells in adjacent area but not known to yield water to wells in this area.
		Greenhorn Limestone	0-125	Chalky shale containing thin beds of crystalline limestone at base and granular to chalky limestone in upper part.	Yields small quantities of water to dug wells in northern Pawnee County.
		Graneros Shale	20-36	Dark-gray shale containing sandy shale and lenses of sandstone.	Yields no water to wells in this area.
	Lower	Dakota Formation	20-300	Consists principally of buff, yellow-brown and brown sandstone and vari-colored clay and sandy clay.	Yields small to moderate quantities of water to domestic and stock wells, and to a few irrigation wells.
		Kiowa Shale	100-230	Dark-gray to black shale containing lenses of sandstone.	Yields no water to wells in this area.
		Cheyenne Sandstone	15-50	Gray, tan and white fine to medium-grained sandstone.	Yields no water to wells in this area due to its considerable depth. Water may be highly mineralized.

Modified from Fishel, 1952.

NOTE: In this report, small quantities refers to yields generally less than 10 gallons per minute (gpm), moderate quantities to 10 to 500 gpm, and large quantities to greater than 500 gpm.

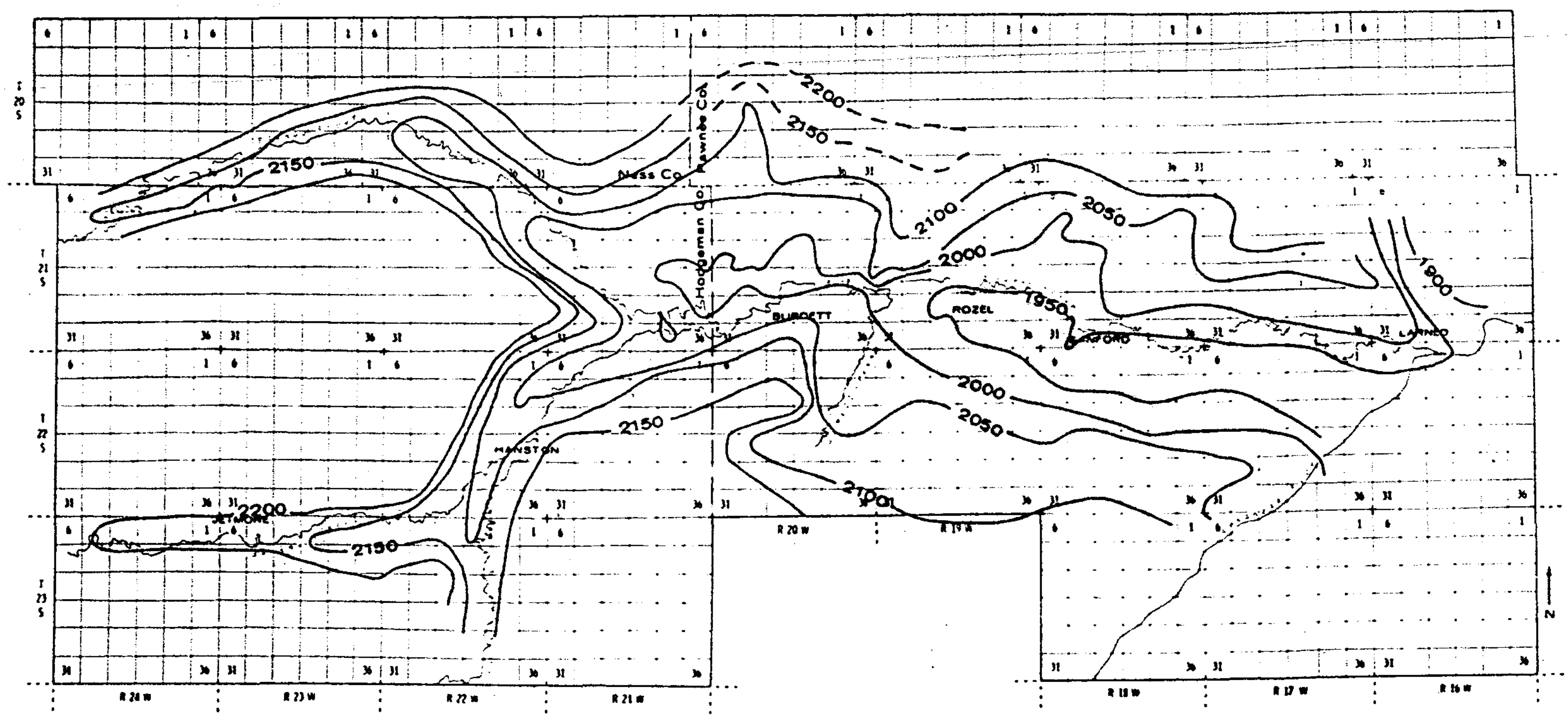
Ness counties. The base of the alluvium is shown by the bedrock contour map (Fig. 9). The alluvium of Pawnee, Buckner, and Sawlog Valleys yields large quantities of water to wells.

Figure 10 is a fence diagram showing the distribution of the various rock units in Pawnee County.

The soils of the Pawnee Watershed were formed mainly from deposits of loess, outwash material, and alluvium. In areas where these deposits are absent, the soils generally formed in material weathered from semi-consolidated caliche or chalky shale interbedded with thin layers of limestone. Figure 11 is a generalized soils association map of the Pawnee Watershed. Construction of this map involved some grouping of various soil associations presented in the general county soil maps (Dodge and others, 1965, 1978; Harner and others, 1965, Sallee and Hamilton, 1965; Tomasu and Roth, 1968; Sallee, 1972; Haberman and others, 1973; Roth, 1973; Rott and Haberman, 1977) and some regrouping of soil associations used in those reports in order to reflect better the pattern of soils in the natural landscapes for the multicounty area. Table 2 is a brief description of the soil association groups used in this map. Table 3 indicates the major soil series, their texture, and their water-holding properties.

The formation of these soils is the result of the action of soil-forming processes on material deposited or altered by geologic forces (Haberman and others, 1973). After the Rocky Mountains were uplifted, the Ogallala Formation, of middle Pliocene age, was deposited by streams that carried debris from these mountains. These deposits mantled the bedrock of the Pawnee Watershed. Much of this

Figure 9
BASE MAP OF PAWNEE VALLEY, KANSAS, ALLUVIAL AQUIFER



EXPLANATION

—50 – Bedrock contour in feet. Dashed where inferred.

Contour interval 50 feet.

Approximate scale: 1:125,000

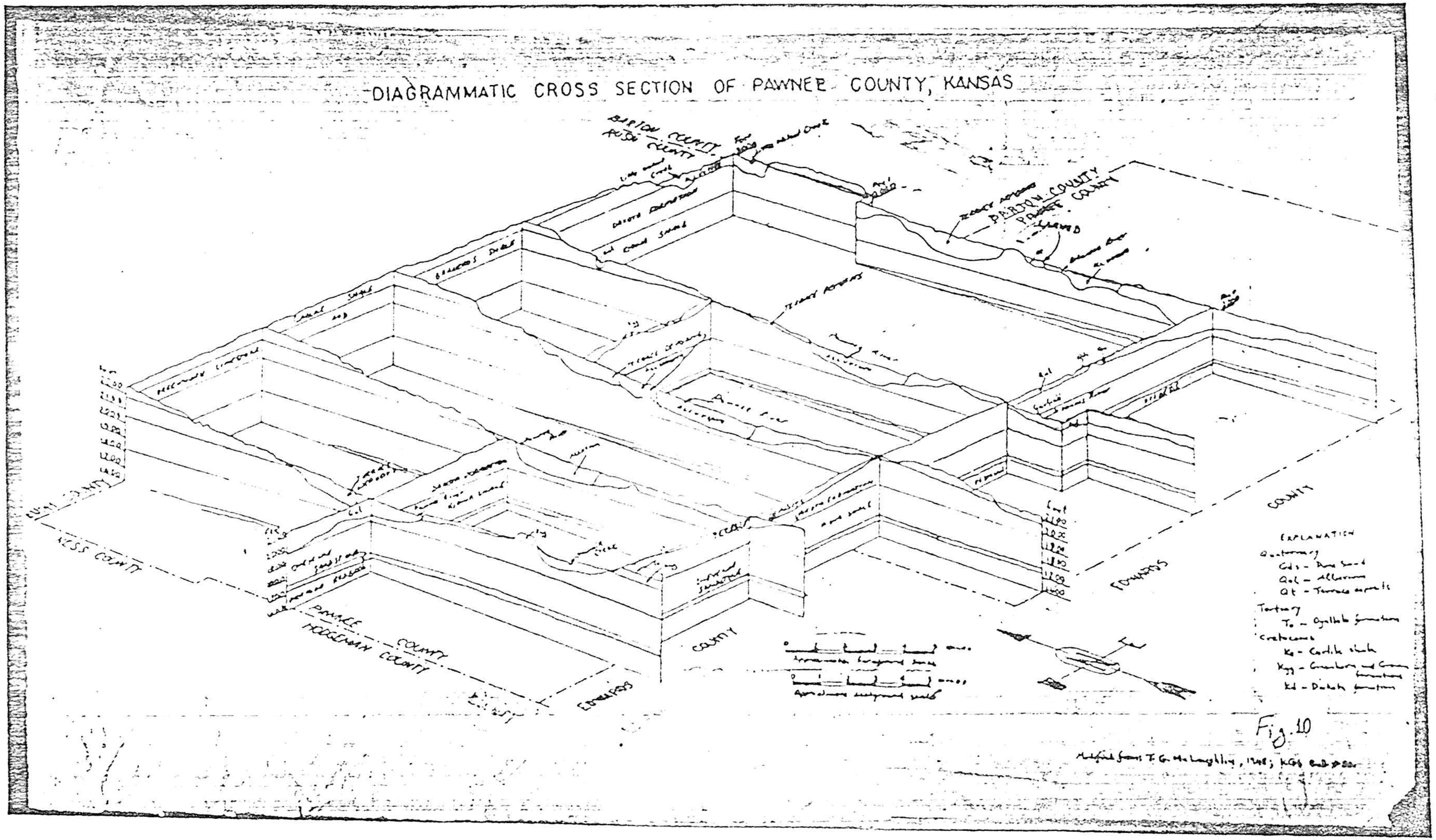
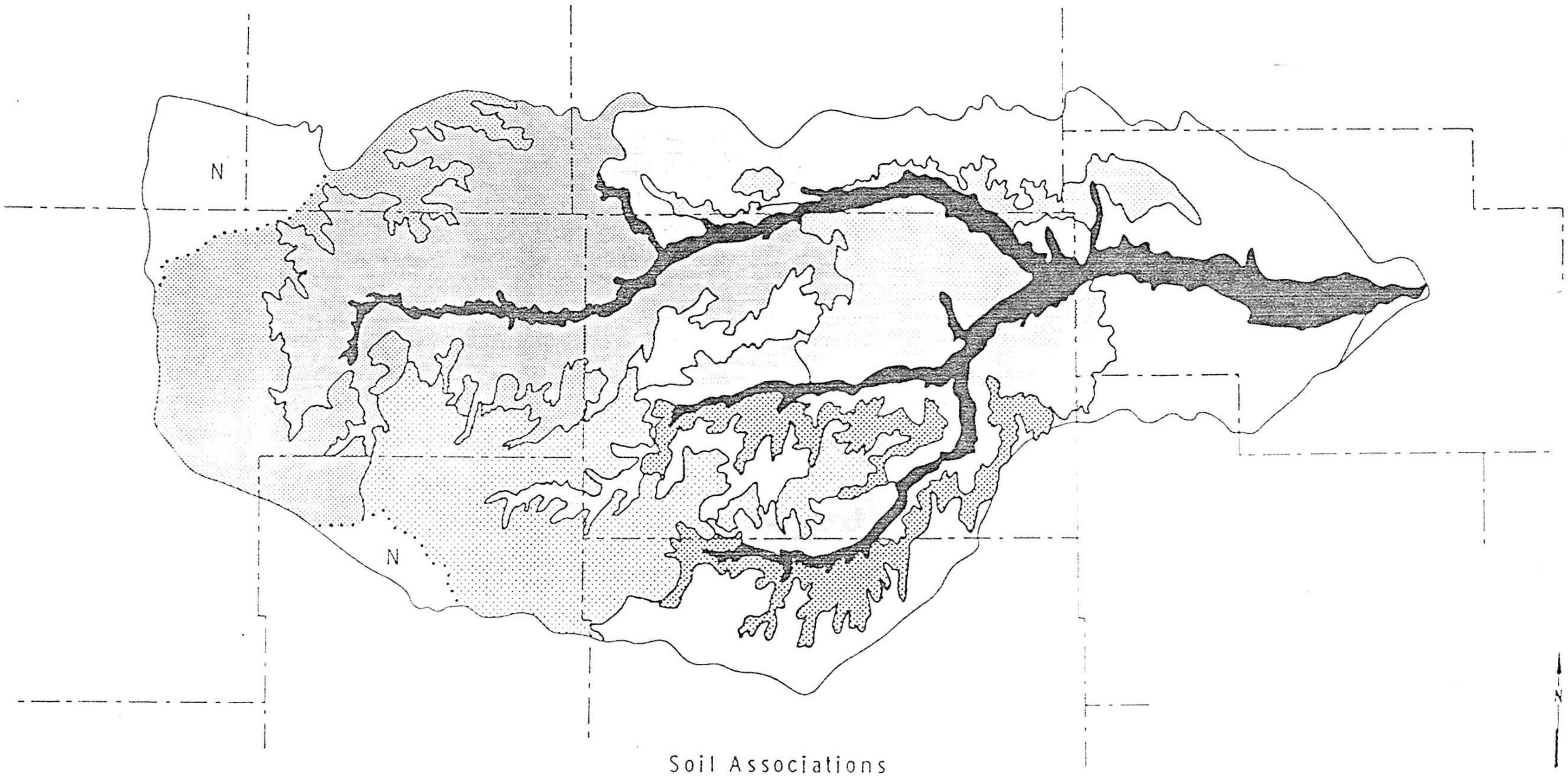


Figure 10. Diagrammatic cross section of Pawnee County, Kansas.

Figure 11
General Soils Map for the Pawnee Watershed



Soil Associations

- Harney-Uly
- Roxbury-Bridgeport-New Cambria-Hord
- Harney-Penden-Wakeen
- Richfield-Penden-Harney-Mansic
- Harney-Spearville
- Penden-Mansic-Campus-Canlon
- Richfield-Harney-Ulysses

N : Non-contributing Areas of the Watershed

Approximate scale 1:500,000

0 10 20 30 40 miles

0 10 20 30 40 50 kilometers

Table 2

Soil Associations of the Pawnee Watershed

1. Harney-Uly: These silty soils are on nearly level to sloping landscapes. They occupy the less sloping areas in the eastern two-thirds of the watershed. Only a small amount of runoff from these areas to stream systems occurs.

2. Roxbury-Bridgeport-New Cambria-Hord: Silty and clayey soils on nearly level flood plains and low terraces. They are well to moderately well drained.

3. Richfield-Penden-Harney-Mansic: These silty and loamy soils are on nearly level to steep landscapes. They occur near the drainageways in the western part of the watershed. There are a few small areas of shallow and moderately deep soils.

4. Harney-Penden-Wakeen: These silty and loamy soils are on nearly level to steep landscapes. They are shallow to deep and occur near the drainageways in the eastern part of the watershed.

5. Harney-Spearville: Silty and clayey soils located on broad, nearly level landscapes. They occur in the southwest part of the watershed. Little or no runoff from these areas to stream systems.

6. Penden-Mansic-Campus-Canlon: These loamy soils are on gently sloping to steep landscapes. They are shallow to deep and occur near drainageways in the south-central part of the watershed.

7. Richfield-Harney-Ulysses: These silty soils are on broad, nearly level landscapes in the western part of the watershed. Little or no runoff occurs from these areas to stream systems.

Note: Individual areas represent soil associations named for the major soils. There are other soils of lesser extent within these associations. All the soils in the watershed are deep unless otherwise stated.

TABLE 3

Characteristics of the major soil series in the Pawnee Watershed

Soil Series	Surface Layer 1 (in)	Surface Layer 2	Subsoil 1 (in)	Subsoil 2	Underlying Material (up to 4 feet) 1 (in)	Underlying Material (up to 4 feet) 2	SMC 3 (in/4')	WP 4 (in/4')
Harney	12	SiL	23	SiCL	13	SiL	9.86	9.10
Uly	10	SiL	8	SiL	30	SiL	10.32	8.64
New Cambria	14	SiCL	21	SiC	13	SiCL	8.10	10.77
Bridgeport	11	SiL	7	SiL	30	SiL	10.30	8.68
Hord	12	SiL	30	SiCL	6	SiL	9.72	9.24
Roxbury	22	SiL	20	SiCL	6	CL	9.56	9.34
Penden	16	SiCL	12	CL	20	CL	8.08	10.68
Richfield	7	SiL	14	SiCL	27	SiCL	9.50	8.70
Wakeen	10	SiL	10	SiCL	16	CL	6.64	7.38
Campus	8	L	8	CL	14	L	5.94	4.44
Canlon	6	L	7	L	--	Caliche	2.71	1.72
Spearville	7	SICL	18	SiC-SiCL	23	SiL	9.11	9.81
Ulysses	6	SiL	9	SiL-SiCL	33	SiL	10.23	8.76
Mansic	9	CL	26	CL	13	CL	7.38	11.34

1. Thickness of layer
2. Textural classification
3. Soil moisture capacity (SMC)
4. Wilting point (WP)

Abbreviations: SiL = Silty loam
SiCL = Silty clay loam
L = Loam
CL = Clay loam

material was removed by subsequent erosion during the early Pleistocene. Later, sedimentation was resumed, and the valleys cut in the Ogallala and the areas where the formation was eroded away were filled with fine-grained sediments. These deposits consist primarily of silt and clay, but contain lesser amounts of sand and gravel. These deposits formed the Meade Formation and terrace deposits. Penden soils formed in the outwash.

Late in the Pleistocene age, the valleys of the Pawnee River and of Buckner and Sawlog Creeks were eroded and cut somewhat below their present depth. This was followed by the deposition of stream-laid silt, sand, and gravel that formed the alluvium in the valleys. Probably, during this time and into Recent time, there was a climatic change and the wind velocity became very strong. A layer of windblown silt, Peorian loess, was deposited over most of the Watershed. The principal soils formed in loess are Harney, Richfield, Spearville, and Uly.

The alluvium deposited in Recent time is the youngest parent material of the watershed soils. Roxbury soil formed in this material. Much of the present topography is the result of erosion and deposition that started during the latter part of the Pleistocene age and has continued until the present.

HYDROMETEOROLOGY

PRECIPITATION AND TEMPERATURE

There are 13 meteorological stations in or near the Pawnee Watershed that have precipitation records of sufficient length and completeness for analysis. (U.S. Weather Bureau, Climatological data, Kansas section). The locations of these stations and the Thiessen polygonal subareas* they cover are shown in Figure 12. The stations inside the watershed measure precipitation only or precipitation and temperature. There are only eight stations in or near the Pawnee Watershed that measure temperature. The location of temperature measuring stations and the Thiessen polygonal subareas they cover are shown in Figure 13.

The mean annual precipitation over the entire watershed for 1949-1978 was 20.5 inches, while the mean temperature for 1946-1978 was 55.2°F. The monthly precipitation and temperature records for the last 20 years (1959-1978) for the Larned and Jetmore stations are shown in Tables 4 and 5, respectively. The average annual precipitation for this period was 24.1 inches for the Larned station and 21.1 inches for the Jetmore station.

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* A Thiessen network is constructed by connecting adjacent stations on a map by straight lines and erecting perpendicular bisectors to each connecting line. The polygon formed by the perpendicular bisectors around a station encloses an area which is everywhere closer to that station than to any other station. This area is assumed to be best represented by the precipitaion at the enclosed station.

Figure 12
THIESSEN POLYGONS FOR MEAN
ANNUAL PRECIPITATION OVER THE PAWNEE WATERSHED

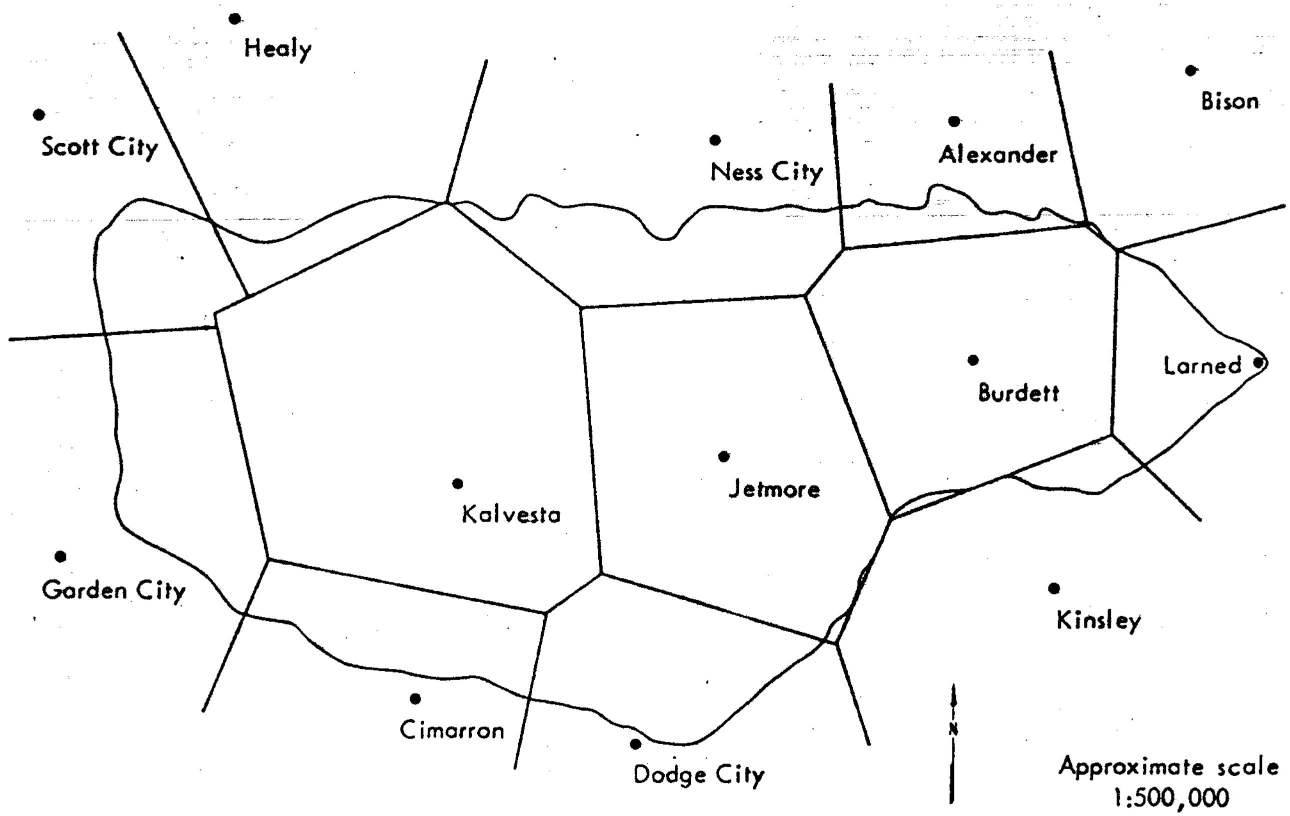

Figure 13
THIESSEN POLYGONS FOR MEAN
ANNUAL TEMPERATURE OVER THE PAWNEE WATERSHED

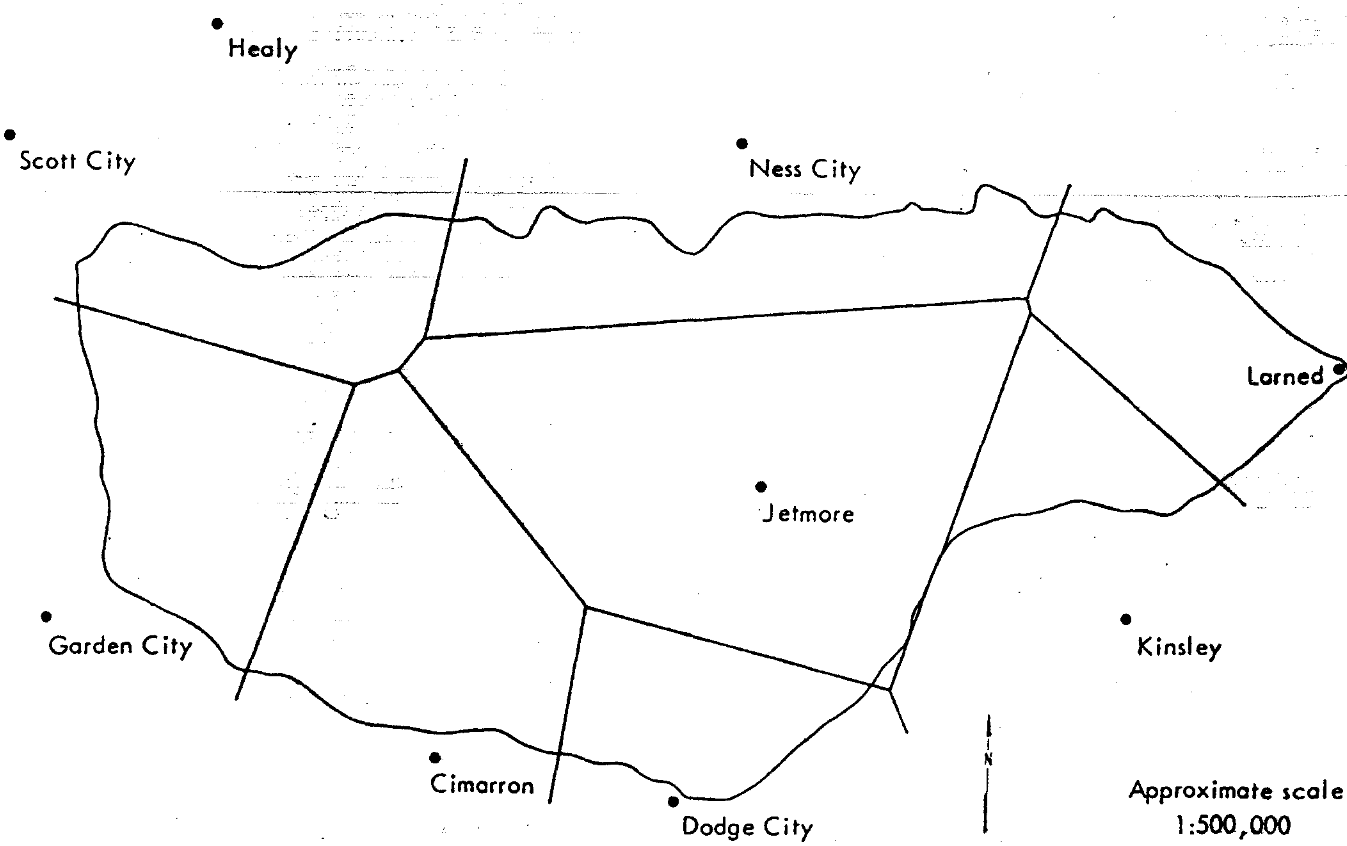

TABLE 4

Monthly precipitation and temperature for Larned, Kansas (1959-1978)

Monthly precipitation (inches)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
1959	0.53	0.75	1.66	0.76	5.03	2.71	4.14	1.32	2.86	4.42	0.14	0.71	25.03
1960	1.33	2.19	1.59	1.07	2.35	4.49	1.14	1.49	3.78	2.90	0.48	0.93	23.74
1961	0.02	0.44	1.94	1.51	5.03	4.95	4.60	7.00	0.74	1.52	1.71	0.35	29.81
1962	0.63	0.62	0.91	1.48	1.51	5.28	8.19	2.27	3.82	0.36	0.77	0.38	26.22
1963	0.22	0.84	1.01	0.08	2.06	4.75	4.81	1.51	4.08	0.70	0.28	0.38	20.72
1964	0.57	0.32	0.88	1.67	2.42	1.68	1.05	1.56	1.86	0.26	3.40	1.12	16.79
1965	0.63	0.97	0.34	1.61	4.05	7.83	2.83	6.28	5.50	2.32	0.02	2.94	35.32
1966	0.32	0.81	0.05	1.52	0.42	2.93	3.80	2.11	1.19	0.19	0.80	0.85	14.99
1967	0.28	0.01	0.17	2.96	1.94	7.47	2.12	3.53	3.90	0.38	0.31	0.90	23.97
1968	0.03	0.18	0.21	0.71	2.17	3.32	4.28	2.17	0.31	4.70	1.46	0.48	20.02
1969	0.08	1.81	2.27	2.58	3.91	2.07	1.49	4.62	3.49	2.49	0.14	0.14	25.09
1970	0.25	0.01	2.51	1.79	2.86	5.86	0.36	2.75	4.92	1.79	0.04	0.09	23.23
1971	0.81	2.41	0.23	2.52	2.95	2.24	5.72	2.57	1.36	3.34	4.90	0.79	29.84
1972	0.17	0.10	0.29	2.10	3.97	5.00	3.15	4.99	2.04	0.76	3.12	0.74	26.43
1973	0.53	0.38	7.70	3.06	1.58	0.51	5.08	3.18	11.15	1.96	1.23	2.43	38.79
1974	0.10	0.03	1.34	1.46	1.82	1.58	0.36	4.08	0.78	2.28	0.74	0.32	14.89
1975	0.50	1.13	1.24	1.58	4.44	3.24	0.71	3.67	1.26	0.	1.61	0.52	19.90
1976	0.03	0.59	1.01	6.62	2.50	0.76	4.41	1.36	5.88	1.54	0.05	0.01	24.76
1977	0.84	0.02	1.67	2.27	4.04	3.09	3.22	4.90	1.20	1.43	1.32	0.60	24.60
1978	0.27	1.35	1.03	0.32	4.64	4.01	1.46	1.21	2.39	0.17	1.68	0.29	18.82

Mean monthly temperature (F)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1959	26.10	34.40	46.00	54.20	67.20	77.20	76.20	80.00	68.90	54.00	41.00	39.50
1960	29.90	27.40	34.20	59.30	63.30	73.30	78.00	79.50	72.10	59.80	44.80	33.10
1961	33.60	38.80	45.00	52.90	63.20	74.00	78.90	75.30	65.00	58.40	40.60	29.40
1962	27.90	38.10	41.90	55.70	73.00	72.70	77.60	79.40	67.90	60.50	45.00	36.50
1963	22.40	41.00	49.80	60.00	69.10	77.00	85.00	82.10	74.30	68.50	47.60	27.40
1964	36.50	34.60	42.10	58.50	70.80	76.40	85.40	78.60	70.40	58.10	45.30	32.20
1965	34.90	33.30	35.80	59.50	68.10	73.70	80.30	78.00	65.70	60.10	49.20	38.00
1966	27.00	32.40	49.20	53.20	66.90	76.80	84.40	74.90	68.20	58.20	44.70	30.60
1967	34.90	38.40	50.10	59.40	63.30	74.30	75.30	75.40	67.30	59.40	43.50	35.50
1968	32.20	35.10	50.50	56.60	61.20	76.70	79.80	79.20	69.20	60.60	40.90	29.10
1969	30.70	35.20	35.40	57.10	65.70	71.90	82.90	77.40	70.50	53.70	44.90	35.00
1970	28.90	41.40	39.10	55.70	70.90	74.10	81.50	82.30	68.60	53.50	42.80	37.70
1971	28.70	31.60	44.30	57.40	63.60	78.50	78.80	77.00	69.80	59.40	45.00	36.20
1972	29.90	38.00	51.80	57.20	63.90	75.40	77.30	76.90	69.80	55.40	39.50	28.50
1973	30.20	37.80	47.10	52.60	63.70	76.90	79.60	80.00	65.60	60.50	45.50	32.30
1974	27.70	41.30	49.70	58.50	69.10	74.80	83.60	74.60	63.20	60.80	44.40	35.40
1975	35.30	31.00	40.90	55.40	65.80	73.80	79.50	81.10	67.40	61.20	44.10	38.10
1976	33.70	46.00	46.10	58.40	62.10	75.30	79.50	79.20	70.10	53.10	39.80	36.80
1977	24.50	36.10	49.40	58.80	69.80	78.20	83.40	77.70	73.10	60.80	44.40	35.20
1978	21.70	23.40	45.20	58.80	63.90	76.40	84.40	80.00	74.90	60.10	43.20	33.00

TABLE 5

Monthly precipitation and temperature for Jetmore, Kansas (1959-1978)

Monthly precipitation (inches)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
1959	0.61	0.46	1.24	0.26	4.20	2.66	2.93	1.17	2.04	4.16	0.74	0.68	21.15
1960	1.28	1.58	1.25	2.25	3.16	3.78	0.28	1.98	2.93	2.40	0.21	0.56	21.66
1961	0.	0.23	1.08	1.68	2.77	5.41	4.24	6.97	1.69	1.06	2.11	0.33	27.57
1962	0.67	0.23	1.31	1.60	1.12	7.41	5.19	2.00	4.80	0.10	0.91	0.51	25.85
1963	0.45	0.68	0.56	1.86	3.26	2.52	2.01	1.22	2.83	2.53	0.67	0.42	19.01
1964	0.53	0.64	0.37	0.69	4.25	1.36	2.58	0.57	1.83	0.47	2.10	0.42	15.81
1965	0.78	0.62	0.17	0.47	4.55	5.27	2.64	3.40	1.84	2.76	0.03	2.05	24.58
1966	0.33	0.44	0.04	0.56	0.11	1.54	2.44	2.47	1.90	0.20	0.07	0.82	10.92
1967	0.27	0.68	0.42	1.90	3.88	4.47	1.50	1.83	1.03	0.34	0.20	0.51	17.03
1968	0.	0.30	0.26	1.01	3.71	5.15	2.87	3.56	0.16	4.12	0.80	0.39	22.33
1969	0.08	1.16	2.00	3.11	3.73	2.03	4.68	4.53	0.92	3.45	0.16	0.15	26.00
1970	0.12	0.03	2.35	2.68	2.92	3.23	1.54	1.69	3.74	0.74	0.14	0.03	19.21
1971	0.	1.93	0.26	1.80	4.52	3.46	3.38	0.88	1.30	2.41	2.29	0.55	22.78
1972	0.06	0.10	0.28	0.84	5.14	3.19	7.27	4.92	1.98	0.07	2.93	0.34	27.12
1973	0.58	0.36	9.04	2.74	1.09	0.24	4.58	4.31	4.64	1.60	0.70	2.02	31.90
1974	0.26	0.03	1.14	0.84	1.78	1.44	0.67	2.94	0.10	2.10	0.75	0.12	12.17
1975	0.21	0.76	0.71	2.40	3.74	3.41	0.12	2.18	0.43	0.	1.80	0.20	15.96
1976	0.06	0.81	0.56	5.92	2.44	0.25	1.84	1.35	3.47	1.23	0.12	0.03	18.08
1977	0.50	0.02	0.54	3.37	2.82	1.70	3.17	9.57	0.63	2.01	0.32	0.48	25.13
1978	0.28	1.05	1.00	0.06	6.18	4.55	0.67	0.19	3.26	0.06	1.43	0.08	18.81

Mean monthly temperature (F)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1959	27.00	33.40	44.20	53.20	66.50	76.20	75.50	80.40	67.80	54.70	40.70	37.70
1960	28.40	26.10	35.70	59.20	63.00	73.70	77.80	78.50	71.00	59.60	43.80	33.70
1961	32.80	39.20	45.00	51.90	63.50	73.80	78.50	76.10	65.30	56.40	39.10	30.00
1962	27.40	38.40	41.80	54.70	72.00	71.50	77.60	79.20	68.20	60.40	45.00	37.70
1963	23.50	40.70	49.70	60.00	69.00	77.20	83.20	80.60	73.20	66.90	47.40	27.90
1964	36.80	33.70	42.00	58.50	70.40	75.10	83.80	78.70	70.20	57.90	45.30	32.90
1965	35.40	33.70	34.90	58.80	67.90	73.10	80.10	76.70	66.40	58.90	48.90	36.90
1966	26.90	31.90	47.60	53.20	66.40	77.00	84.70	75.10	68.50	57.70	43.00	29.80
1967	34.00	38.50	50.60	60.00	63.40	74.00	76.90	76.20	68.30	60.80	42.70	35.40
1968	33.00	35.40	49.40	56.20	60.90	76.90	79.60	79.20	69.50	61.00	41.90	28.80
1969	34.70	35.90	34.20	57.60	66.60	71.30	82.30	78.90	70.90	53.10	44.80	34.80
1970	29.80	41.10	37.90	54.00	69.00	74.10	81.00	81.70	70.20	53.20	43.00	37.10
1971	30.60	32.20	43.90	56.10	63.60	78.40	79.00	76.80	70.40	60.10	44.70	36.70
1972	30.60	38.40	53.00	57.70	64.60	75.60	78.40	77.40	71.10	57.30	39.70	28.60
1973	30.80	38.10	47.70	52.30	63.70	76.70	80.30	81.30	66.80	58.70	44.60	34.80
1974	28.00	41.40	50.00	59.20	69.20	75.60	83.30	75.30	64.20	61.70	44.10	34.10
1975	36.30	32.40	42.60	56.10	65.70	74.00	79.30	81.60	68.80	61.40	43.10	38.70
1976	34.10	42.70	46.90	58.60	61.30	75.10	79.80	79.80	69.10	51.20	40.10	36.70
1977	25.30	36.10	48.20	59.20	69.50	79.80	84.00	78.50	71.80	60.90	42.80	36.80
1978	23.00	23.00	45.50	57.70	62.20	74.50	83.10	79.00	73.80	59.40	42.30	32.10

EVAPOTRANSPIRATION AND WATER-BALANCE DIAGRAMS

Evapotranspiration is the combined process of evaporation from free water and bare soil surfaces and transpiration by plants. Potential evapotranspiration is defined as the evapotranspiration that would occur from a vegetation-covered soil surface that is never short of water. Since moisture is never restricted, potential evapotranspiration is limited solely by available energy, primarily solar energy. If there is a shortage of moisture, actual evapotranspiration will fall short of potential evapotranspiration.

No direct measurements of evaporation or evapotranspiration are available in the Pawnee Watershed. As an approach to the problem of estimating potential evapotranspiration, the empirical method of Thornthwaite (1948) has been applied to the data of the stations at Larned and Jetmore, representing the two opposite ends of that part of the watershed studied in greater detail in this report. The minimum amount of meteorological data required for this method and its simplicity were the factors considered in choosing this method, although the results are only a rough approximation of evapotranspiration.

The formula developed by Thornthwaite for determining potential evapotranspiration from temperature data is:

$$E = 1.62\ (10T/I)^{a} \qquad (1)$$

where E is the monthly evapotranspiration in centimeters, T is the mean monthly temperature in degrees Centigrade, I is the heat index determined by adding for 12 months the expression $(T/5)^{1.514}$, and $a = 67.5 \times 10^{-8} I^{3} - 77.1 \times 10^{-6} I^{2} + 0.0179I + 0.492$. The computed potential evapotranspiration is adjusted for day length, which is determined by the latitude of the data-collecting station.

The average monthly and yearly values determined by the Thornthwaite approach for the Larned and Jetmore stations are listed in Tables 6 and 7. The average annual potential evapotranspiration from these two stations is approximately 32 inches.

In order to obtain an estimate of lake evaporation in the general vicinity of the Pawnee Watershed, the three pan evaporation stations nearest to the watershed were considered. These were the Cedar Bluff Dam and the Kanopolis Dam stations, with a record from 1950 to the present; and the Garden City Experiment Station, with a record from 1957 to the present. The mean pan-evaporation values for each of these three stations over the period of record are 66.07, 60.47, and 68.15 inches, respectively. The relatively small capacities and shallow depths of pans, in comparison to lake and river volumes, and their situation at or near the land surface allows proportionately greater amounts of advected heat from the atmosphere to be absorbed by the water in the pan through the sides and bottom than is absorbed by natural open water. Pan evaporation is therefore usually too high; thus a pan coefficient has to be applied. The pan coefficients range from 0.60 to 0.77. Applying a pan coefficient of 0.7 to the pan evaporation data, resulted in the following mean lake evaporation values:

Cedar Bluff Dam (1950-1978): 46.25 inches

Kanopolis Dam (1950-1978): 42.33 inches

Garden City Exp. Sta. (1957-1978): 47.70 inches

The Jensen-Haise (1963) method for calculating potential evapotranspiration, which is generally considered applicable to the western United States, gave very high values of potential evapotranspiration, very

TABLE 6

Thornthwaite potential evapotranspiration for Larned, Kansas (1959-1978)

(inches per month)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
1959	0.	0.05	0.88	1.87	4.16	6.08	5.93	6.27	3.77	1.61	0.37	0.28	31.28
1960	0.	0.	0.06	2.55	3.49	5.32	6.29	6.18	4.27	2.28	0.63	0.02	31.08
1961	0.04	0.28	0.86	1.81	3.58	5.50	6.49	5.42	3.28	2.20	0.39	0.	29.85
1962	0.	0.19	0.49	2.00	5.18	5.16	6.19	6.15	3.57	2.32	0.61	0.12	32.00
1963	0.	0.24	0.97	2.29	4.20	5.93	7.97	6.76	4.47	3.18	0.63	0.	36.64
1964	0.10	0.04	0.46	2.28	4.69	5.87	7.94	5.98	3.90	1.94	0.58	0.00	33.79
1965	0.06	0.02	0.12	2.53	4.28	5.37	6.76	5.88	3.26	2.28	0.95	0.19	31.70
1966	0.	0.00	1.15	1.70	4.06	5.98	7.66	5.28	3.63	2.04	0.59	0.	32.10
1967	0.07	0.23	1.31	2.57	3.50	5.52	5.76	5.41	3.54	2.25	0.54	0.09	30.78
1968	0.00	0.07	1.30	2.14	3.10	5.97	6.66	6.11	3.78	2.34	0.35	0.	31.81
1969	0.	0.08	0.11	2.27	3.92	5.07	7.31	5.78	4.03	1.60	0.65	0.08	30.90
1970	0.	0.37	0.29	1.99	4.77	5.43	7.02	6.74	3.67	1.50	0.45	0.17	32.41
1971	0.	0.	0.70	2.25	3.50	6.33	6.45	5.69	3.88	2.20	0.62	0.11	31.73
1972	0.	0.21	1.48	2.27	3.60	5.73	6.15	5.68	3.91	1.77	0.29	0.	31.09
1973	0.	0.19	0.97	1.65	3.53	6.01	6.62	6.27	3.26	2.35	0.67	0.00	31.51
1974	0.	0.35	1.18	2.35	4.42	5.56	7.49	5.21	2.86	2.33	0.55	0.07	32.39
1975	0.08	0.	0.43	1.99	3.88	5.39	6.60	6.49	3.52	2.43	0.56	0.20	31.58
1976	0.03	0.70	0.87	2.39	3.26	5.69	6.60	6.12	3.93	1.49	0.29	0.14	31.51
1977	0.	0.08	1.05	2.27	4.46	6.24	7.49	5.78	4.32	2.23	0.49	0.05	34.45
1978	0.	0.	0.70	2.33	3.43	5.87	7.70	6.27	4.66	2.19	0.44	0.01	33.60

TABLE 7

Thornthwaite potential evapotranspiration for Jetmore, Kansas (1959-1978)

(inches per month)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
1959	0.	0.03	0.75	1.79	4.08	5.90	5.81	6.35	3.64	1.73	0.37	0.20	30.65
1960	0.	0.	0.13	2.56	3.46	5.40	6.26	5.99	4.11	2.28	0.57	0.03	30.78
1961	0.01	0.31	0.88	1.71	3.65	5.48	6.41	5.57	3.33	1.99	0.31	0.	29.64
1962	0.	0.21	0.50	1.90	5.00	4.95	6.20	6.11	3.64	2.32	0.62	0.18	31.63
1963	0.	0.24	1.00	2.35	4.23	6.00	7.48	6.40	4.29	2.98	0.65	0.	35.62
1964	0.12	0.02	0.47	2.31	4.64	5.61	7.55	6.00	3.89	1.95	0.60	0.01	33.17
1965	0.09	0.03	0.08	2.47	4.27	5.27	6.72	5.64	3.39	2.17	0.95	0.15	31.23
1966	0.	0.	1.01	1.71	3.98	6.03	7.72	5.33	3.68	2.00	0.48	0.	31.94
1967	0.04	0.22	1.32	2.62	3.48	5.44	6.06	5.54	3.66	2.38	0.47	0.08	31.31
1968	0.01	0.08	1.18	2.08	3.05	6.01	6.62	6.11	3.83	2.39	0.41	0.	31.78
1969	0.06	0.11	0.06	2.32	4.06	4.94	7.18	6.06	4.08	1.52	0.64	0.07	31.12
1970	0.	0.36	0.23	1.81	4.44	5.45	6.91	6.61	3.94	1.49	0.48	0.15	31.89
1971	0.	0.00	0.67	2.08	3.50	6.31	6.49	5.65	3.98	2.29	0.60	0.13	31.70
1972	0.	0.21	1.57	2.28	3.66	5.74	6.36	5.76	4.08	1.94	0.28	0.	31.87
1973	0.	0.20	1.01	1.60	3.51	5.97	6.76	6.53	3.42	2.11	0.59	0.06	31.78
1974	0.	0.35	1.18	2.42	4.42	5.71	7.44	5.33	2.98	2.42	0.52	0.03	32.81
1975	0.11	0.00	0.55	2.06	3.84	5.42	6.55	6.59	3.71	2.43	0.48	0.22	31.96
1976	0.04	0.48	0.97	2.45	3.16	5.66	6.66	6.23	3.80	1.31	0.32	0.14	31.23
1977	0.	0.08	0.92	2.32	4.39	6.60	7.64	5.95	4.09	2.23	0.39	0.10	34.71
1978	0.	0.	0.78	2.25	3.23	5.51	7.38	6.07	4.50	2.17	0.42	0.00	32.32

close to pan evaporation values without the pan coefficient adjustment, and was therefore discarded for the Pawnee Watershed.

In order to estimate actual evapotranspiration, two methods were followed: 1) the method of Turc (1954) and 2) the soil moisture budget approach.

Turc (1954) developed formulas based on a statistical study of data collected from 254 watersheds located in all parts of the world--including most regions of the U.S.A.--to relate evaporation, rainfall, and temperature over watersheds. He suggested that annual evaporation or evapotranspiration may be estimated as follows:

$$E = P/[0.90 + (P/I_T)^2]^{½} \qquad (2)$$

where E is the annual evaporation or evapotranspiration in millimeters; P is the mean annual precipitation in millimeters; $I_T = 300 + 25T + 0.05T^3$; and T is the mean air temperature in degrees Centigrade. Despite the fact that the vegetation factor, which significantly influences evapotranspiration, does not enter in the above formula*, that equation was found closer to reality than others by many scientists.

Using the Thiessen subareas for precipitation and temperature indicated in Figures 12 and 13, the average areal precipitation and temperature over the entire watershed for 1946-1978 were found to be 20.5 inches and 55.2°, respectively. Using these figures in the Turc formula, the average annual actual evapotranspiration for 1946-1978 was found to be 17.3 inches.

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* Turc also suggested a more complex formula to give evapotranspiration over short periods of time, in which he attempted to take into account the effect on evapotranspiration of different levels of soil-moisture consumption by different crops (see, for example, McKay, 1970). However, to apply this method, more data and crop factors and constants are required.

The measured precipitation and the calculated potential evapotranspiration values have been used together with the Holmes and Robertson (1959) moisture budget technique* to determine the monthly and annual actual evapotranspiration and the moisture surplus available for run-off and groundwater recharge. This method takes into account the soil texture, the expansion of the roots during the growing season, and the fact that evapotranspiration withdraws moisture from the root zone at decreasing rates with increasing moisture stress. With the aid of a computer program (Freeze, 1967), the analysis was carried out for six different soil-moisture capacities varying from 2.5 to 10.5 inches. These soil-moisture capacity values cover the range of values observed in the watershed area (Table 3). Table 8 lists the soil associations present in the Pawnee Watershed together with an estimate of their areal distribution and their soil-moisture capacity. There follows a brief discussion on the basic concepts involved in soil-moisture budget analysis (see also the section "Estimates of Regional Groundwater Recharge").

An accurate visual representation of wet and dry seasons of an area is usually represented by a water-balance diagram. A complete water-balance diagram consists of comparing potential and actual evapotranspiration with the amount of precipitation, usually on a monthly basis. This comparison then gives information on the amount of deficit or surplus water available during different seasons. During periods when

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* Although other similar but more sophisticated techniques--such as Baier and Robertson's (1966) Versatile Budget technique--are available, the available data are not sufficient to justify their use.

TABLE 8

Soil Association Coverage of the Pawnee Watershed

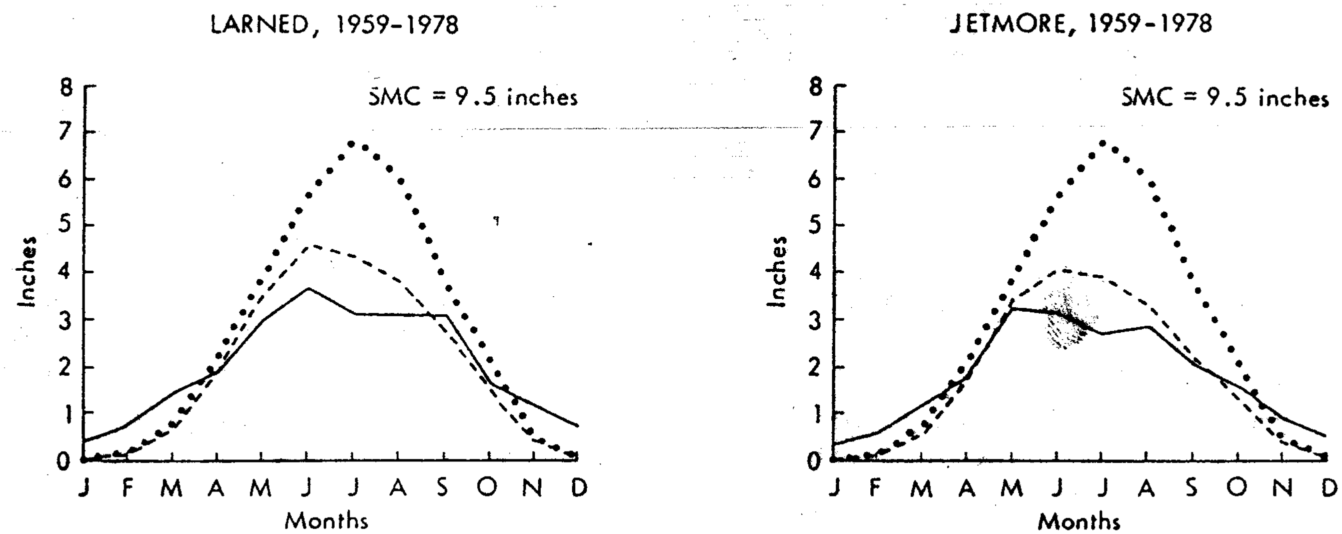
Item	Soil Association	Approximate percentage of the effective drainage area covered	Estimated soil moisture capacity (SMC) in inches in upper 4 feet of soil
1.	Harney-Uly	27.2	9.9
2.	Roxbury-Bridgeport-New Cambria-Hord	21.5	8.8
3.	Harney-Penden-Wakeen	13.7	8.9
4.	Richfield-Penden-Harney-Mansic	21.5	8.8
5.	Harney-Spearville	12.4	9.6
6.	Penden-Mansic-Campus-Canlon	5.6	6.7
7.	Richfield-Harney-Ulysses	11.5	9.7

* * * * * *

Soil association item	Assigned SMC	Approximate % area covered
1 + 4 + 5 + 6	9.5	59
2 + 3	8.5	35
7	6.5	6

the evapotranspiration rate is higher than the precipitation rate, the soil moisture is used until depleted, then a moisture deficiency occurs. During periods when the precipitation rate exceeds the evapotranspiration rate, soil moisture recharge occurs. In addition to variations with location, the appearance of the water balance can vary considerably in one location from year to year. Water-balance diagrams based on 20-year means (1959-1978) for the Larned and Jetmore stations are shown in Figure 14. These diagrams are based on the most prominent soil-moisture capacity of the Pawnee Valley soils. As can be seen from these diagrams, precipitation increases during the warm months as do potential and actual evapotranspiration. A mild bimodal precipitation distribution occurs with peaks in May-June and August-September. A bimodal characteristic is prevalent in a large portion of the central United States (Eagleman, 1975). This reflects the influence of frontal systems in the spring and fall with slightly less precipitation from air-mass thunderstorms in midsummer. Agricultural practices and crop distributions can be related directly to the water balance. In Pawnee and Hodgeman counties, as can be seen from these diagrams, adequate moisture occurs during the months of November through April. This is the period when water is needed for growing wheat, the major crop of the area.

Information on many aspects of the water relations at any place can be obtained from those diagrams (Mather, 1974). The difference between the potential and actual evapotranspiration provides a measure of the moisture deficit of a place (i.e., the amount by which the available moisture fails to satisfy the demand for water). Knowledge of the moisture deficit is basic to any understanding of the economic



	Precipitation	Potential ET	Actual ET
Larned	24.16 *	32.11	23.78
Jetmore	21.15	31.95	21.15

Figure 14. Water balance diagrams for Larned and Jetmore, Kansas (1959-1978)

* 20-yr average values in inches.

[redacted]

feasibility of irrigation, for it provides information on the total volume of water needed at any time and gives a definitive measure of drought. Information on the water surplus, the amount by which precipitation exceeds the water needs when the soil is at field capacity, is fundamental in hydrologic studies that deal with the recharge of groundwater or with the runoff of water in streams and rivers. By definition, the water surplus is the water that does not remain in the surface soil layers but is available for deep percolation to the water table and overland or subsurface flow to the water courses. Thus, information on water surplus, climatically determined from the water budget, provides a knowledge of streamflow that can otherwise only be obtained from extensive stream-gauging installations and from data on flow to the groundwater table that requires detailed well records.

HYDROLOGY

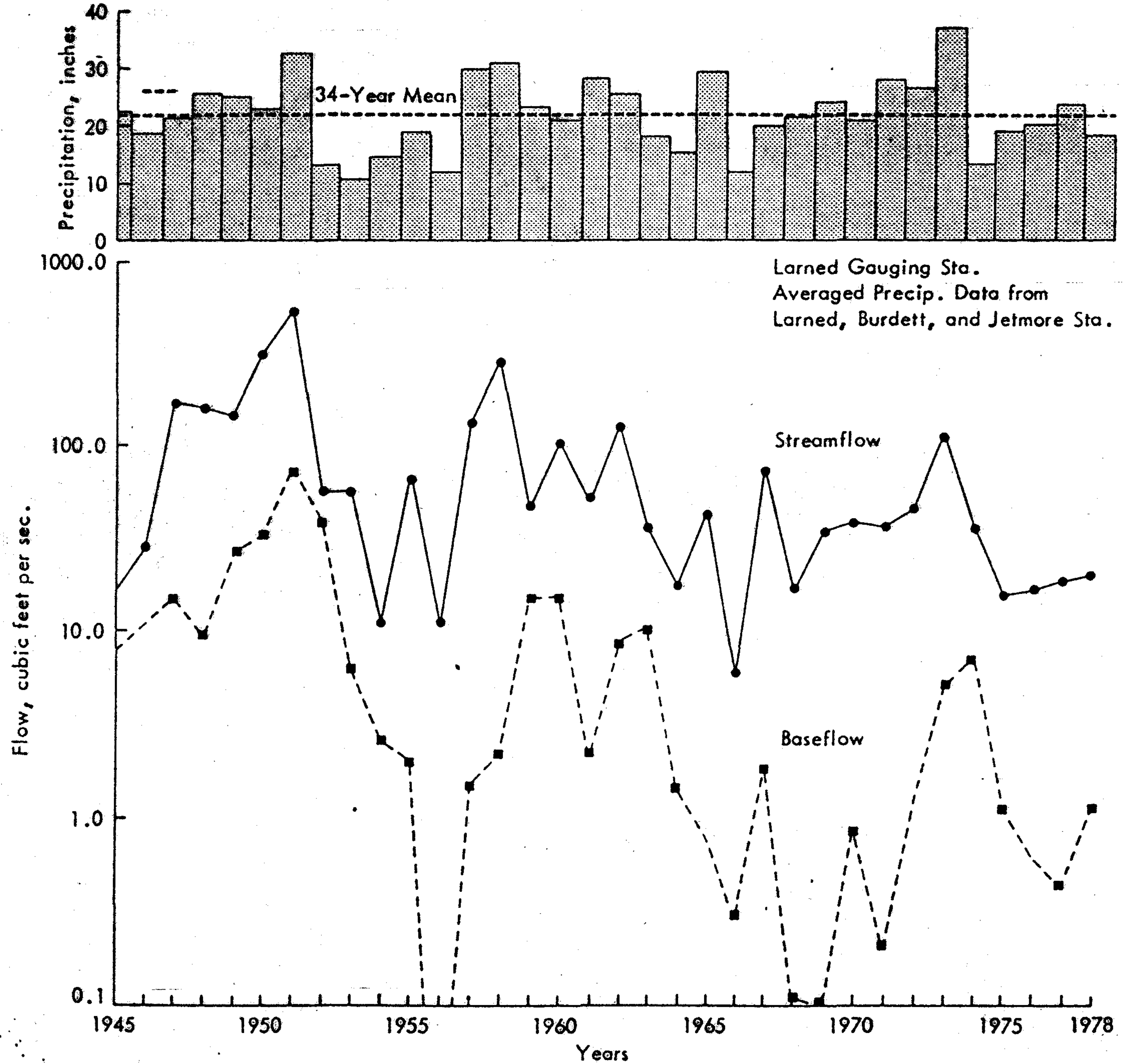
STREAMFLOW AND BASEFLOW

The runoff from the Pawnee watershed is measured at the Pawnee River near Larned (U.S. Geological Survey station #07141200). The location of the station is shown in Figure 3. The gross drainage area of the Pawnee Watershed is approximately 2,735 square miles. The effective drainage area appears to be 2,590 square miles or less. Numerous small undrained depressions and the lack of integrated drainage, especially in the western part of the watershed, make an accurate calculation of the effective drainage area difficult. Surface runoff in the non-contributing portion of the basin takes the form of overland flow into local depression systems.

The streamflow records for the Larned station have been analyzed for 1945-1978. The average streamflow over this period if 85.95 cubic feet per second (cfs), (62,225 acre-feet per year (aft/yr)). Figure 12 shows the total annual streamflow and baseflow (the groundwater contribution to streamflow) data for that period of record, together with the mean precipitation over the area. Baseflow data were obtained from streamflow data following the separation procedures outlined by Busby and Armentrout (1965). In order to distinguish more clearly the data trend, a seven-year and a 13-year moving average time-trend analyses are applied to these data, as shown in Figures 16 and 17, respectively. A comparison of these figures to Figure 15 indicates how the major or long-term features of the record are emphasized at the expense of shorter variations. A computer program to perform m-term smoothing is applied to these data (Davis, 1973). Smoothing reduces the variance of the original sequence; the longer the interval m, the greater the reduction. The percentage figures next to the smoothed curve (Figures 16 and 17) denotes the goodness of fit, which is a measure of the effectiveness of the smoothing process. A continuous streamflow decline is evident from these data, although average areal precipitation over the same period of record does not decrease (Figs. 15, 16). This fact indicates that a growing increase in groundwater use is probably one major cause of this streamflow decline.

In order to estimate the average yearly declines in streamflow and baseflow, a linear regression on the log-transformed data was performed with the resulting straight lines on the semi-log paper plotted in Figure 17. Projection to the future is possible by merely extending

Figure 15 ANNUAL STREAMFLOW, BASEFLOW, AND PRECIPITATION FOR THE PAWNEE RIVER VALLEY



[redacted]

Figure 16 SEVEN-YEAR MOVING AVERAGE OF ANNUAL STREAMFLOW, BASEFLOW, AND PRECIPITATION FOR THE PAWNEE RIVER VALLEY

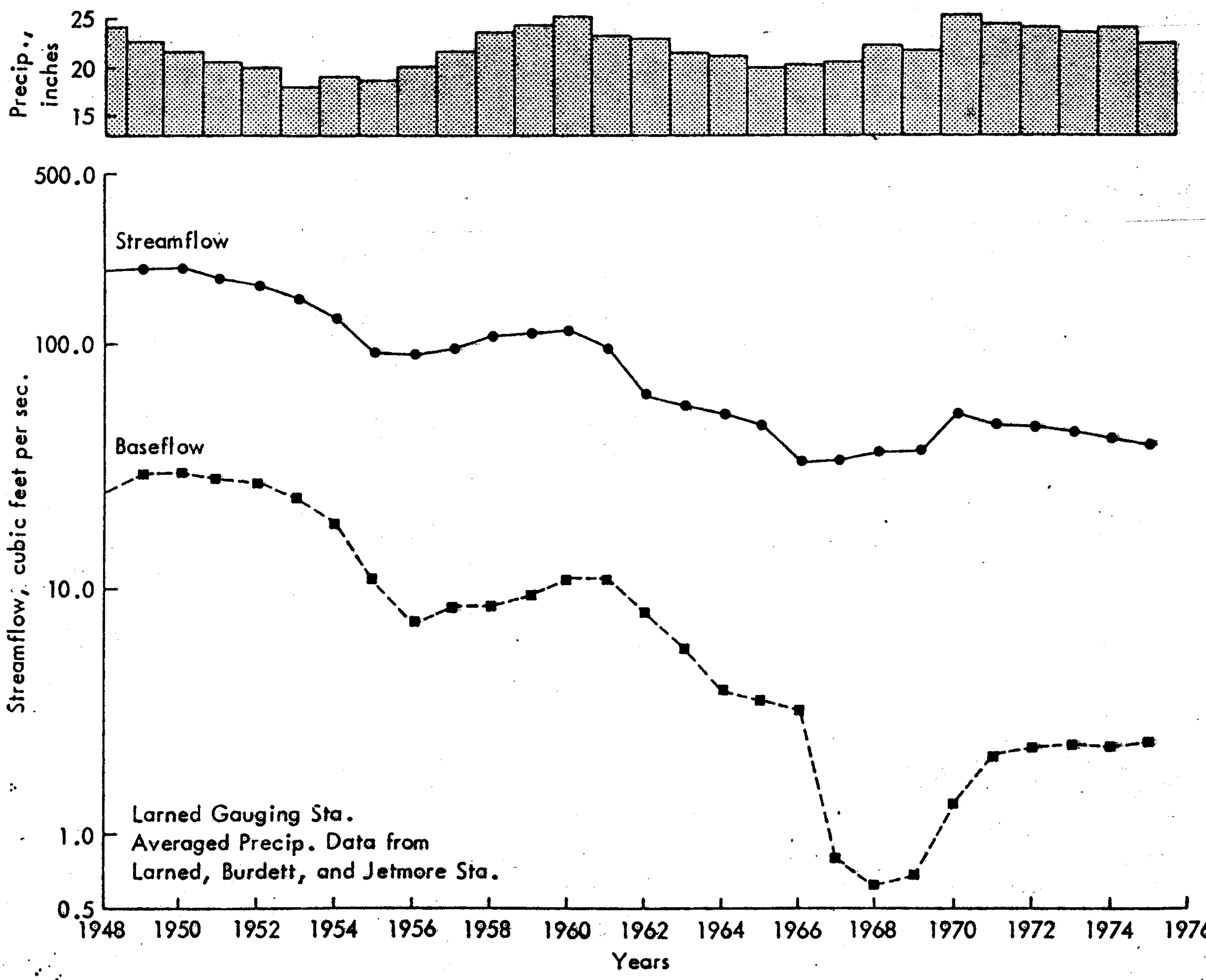
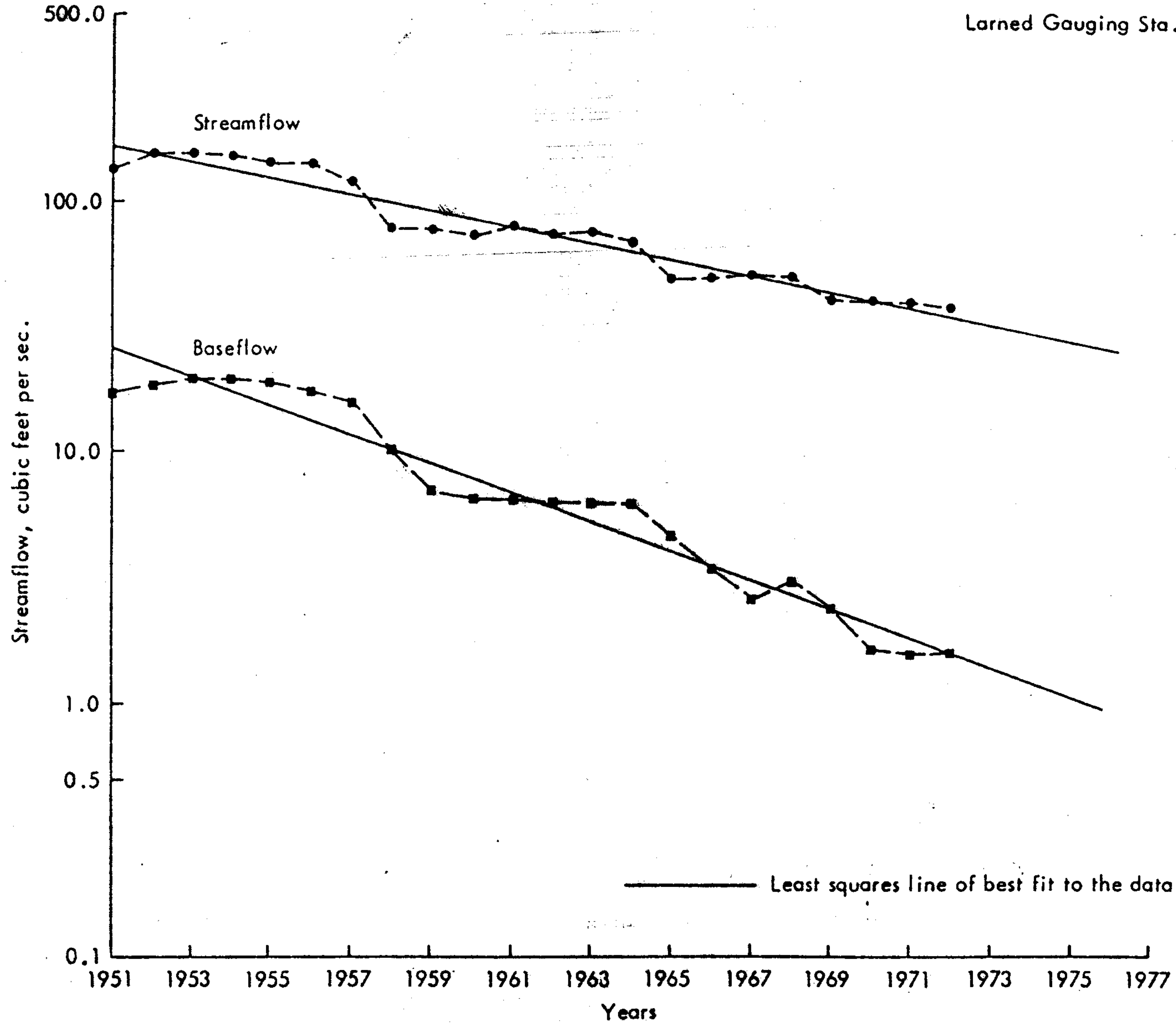


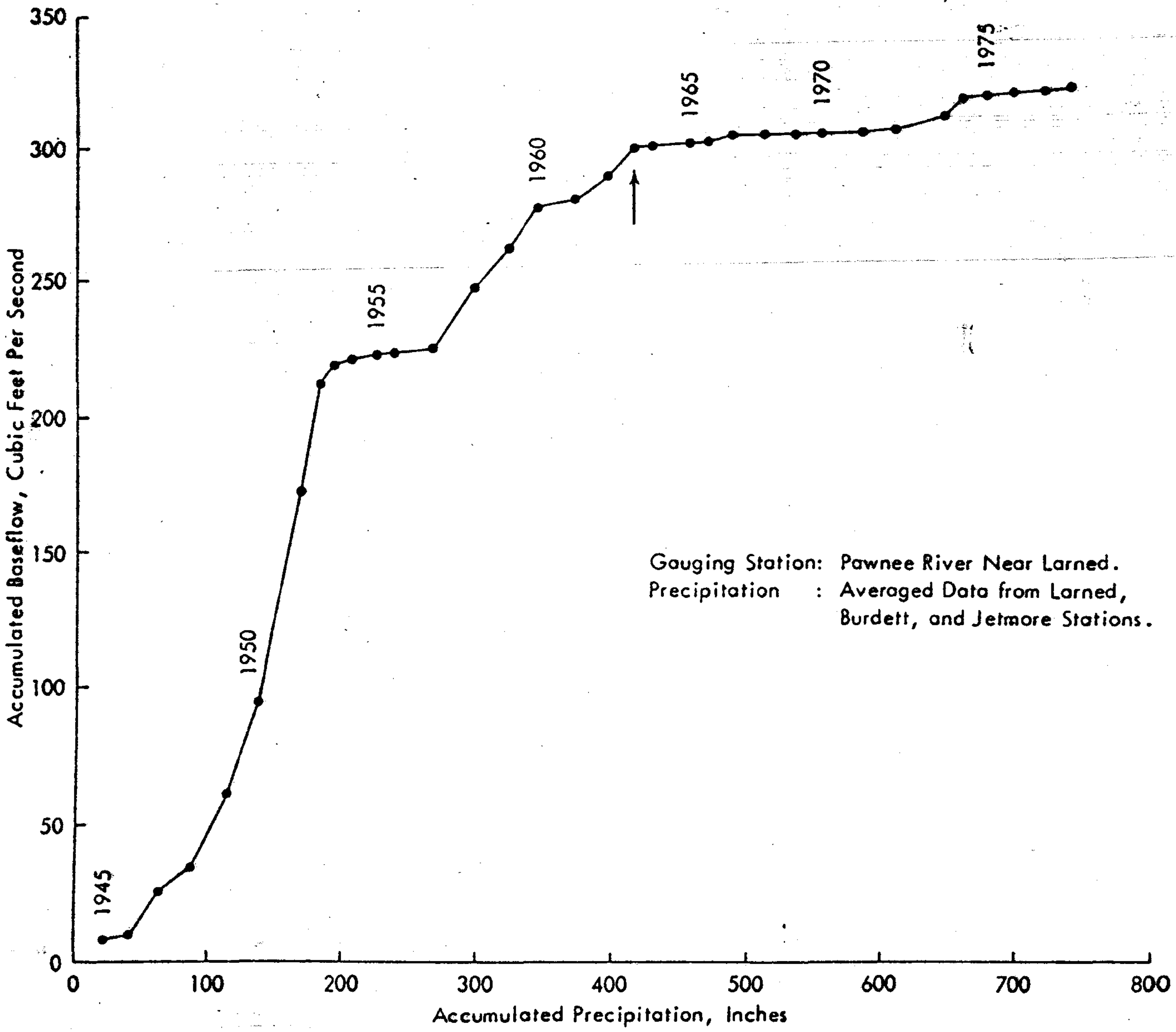
Figure 17 13 - YEAR MOVING AVERAGE OF ANNUAL STREAMFLOW AND BASEFLOW FOR THE PAWNEE RIVER VALLEY LARNED



the straight line into the future years. Correlation coefficients of 93.98 percent for the streamflow and 95.16 percent for baseflow are calculated, indicating that the straight line on the semi-log plot adequately approximates the flow data. From that figure, it can be seen that during the 1950's, the long-term average streamflow was approximately 129 cfs and baseflow approximately 17 cfs; during the 1960's, the average streamflow was approximately 64 cfs and baseflow approximately 5 cfs; while during the 1970's, they were approximately 30 and 1.3 cfs.

Thus, a steeper decline in baseflow is observed during the same period of record, providing further evidence of heavy groundwater withdrawals. In order to examine this observation further, a double mass analysis of cumulative baseflow versus cumulative precipitation for the study period was performed (Fig. 18). Effects of the drought in the early 1950's are evident and an apparent change in baseflow regiment occurs in the mid-60's. Average baseflow for 1945 through 1963 was 15.8 cfs (11,431 aft/yr), while the average for 1963 through 1978 was 1.5 cfs (1,093 aft/yr), which indicates a drastic reduction in baseflow after the mid-60's. This break in slope of the mass curve (Fig. 18) after 1963 coincides with a significant increase in the development of groundwater for irrigation, as can be seen from the increase in irrigated acreage (Figs. 4, 5) and the increase in well registrations (Figs. 6, 7). Reduced precipitation is not a cause of depletion of the flow in the stream since 1963 (Fig. 15). The only remaining reasonable causes of the depletions are capture by irrigation wells of water normally discharged to streams and changes

Figure 18 ACCUMULATED BASEFLOW VERSUS ACCUMULATED PRECIPITATION FOR THE PAWNEE RIVER



in land-use practices. Among others, the latter include larger tractors and machinery to cultivate the soil, construction of terraces on land, contour farming, higher crop yields from summer fallowing (which result in greater soil moisture depletion and consequent decrease of runoff to streams) and construction of small dams. However, quantitative evaluation of such practices is not feasible at the present time.

HYDROGEOLOGY

Groundwater is the major, if not the sole, source of water for irrigation, municipal, and domestic uses in the study area. The major aquifer in the area consists of the alluvial and terrace deposits along the Pawnee River and its tributaries. The alluvial aquifer overlies the Dakota Formation and Greenhorn Limestone. The configuration of this bedrock surface, based on available drilling records, is shown in Figure 9.

There is not much information related to the interaction of the unconsolidated and bedrock aquifers in the Pawnee Valley, especially on the relationship between the alluvial and Dakota aquifers. A piezometric map of the Dakota aquifer in the western part of the Pawnee Valley (Fig. 19) during 1973 (Lobmeyer and Weakly, 1979) shows the elevation of the piezometric surface* to be less than the water-table elevation of the alluvial aquifer during 1979, indicating that there is not any potential gradient forcing water from the Dakota into the alluvium. However, the Dakota aquifer is hydraulically connected with the overlying alluvial aquifer in places where the Dakota aquifer directly underlies the alluvial aquifer.

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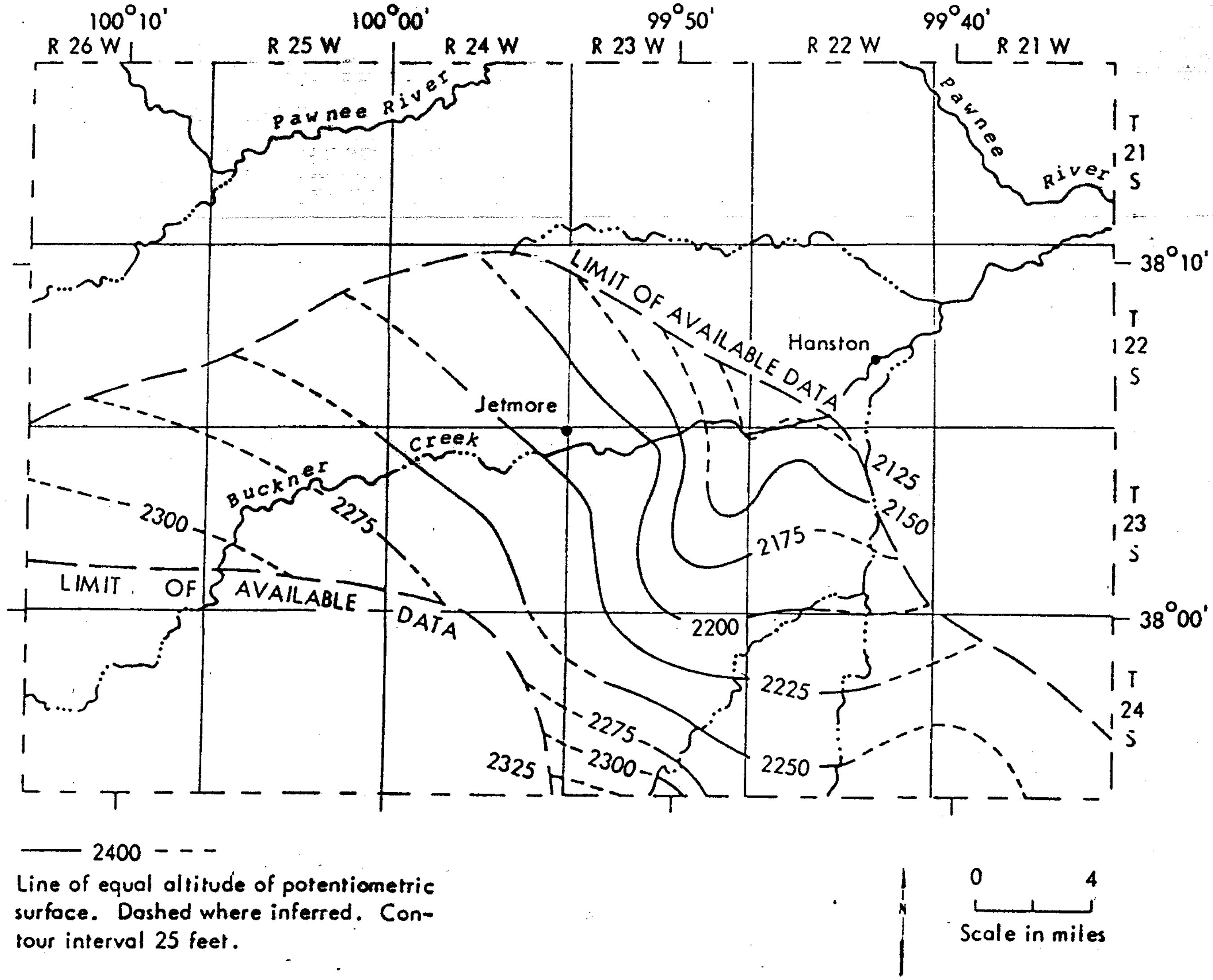
* Piezometric surface is an imaginary surface that everywhere coincides with the static level of the water in a confined aquifer.

Figure 19

CONFIGURATION OF THE POTENTIOMETRIC SURFACE OF THE DAKOTA FORMATION, HODGEMAN COUNTY, SPRING 1973



WATER-TABLE CONFIGURATION AND DECLINE

The configuration of the water table is shown in Figure 20. This map is based on mid-June 1979 water-level data collected during an extensive field survey of the area that yielded more than 170 data points.* This is the only extensive water-level measurement survey since the one conducted by Fishel (1952) in 1945-47. The water-level survey published periodically by the U.S. Geological Survey (Water Resources Data for Kansas or other related reports) consists of only seven wells in the Pleistocene deposits of the Pawnee Valley in Pawnee County and 11 wells in the Pleistocene sediments in Hodgeman County. These are not sufficient for an adequate evaluation of the Pawnee Valley.

The water table, as shown in Figure 20, slopes generally to the east. The water-table contours bend upstream, indicating that groundwater is discharging into the streams. The hydraulic gradient varies inversely with distance between lines of equal head, in this case between water-table contours. Relatively uniform hydraulic conductivity gives rise to equidistant spacing of water-table contours. The variable contour spacing of the water-table map gives an indication of the variable hydraulic conductivity distribution over the alluvial aquifer. Movement of groundwater through intergranular spaces in porous materials is diffuse and fairly uniform, but the most permeable materials, such as sands and gravels, are commonly laid down by running water, and consequently have directional properties; the hydraulic conductivity in one direction may be many times greater than in another. Normally

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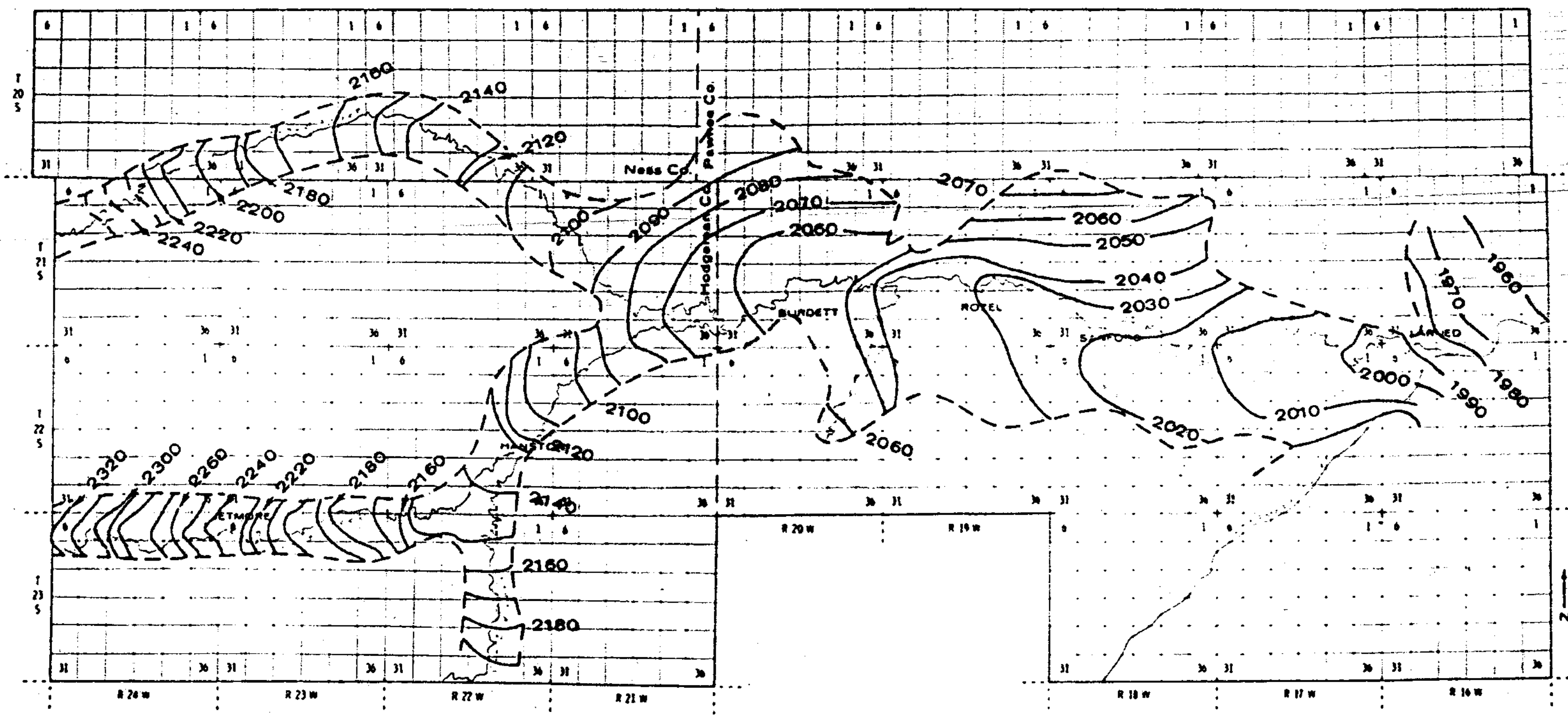
* The 1979 water-level survey was supplemented and checked for questionable data using a January 1980 water-level survey. A suspect water-level depression indicated in the 1979 water survey in the area around Frizell was thus corrected. The water-level difference between the June 1979 and January 1980 water level surveys was within one to two feet on the average, not enough to make a difference on the water-level map (Fig. 20).

Figure 20

WATER-TABLE MAP OF PAWNEE VALLEY, KANSAS, ALLUVIAL AQUIFER DURING 1979-80



EXPLANATION

—2100— Water-table contours in feet. Dashed where inferred.
Contour interval 10 feet.

– – – – Approximate extent of the alluvial aquifer (zero saturated thickness outline).

Approximate scale: 1:125,000

the horizontal components are greater than the vertical, but even these may vary greatly in direction and between individual sand layers in a single sand deposit. It is the varying hydraulic conductivities and the direction of greatest hydraulic conductivity that gives rise to the seemingly anomalous occurrences of groundwater, which has led to the belief in mysterious underground lakes and streams. In the Pawnee Valley, the deep valley has been eroded and filled with very permeable materials, and later deeply covered by less permeable material. This is a highly productive aquifer. Because of the relative scarcity of water on either side of the valley, it may be interpreted as an underground stream, which in a certain sense it is. However, the flow is through permeable materials and not through an actual channel-way as in a surface stream.

Figure 21 contains hydrographs of selected irrigation and observation wells in the study area, as well as the distribution of mean precipitation over the area. Water levels change with time depending upon the temporal variations in the balance between recharge and discharge. This balance is affected by both natural climatic variations and agricultural development. The response of water levels to local variations in climate is typified by the well hydrographs prior to the early 60s. The periods of water-level rise correspond to wet periods and declines correspond to dry periods. Water-level changes caused by agricultural practices have been superimposed on these natural fluctuations. Water-level declines since the mid-60s are the direct result of increased discharge from the aquifer to supply the consumptive use of irrigated crops.

In order to evaluate the extent of these water-level declines, the 1945-47 water-level survey (Fishel, 1952) was used (see Fig. 22) in

Figure 21
HYETOGRAPH AND HYDROGRAPHS FOR SELECTED WELLS IN PAWNEE VALLEY

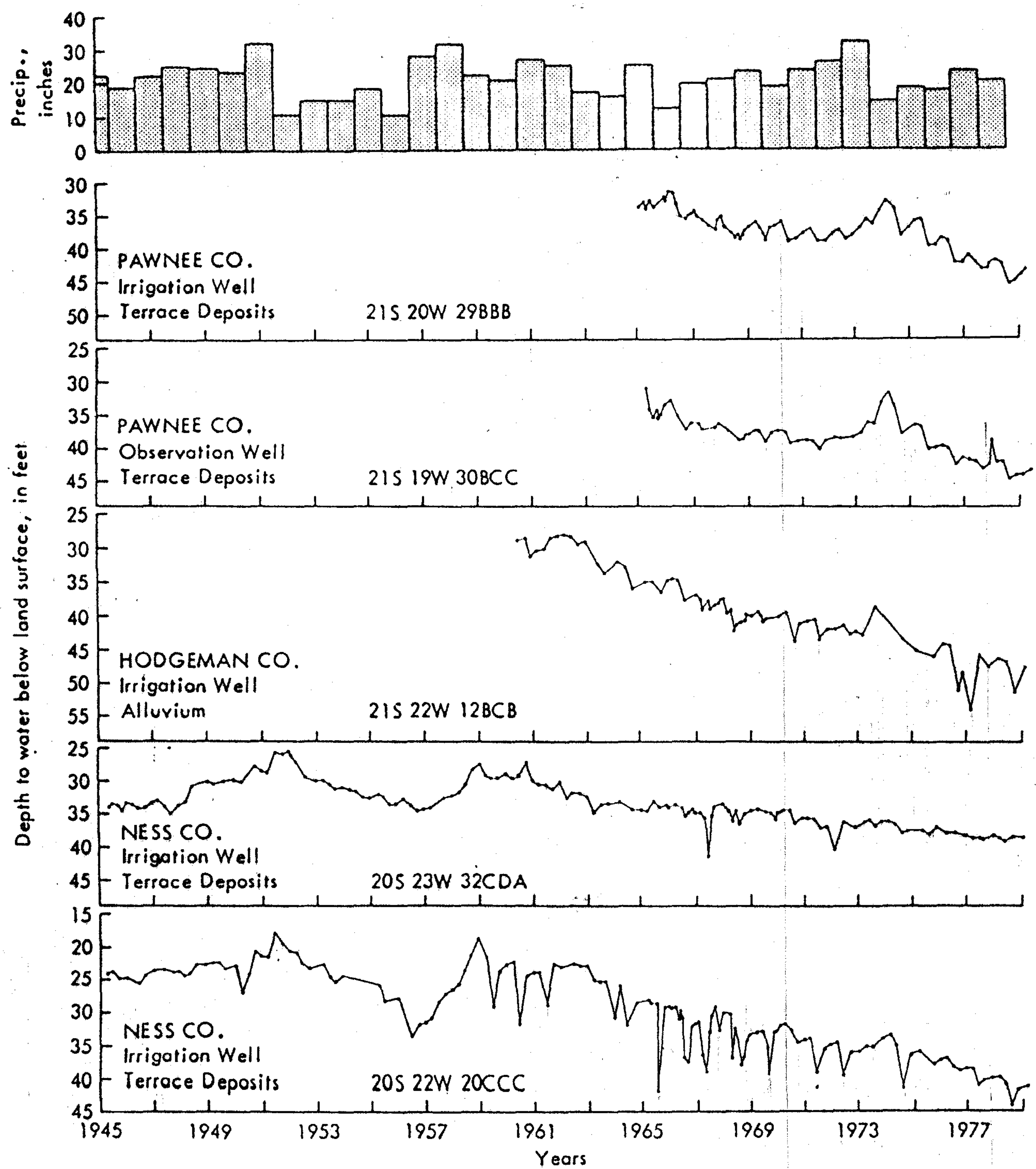
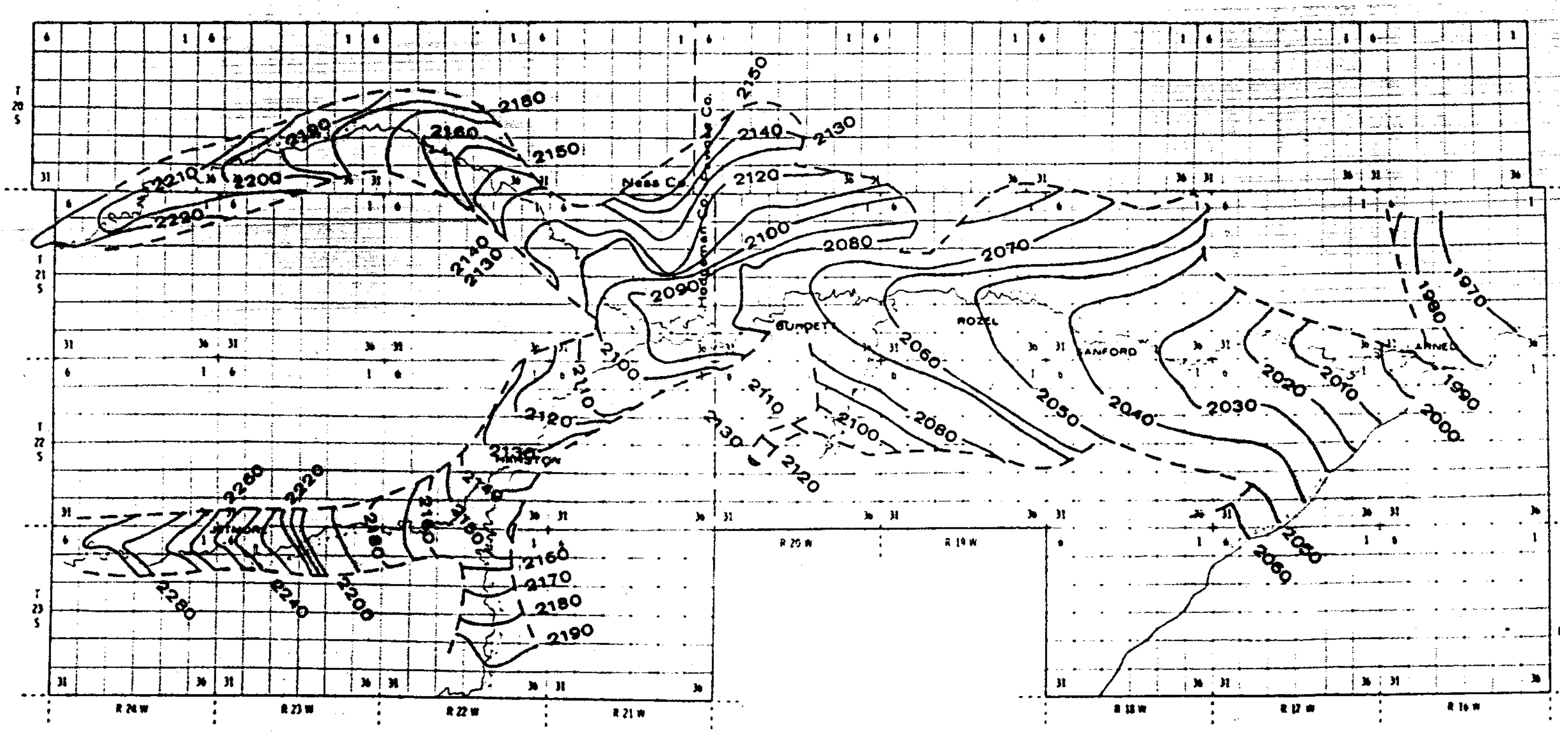


Figure 22

WATER-TABLE MAP OF PAWNEE VALLEY, KANSAS, ALLUVIAL AQUIFER DURING 1945-47



EXPLANATION

— 2190 — Water-table contours in feet.

Contour interval 10 feet.

– – – – Approximate extent of the alluvial aquifer (zero saturated thickness outline).

Approximate scale: 1:125,000

conjunction with the 1979-80 water-level map (Fig. 20). Based on these two maps, a 1945-47 to 1979-80 water-level decline map was produced (Fig. 23). Declines of greater than 30 feet are calculated for the area of the Pawnee Valley south of the Burdett-Rozel-Sanford area as well as for the area surrounding the Hodgeman-Ness-Pawnee county boundaries (Fig. 23). An approximate 15 percent shrinkage of the Pawnee Valley aquifer from 1945-47 to 1979, a result of increased pumpage, is indicated by the zero saturated-thickness contour outline.

WATER IN STORAGE

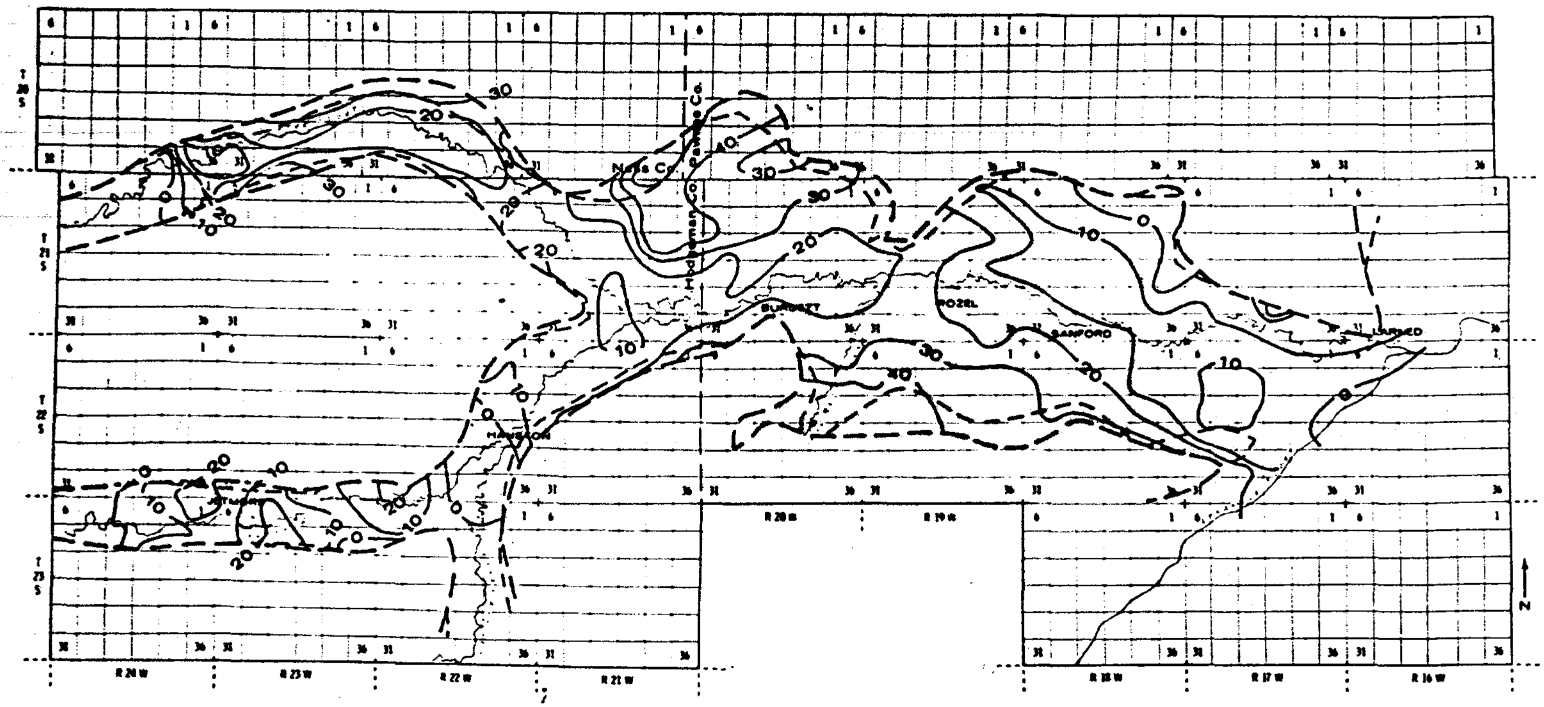
Groundwater is stored in the pore spaces of the unconsolidated deposits comprising the alluvial aquifer. The total volume of water stored at a given point in the aquifer is determined by the thickness and total porosity of the aquifer. Recoverable water in storage is determined by aquifer thickness, the amount of water that can be derived by gravity drainage, the expansion of water, and the compression of the aquifer matrix.

The saturated thickness of the Pawnee Valley alluvial aquifer ranges from zero along the edges of the valley to more than 80 feet near the center of the valley. Figure 24 is a saturated-thickness map as of 1979-80, and was constructed by contouring the difference between the water-table and the bedrock maps.

In order to study any possible reductions of water in storage since the 1945-47 (Fishel, 1952) survey, a new 1945-47 saturated-thickness map was constructed (Fig. 25). This map is somewhat different from the one published by Fishel (1952) because, in the construction of this

Figure 23

WATER-LEVEL DECLINE MAP OF PAWNEE VALLEY, KANSAS, ALLUVIAL AQUIFER FROM 1945-47 TO 1979-80



EXPLANATION

—20— Water-level decline contours in feet.
Contour interval 10 feet.

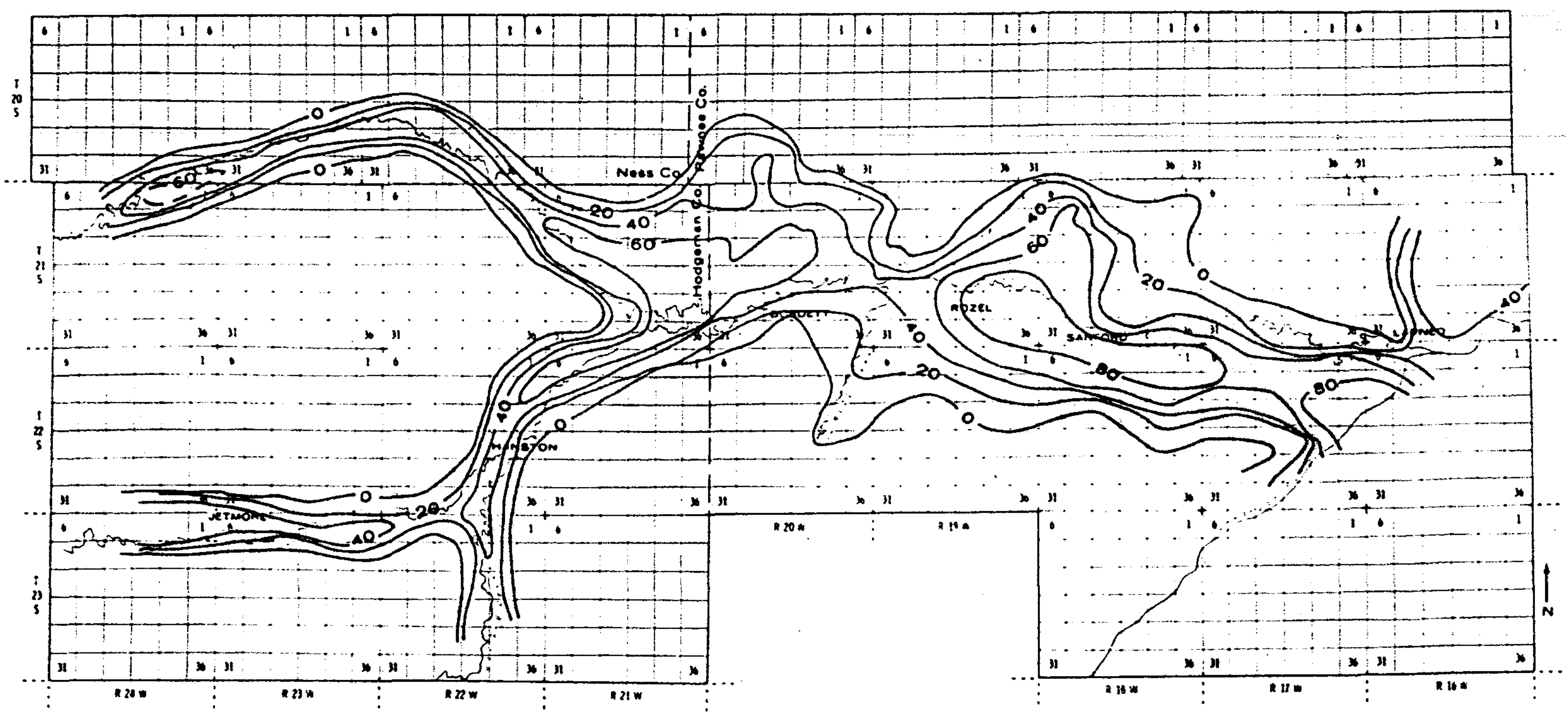
— — — Approximate extent of the alluvial aquifer during 1945-47.

- - - - Approximate extent of the alluvial aquifer during 1979-80.

Approximate scale: 1:125,000

Figure 24

SATURATED-THICKNESS MAP OF PAWNEE VALLEY, KANSAS, ALLUVIAL AQUIFER DURING 1979-80

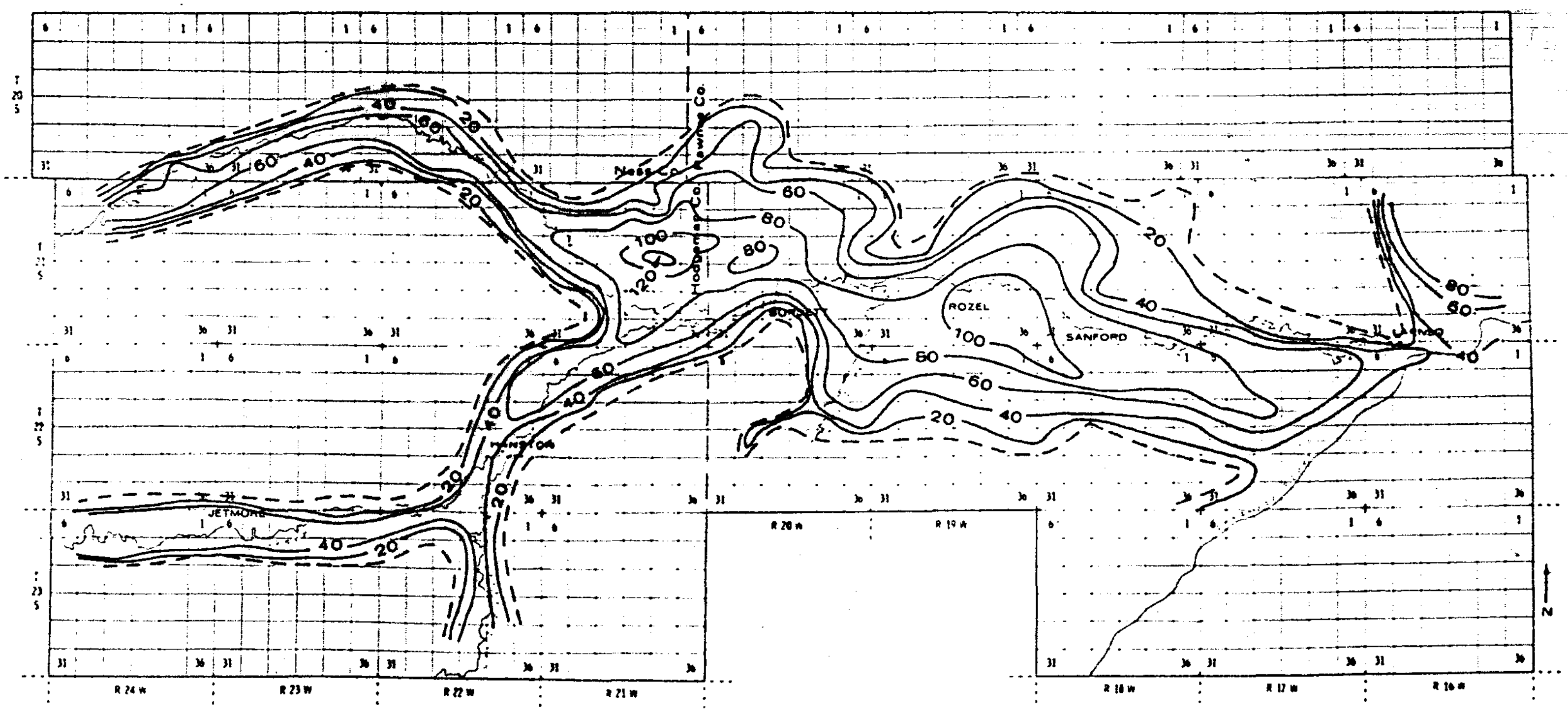


EXPLANATION

—40 – Saturated-thickness contours in feet. Dashed where inferred.
Contour interval 20 feet.
Approximate scale: 1:125,000

Figure 25

SATURATED-THICKNESS MAP OF PAWNEE VALLEY, KANSAS, ALLUVIAL AQUIFER DURING 1945-47



EXPLANATION

—40— Saturated-thickness contour in feet.

Contour interval 20 feet.

- - - - Approximate extent of the alluvial aquifer (zero saturated thickness outline).

Approximate scale: 1:125,000

saturated-thickness map, an updated bedrock map based on more data points than Fishel's was used. It should be noted that the 100- and 120-foot saturated-thickness contours in the 1945-47 map do not appear in the 1979-80 map, reflecting the increased use of groundwater.

Table 9 compares the volume of water in the saturated deposits by county for 1945-47 and the present. These volumes were calculated by measuring the area between each pair of saturated-thickness contours using the planimeter method and then multiplying by the average saturated thickness. Assuming, as Fishel (1952) did, an average specific yield of 15 percent, the total volume of water available for pumping would be 15 percent of the volume of water-saturated deposits; these figures are also given in Table 9. From a practical standpoint, much less than this quantity of water would be available for irrigation use. An average depletion of water in storage of 37 percent is evident since 1945-47.

Comparison of the 1945-47 volume of water-saturated deposits reported here and that indicated in Fishel's report (1952) indicates a significant difference. This discrepancy is not due to planimeter errors but is the result of the following:

a) A greater aquifer area is considered in this report than in the Fishel report;

b) Because of the availability of more drilled well data since the Fishel report, a new bedrock map (Fig. 9) was constructed and the 1945-47 saturated thickness map was rederived (Fig. 25).

TABLE 9

Volume of water-saturated aquifer deposits in the Pawnee Valley

County occupying portion of Pawnee Valley	1945-47 volume of water in saturated deposits in acre-feet	Maximum 1945-47 volume of water available for pumping in acre-feet*	1979-80 volume of water in saturated deposits in acre-feet	Maximum 1979-80 volume of water available for pumping in acre-feet	Overall depletion of water from storage
Pawnee	7,089,745	1,063,460	4,652,765	697,915	
Hodgeman	3,013,835	452,075	1,928,210	289,230	
Ness	1,043,715	156,555	442,570	66,385	
TOTAL	11,147,295	1,672,090	7,023,545	1,053,530	37%

* Based on an assumed specific yield of 15 percent.

AQUIFER PROPERTIES

In order to understand and analyze the operation of the hydrogeologic system of an area, an understanding of the hydrogeologic properties of the aquifer deposits is required. Those properties of greatest significance are the ability of the aquifer to transmit water, which is measured by the transmissivity or hydraulic conductivity of the aquifer material, and the ability of the aquifer to store or release water, which is measured by the storativity or specific yield of the aquifer. Very little information regarding these parameters is available for the Pawnee Valley area.

Fishel (1952) reported that the hydraulic conductivity of the alluvium in the Pawnee Valley was determined by five pumping tests. The results of those pumping tests were analyzed by the recovery method for computing the transmissivity of the aquifer and are summarized in Table 10. The variability of the aquifer material is demonstrated from these results. However, none of the reported pumping tests were designed or run long enough for a satisfactory calculation of the aquifer storativity.

The report by Jenkins and Pabst (1977) on Ness County contains some specific-capacity data for wells in the Pawnee Valley portion of Ness County. High specific capacities usually indicate a high transmissivity and vice versa. The relationship between specific capacity and transmissivity is dependent upon the storage coefficient, the well diameter, and the duration of pumping. Walton (1970) presents the following relationship between specific capacity (Q/s) and transmissivity (T)

$$\frac{Q}{s} = \frac{T}{264 \log (Tt/(2693 r_w^2 S)) - 65.5} \qquad (3)$$

where Q is the well discharge in gpm, s is the drawdown in feet, Q/s is the specific capacity in gpm/ft, T is the transmissivity in gpd/ft,

TABLE 10

Results of Pumping Tests Made on Wells in the Pawnee Valley

County	Well Location	Specific Capacity in gpm/ft	Transmissivity in gpd/ft	Hydraulic Conductivity in gpd/ft^2
Hodgeman	21-21-21bc	60	460,000	12,000
Hodgeman	21-21-35ba	66	95,000	1,550
Hodgeman	21-21-35cc	57	139,000	2,900
Hodgeman	22-22-23bc	45	51,000	620
Hodgeman	23-22-11cc	37	44,800	590
Ness	20-22-29cbb	16	14,530	
Ness	20-22-23aab	17	25,420	
Ness	20-23-23ccd	44	44,390	
Ness	20-23-26cab	6	9,700	
Ness	20-23-27dcb	44	79,660	

S is the dimensionless storativity, r_w is the nominal radius of the well in feet, and t is the time after pumping started in minutes. This equation was programmed in the computer to calculate T with the specific capacity Q/s, duration of pumping t, and well radius r_w being known and an assumed storativity S of 0.15. The calculated transmissivities, T, are shown in Table 10.

ESTIMATES OF REGIONAL GROUNDWATER RECHARGE

There are several methods by which estimates of regional groundwater recharge can be made (Meyboom, 1966; Freeze, 1969), such as:

a) Actual field measurements at the recharge end of the flow system;

b) Interpretation of streamflow records at the discharge end of the flow system;

c) The use of soil-moisture budgets based on hydrometeorological data;

d) Calculation of quantitative regional flow by analytical or numerical model analysis.

In this report, the second and third methods have been employed to estimate groundwater recharge.

The long-term average recharge to the alluvial aquifer was assumed to equal the long-term average groundwater outflow during the early times of the Pawnee Valley irrigation development. According to Fishel (1952), during 1925 there were 35 irrigation wells in Pawnee Valley, while by 1945, the number of wells had increased to 132. The average annual baseflow during the period 1925 to 1945 was 5.04 cfs

(3,651 aft/yr). Assuming that each irrigation well pumped about 90 aft of water per year, the average amount of groundwater pumped during that period was approximately 7,515 aft/yr. Making the further assumption that approximately 10 percent of that water returned to the aquifer by deep percolation (H. Dickey, 1979, oral communication), the net amount of pumpage during that period was 6,763 aft/yr. Thus, the total groundwater outflow (baseflow plus pumpage) for 1925 to 1945 was about 10,414 aft/yr, which--under the assumption of equilibrium--represents the amount of groundwater recharge. Groundwater outflow through evapotranspiration is presumed very small and therefore not considered in the calculations. As the area of the Pawnee Valley alluvial aquifer during 1945 (Fig. 22) was approximately 325 square miles, that quantity of recharge represents 0.60 inches per year over the aquifer area.

The second method for estimating regional groundwater recharge in the Pawnee Valley is the moisture-budget technique. Before the results of the soil-moisture budget analysis are presented, the basic concepts involved will be briefly discussed (Meyboom, 1966). A soil is saturated with water if all its interstices are filled. When the soil is permitted to drain freely, some water will be removed. This amount, expressed as a volume ratio, is called the specific yield of the soil. After gravitational water has drained out, the soil is said to be at field capacity. The moisture tension at field capacity is normally between 0.1 and 0.3 atmospheres. Field capacity is the upper limit of moisture available to plant life; the lower limit is reached at the wilting point, which corresponds to a moisture tension of about 15 atmospheres. The actual amount of moisture stored in the root zone between moisture tensions of 0.1 and 15 atmospheres depends mainly on the soil texture and is called the available storage capacity, or soil-moisture capacity.

Two concepts that are related to certain moisture conditions are relevant to the following discussion--soil-moisture deficit and soil-moisture surplus. Soil-moisture deficit is the amount of moisture that has to be added to a four-foot root zone to bring it to field capacity. A soil-moisture surplus exists when more moisture has been added to the root zone than the amount required to satisfy the transpiration demands of the vegetation and to bring the soil to field capacity. Thus, rain infiltrating the ground first meets the vegetation demands, and any excess thereafter can only pass below the root zone and eventually to the water table if the soil in the root zone is at field capacity*. It is therefore possible to determine whether percolation will take place or whether it has taken place, by knowing the relationship among precipitation, actual and potential evapotranspiration, and antecedent soil-moisture conditions. This relation, which is generally presented in the form of a soil-moisture budget, can be calculated from meteorological records.

There are several techniques for calculating soil-moisture budgets. The technique used here is the Thornthwaite method for calculating potential evapotranspiration in conjunction with the modulated soil

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* It should be recognized that the concepts of field capacity and permanent wilting point are vaguely defined concepts that do not represent unique, intrinsic physical properties, independent of the way they are measured. It has become increasingly clear that in a dynamic system, such as the soil, flow takes place almost incessantly, though in varying fluxes and directions, and static situations, as implied by the above static concepts, are exceedingly rare. However, such concepts are considered to provide a useful practical criterion for the upper and lower limits of soil water content that can be more or less depended upon in the field.

moisture technique devised by Holmes and Robertson (1959) to arrive at the actual evapotranspiration and moisture surplus and deficit. Table 11 presents the calculated average monthly moisture surpluses for the Larned and Jetmore stations, together with the frequencies at which surpluses occurred during 1959-1978. The table indicates that in the Pawnee Valley, and for the predominant soil-moisture capacity of 9.5 inches, moisture surpluses occur 15 percent or less of the time from January to March; five percent or less of the time during April, September, November, and December; and never during May, June, July, August, and October. Column 3 of Table 11 shows the total average moisture surplus, which constitutes potential groundwater replenishment. Column 4 shows the same amount as a percentage of the average total annual precipitation from 1959 to 1978. In the summary Table 12 as well as in Table 11, the moisture surplus for various soil-moisture capacities representative of Pawnee Valley soils is listed for the two meteorological stations mentioned previously. The soils map (Fig. 11) has been interpreted in terms of the percentage of the effective drainage area covered by soils representing each of the soil-moisture capacities (see Tables 3 and 8).

If 20 years of record (1959-1978) at the Larned and Jetmore stations are at all representative of the average conditions in the Pawnee Valley, moisture budgets indicate that the average potential annual groundwater replenishment in this watershed varies from 0.28 inches (soil moisture capacity 10.5 inches; Jetmore hydrometeorological conditions) to 1.27 inches (soil moisture capacity 6.5 inches; Larned hydrometeorological conditions). Or, in other terms, the potential annual recharge in this area lies between 1.3 and 5.3 percent of the average total annual precipitation. Tables 11 and 12 show that as the soil moisture capacity increases, the percentage of the available water that is actually evapotranspired increases at the expense of the moisture surplus. The actual evapotranspiration plus the moisture surplus should equal the precipitation amount; the small discrepancies in Table 12 are the result of the averaging of the budgeting procedure.

Applying the percentages of the effective drainage area covered by soils representing each of the soil-moisture capacities (Table 8) to the average moisture surplus over the basin for each soil-moisture capacity gives rise to an average annual surplus of 0.64 inches in the Pawnee Watershed. The moisture surplus must, however, satisfy the surface runoff as well as groundwater recharge. The average total runoff from the Pawnee Watershed, as measured at the gauging station west of Larned during 1959-78 for which the moisture budget is performed, is 0.267 inches (45.095 cfs). Of this, 0.022 inches (3.75 cfs) represents baseflow from groundwater discharge. Subtracting this from the total runoff yields a surface runoff value of 0.245 inches per year (41.34 cfs) over the effective watershed drainage area above the gauging station west of Larned (i.e., 2290 square miles). This figure, when subtracted from the average annual surplus, results in a value for regional groundwater recharge of 0.39 inches per year. This value is of the same order of magnitude as the one calculated from baseflow measurements.

TABLE 11

Average monthly soil-moisture surplus (in.) for 1959-1978 calculated from year to year for different soil moisture capacities according to the modulated soil-moisture budget technique of Holmes and Robertson (1959) for two stations in the Pawnee Valley.

SOIL MOISTURE CAPACITY= 6.50

Station	JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		PERIOD	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	4
LARNED, KS	0.09	20	0.18	25	0.56	20	0.11	15	0.	0	0.03	5	0.	0	0.	0	0.11	5	0.	0	0.01	5	0.18	15	1.27	5.3
JETMORE, KS	0.07	10	0.07	15	0.48	15	0.08	10	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.70	3.3

SOIL MOISTURE CAPACITY= 8.50

Station	JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		PERIOD	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	4
LARNED, KS	0.19	15	0.10	15	0.40	15	0.07	5	0.	0	0.	0	0.	0	0.	0	0.04	5	0.	0	0.01	5	0.12	10	0.94	3.9
JETMORE, KS	0.17	5	0.02	5	0.33	15	0.06	5	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.57	2.7

SOIL MOISTURE CAPACITY= 9.50

Station	JAN		FEB		MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		PERIOD	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	4
LARNED, KS	0.01	10	0.08	15	0.39	15	0.07	5	0.	0	0.	0	0.	0	0.	0	0.03	5	0.	0	0.01	5	0.12	5	0.70	2.9
JETMORE, KS	0.00	5	0.02	5	0.28	15	0.06	5	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.36	1.7

**EXPLANATION OF COLUMNS:

1. Average monthly moisture surplus (in.) for 1959-1978.
2. Percentage of years during 1959-1978 in which moisture surplus occurred during the month indicated.
3. Total average moisture surplus from Jan to Dec (in.).
4. Total average moisture surplus from Jan. to Dec. expressed as percentage of average total annual precipitation 1959-1978.

TABLE 12

Thornthwaite Potential Evapotranspiration and Holmes and Robertson(1959) moisture budget summary for two stations in the Pawnee Valley.

Station	Period for which Records Analysed	Precip. (inchs)	Thornwt Potent Evaptpt (inchs)	Holmes and Robertson Moisture Budget											
				Actual Evapotranspiration(inches) for various soil moisture capacities						Moisture Surplus(inches) for various soil moisture capacities					
				2.5 (in)	4.5 (in)	6.5 (in)	8.5 (in)	9.5 (in)	10.5 (in)	2.5 (in)	4.5 (in)	6.5 (in)	8.5 (in)	9.5 (in)	10.5 (in)
LARNED, KS	1959-1978	24.15	32.11	21.20	22.59	23.11	23.70	23.79	23.88	2.95	1.66	1.27	0.94	0.70	0.59
JETMORE, KS	1959-1978	21.15	31.96	19.29	20.37	20.76	21.09	21.15	21.20	1.89	0.90	0.70	0.57	0.36	0.28

Thus, the average estimated regional groundwater recharge for the Pawnee Valley is about 0.5 inches per year, which represents only 2.5 percent of the average annual precipitation. During 1978-79, the groundwater appropriations in the Pawnee Valley alluvial aquifer (which reached at least 84,000 aft) amounted to about eleven times the amount of estimated natural groundwater replenishment for the Pawnee Valley.

HYDROGEOCHEMISTRY

The quality of the groundwater in the alluvial aquifer is believed to be generally acceptable for most uses. Very little information is available, however, on the alluvial aquifer water quality. There is only one well in the Pawnee Valley alluvial aquifer (22-19-10bbb) that is sampled yearly for chemical analysis.* Table 13 summarizes that water chemical analysis.

CONCLUDING REMARKS

Not enough information to conduct a detailed hydrogeologic study of the Pawnee Valley is available at present. Detailed information related to the following items is not available:

a) groundwater quality of the alluvial aquifer;

b) extended water-level surveys over several years;

c) streamflow water quality on a periodic basis;

d) bedrock aquifers' water levels and quality;

e) stream gauging of tributaries and streamflow gains and losses;

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* The Kansas Geological Survey is planning an extensive groundwater quality sampling program in the area for the summer of 1980.

TABLE 13

Chemical analysis of groundwater collected on August 25, 1978 from a well 130 feet deep into Pleistocene deposits in Pawnee County (22-19-10bbb)

Constituent	Chemical content, mg/l
Ca	80
Mg	17
Na	65
K	5
HCO_3	310
CO_2	25
SO_4	48
Cl	73
F	0.9
NO_3	4
N	0.9
P	0.02
SiO_2	10
Total dissolved solids	456
Alkalinity	254 (as $CaCO_3$)
Hardness	270 (as $CaCO_3$)

* * * * * * * *

Sodium Absorption Ratio	1.7
Specific Conductance	930 µmhos
pH	7.3
Temperature	15.0°C

f) hydrogeologic parameters of both alluvial and bedrock aquifers;

g) amount of water pumped and period of operation of pumping wells;

h) complete hydrometeorological data;

i) surface-ground waters interaction studies and recharge mechanisms investigations.

However, best use has been made of all data in the limited time available. The results presented here are as accurate as the data available. Therefore, the general trends indicated by the available data and conclusions drawn from these are believed to be true representations of the hydrogeologic conditions in the Pawnee Valley.

PART B

DIGITAL SIMULATION OF THE PAWNEE VALLEY ALLUVIAL AQUIFER

INTRODUCTION

The rate of water-level decline is the most important piece of information needed by the groundwater management districts in the study area. In particular, it is of paramount importance to know how rapidly the resource is being depleted, where and when water-level declines will seriously affect existing investments, and what impacts alternative developments or management practices will have on the system. Digital simulation offers a reliable means for evaluating the effects of various development alternatives on an aquifer system such as the Pawnee Valley alluvial aquifer.

A simulation model is a simplification or abstraction of a complex physical reality and its processes. There is no need to elaborate on the fact that most real systems, and certainly the aquifer system, are indeed complicated beyond our capability to describe them and to treat them exactly as they really are. Simplifications are necessary. They take the form of a set of assumptions that should be kept in mind whenever the model is being employed in the course of investigations. On the basis of these simplifying assumptions, a model of an investigated groundwater system is constructed. Because groundwater flow obeys a well-defined set of physical laws which can be expressed mathematically, it is possible to replace actual problems in groundwater flow by analogous mathematical problems (models). This is the reason why models are always presented in the form of a set of mathematical equations, the solution of which yields the behavior of the considered system. In almost all cases, the equations are balance equations based on the principle of conservation of mass and on Darcy's law.

Obviously, it is impossible either to carry out experiments and tests in the aquifer itself to determine its response to various management alternatives or to make comparisons among responses to different possible alternatives to determine the most desirable one. Whenever the treatment of real systems or phenomena is impossible or the cost of such treatment is prohibitive, models of the considered system or phenomena are introduced. Instead of treating the real system, we manipulate its model and use the results of these manipulations in order to make decisions regarding the operation of the real system.

GROUNDWATER SIMULATION MODEL

The mathematical equation describing the two-dimensional groundwater flow through an areally extensive aquifer is given by the following partial differential equation (Bittinger and others, 1967)

$$\frac{\partial}{\partial x}\left[Kb\frac{\partial H}{\partial x}\right] + \frac{\partial}{\partial y}\left[Kb\frac{\partial H}{\partial y}\right] = S\frac{\partial H}{\partial t} + \frac{Q}{\Delta x \Delta y} \qquad (4)$$

where, K = hydraulic conductivity [L/T]*

b = saturated thickness [L]

*[L] denotes units of length, [T] units of time

H = hydraulic head [L]

S = storativity or specific yield (dimensionless)

Q = net withdrawal flow $[L^3/T]$

$\Delta x, \Delta y$ = incremental distances

x,y = space dimensions

t = time

This equation is based on the continuity equation and Darcy's law and is consistent with the Dupuit assumptions. The Dupuit assumptions are (1) the velocity of groundwater flow is proportional to the slope of the hydraulic gradient, and (2) groundwater flow is horizontal and uniform everywhere in a vertical section (Todd, 1959). Equation (4) also assumes that both hydraulic conductivity and storativity are isotropic and that the density of the fluid is constant in time and space.

Equation (4) has no general analytical solution; therefore a finite difference approximation is used to allow a numerical solution with a digital computer. Application of the finite difference approach requires subdivision of the study area into a system of finite grids or subregions. Approximating the differentials of equation (4) by first-order finite-difference expressions and using the Crank-Nicholson implicit method (Remson and others, 1971) leads to the following expression for a water-table groundwater flow system (Knowles and others, 1972)

$$\frac{1}{16}\sum_{m,n} [K_{i,j} + K_{m,n}] \frac{W_{m,n}}{L_{m,n}} [H^{k}_{i,j} + H^{k+1}_{i,j} - 2B_{i,j} + H^{k}_{m,n} + H^{k+1}_{m,n} - 2B_{m,n}$$

$$[H^{k}_{m,n} + H^{k+1}_{m,n} - H^{k}_{i,j} - H^{k+1}_{i,j}] + A_{i,j}Qnet_{i,j} = \frac{A_{i,j}S_{i,j}}{\Delta t} [H^{k+1}_{i,j} - H^{k}_{i,j}] \quad (5)$$

where,

$A_{i,j}$ = cross-sectional area for node i,j

$W_{m,n}$ = width of the face shared by node i,j and any adjoining node m,n

$L_{m,n}$ = distance along the direction of flow between nodes m,n and i,j

$K_{i,j}, K_{m,n}$ = hydraulic conductivity for node i,j or m,n

$H^k_{i,j}, H^k_{m,n}$ = hydraulic head for node i,j or m,n at any time k

$B_{i,j}, B_{m,n}$ = elevation of the bottom of the aquifer at node i,j or m,n

$S_{i,j}$ = storativity for node i,j

$Qnet_{i,j}$ = net rate of water crossing the horizontal boundary for node i,j

Δt = time step

Characteristic values of all variables in the above finite-difference expression are specified for each grid or subregion. These discrete values are assigned to the centers of the grids which are called nodes. Equation (5) is written for each interior node in the ground-water system, and the resulting system of finite difference equations--which are algebraic in form--are solved simultaneously to yield the head at each node for each time step.

A computer simulation program based on equation (5), as applied to a rectangular model system (Knowles and others, 1972) and suitably modified to conform to our own requirements, is used to simulate the alluvial aquifer system in the Pawnee Valley. In this simulation the lower boundary (the base of the alluvial deposits), is considered impermeable.

BOUNDARY CONDITIONS AND INPUT REQUIREMENTS FOR THE SIMULATION MODEL

In order to solve the previously described system of finite-difference equations, some initial and boundary conditions must be specified. The initial conditions consist of initial values of hydraulic head, hydraulic conductivity, elevations of the aquifer base, and quantities of water produced by sources (recharge) or sinks (pumpage) for every node in the region of interest. The boundary conditions consist of: 1) no-flow condition, 2) specified amount of flow, 3) specified head, and 4) exterior nodes. The no-flow condition corresponds to an impermeable barrier, in our case the valley walls. The condition of specified flow or constant flux across the boundaries represents a specific underground flow, and the specified or constant head condition could correspond to a lake or stream of fixed water-surface elevation. An exterior node is external to the groundwater system.

The input for the program consists of:

1) the nodal spacing in each direction, in miles;

2) the type declaration of each node indicating if it is an interior, boundary or exterior node;

3) the physical data for each node, including: a) the water-table elevation in feet, b) the aquifer base elevation in feet, c) the hydraulic conductivity expressed in units of acre-feet per square foot per year, and d) the storativity or specific yield (dimensionless); and

4) the net withdrawal values for each interior node in acre-feet per acre per year.

The pumping rate assigned to each well was determined by assuming that the total volume of water withdrawn was done on a steady continuous basis over the year. The time step used throughout the simulations is one year.

IMPLEMENTATION OF THE MODEL TO THE PAWNEE VALLEY

The previously mentioned computer model was applied to the Pawnee Valley alluvial aquifer. The modeled area has approximate dimensions of 49 miles by 19 miles. A non-uniform grid spacing ranging from one to three miles was chosen and the resulting grid system consisting of 19 columns and 19 rows, is shown in Figure 26. The modeled system contains 361 nodes. Of these nodes, five are specified flux boundary nodes, six are specified head boundary nodes, 100 are interior nodes, and 59 are no-flow boundary nodes. The rest are exterior nodes to the study area.

The 1945-47 water-level map of Pawnee Valley was employed to calculate the hydraulic gradients at the western and southwestern boundaries of the modeled aquifer (Fig. 26). The fluxes at these boundaries were calculated using Darcy's law, which in a simplified form may be expressed as

$$Q = K\ A\ I \qquad (6)$$

where, Q = amount of groundwater entering the study area (L^3/T)

K = hydraulic conductivity of the aquifer material (L/T)

A = cross-sectional area through which flow takes place (L^2)

and I = hydraulic head gradient or slope of the water-table (L/L)

The hydraulic conductivity used was the initial average value of hydraulic conductivity for the Pawnee Valley sediments derived from the pump tests described in Fishel (1952; see Part A of this report). The averaging procedure used for the hydraulic conductivity is the geometric mean.*

---

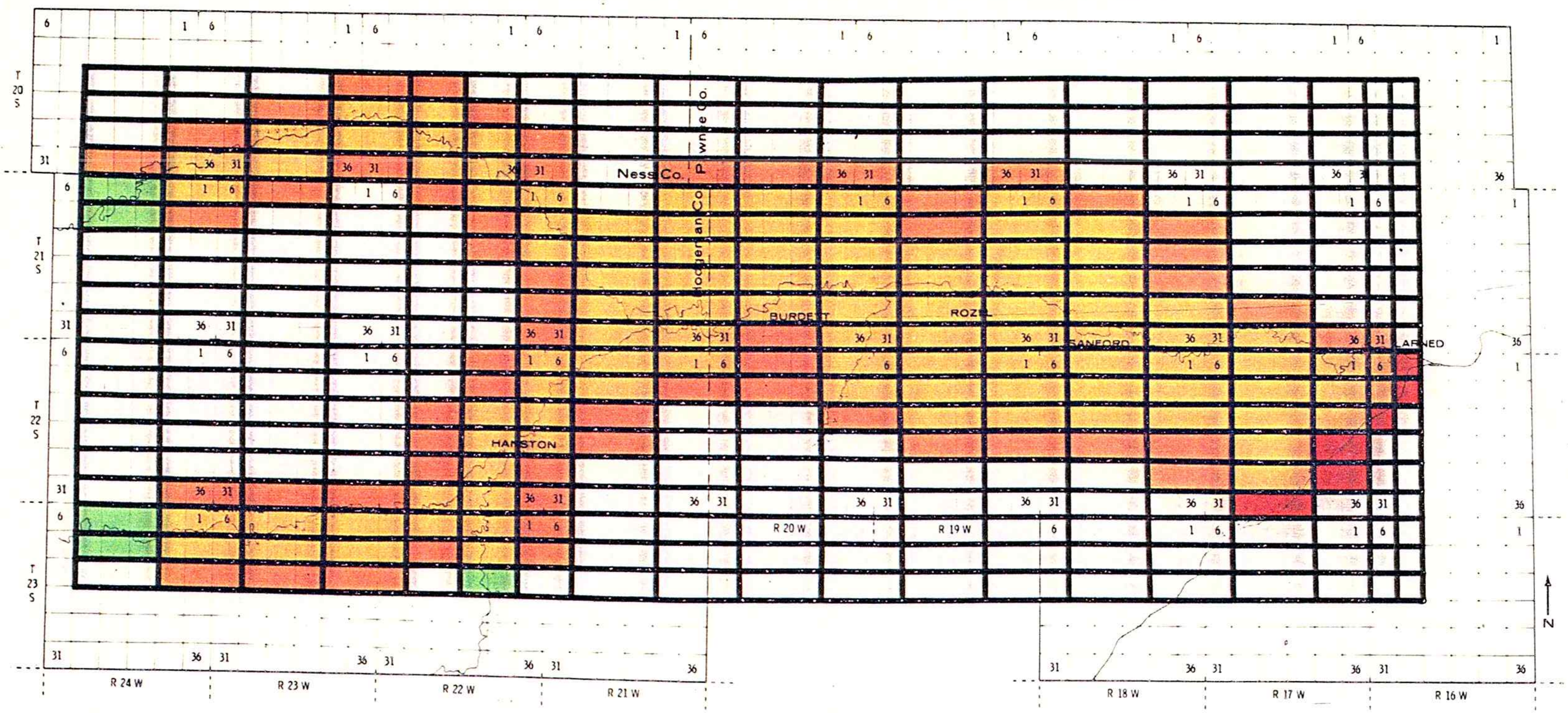
*The geometric mean G of a set of N numbers $X_1, X_2, \ldots, X_N$ is the Nth root of the product of the numbers:

$$G = \sqrt[N]{X_1 \cdot X_2 \cdot \ \ldots, \ X_N}$$

The logarithm of the geometric mean is the mean of the logarithms of the individual values. The geometric mean of a set of positive numbers $X_1, X_2, \ldots, X_N$ is less than or equal to their arithmetic mean, but is greater than or equal to their harmonic mean. The equality holds only if all the numbers $X_1, X_2, \ldots, X_N$ are identical. Of the five pump tests described in Fishel (1952), the arithmetic mean is 472.2 ft/day, the geometric mean is 242.7 ft/day, and the harmonic mean is 152.6 ft/day.

Figure 26

NODAL GRID SYSTEM SHOWING NODAL-TYPE DECLARATIONS



EXPLANATION

- Interior node
- Boundary node-constant flux
- Exterior node
- Boundary node-no flow
- Boundary node-constant head

Approximate scale
1:125,000

There is a large body of evidence (Freeze, 1975) to support the observation that the probability density function for hydraulic conductivity is log normal. In log normal distributions the appropriate average is the geometric mean, which has properties analogous to those of the arithmetic mean of a normal distribution.

Using the above data and the parameter adjustment routine built into the model (see further explanations under the section "Parameter estimation or model calibration"), the net groundwater fluxes entering the western boundaries of the model area were calculated to be approximately 650 acre-feet per year for the Ness-Hodgeman portion of the valley, and approximately 11,830 acre-feet per year for the valley portion west of Jetmore; the net groundwater flux entering the southwestern portion of the valley near the confluence of Saw Log Creek and Buckner Creek was found to be approximately 1,190 acre-feet per year. It should be noted that the net groundwater fluxes were calculated by subtracting from the boundary fluxes the amount of annual appropriated pumpage to the wells in the boundary grid subregions over which the fluxes were calculated. The high values of incoming fluxes in the Jetmore area, compared to the other boundary fluxes, suggest that groundwater contributions to the alluvial aquifer from the underlying Dakota aquifer are probable in that area.

These calculated boundary fluxes are kept constant throughout the predictive period employed in this report (20 years). This is a conservative assumption because, despite the water level declines and saturated-thickness reductions, the boundary fluxes are assumed constant.

The eastern boundary of the modeled area is the Arkansas River. This boundary is treated as a classical constant-head boundary that is time invariant. Such assumption is very conservative since the river becomes an unlimited source of water to the groundwater system as the water levels decline in the vicinity of the stream. This situation has led to the most optimistic forecasts for water levels in the region close to the Arkansas River; therefore, results should be viewed accordingly.

The bedrock and water-level data put into the model are described in the first part of this report. Initially uniform average values of hydraulic conductivity and storativity were used for all nodes. The average hydraulic conductivity used, using the averaging procedure described previously, was 2.04 acre-feet/ft^2/year, while an assumed value for storativity (Fishel, 1952; see Part A of this report) of 0.15 was employed.

The values of the net pumpage required by the model for each node were determined as follows. First, all registered wells were inventoried from the records of the Kansas State Board of Agriculture, Division of Water Resources in Topeka and their field office in Stafford, as well as from Groundwater Management Districts No. 3 and No. 5. Special care was taken to check the location and appropriate pumpage of the wells by contacting the groundwater management districts' managers and checking questionable data at the Water Resources Division. In order to put all these wells into the model, the following procedure was used. All wells located within a grid subregion were assigned to the node at the center of the grid. In very few cases, if the grid was near a no-flow boundary and its average saturated thickness was very small, and that grid had one or more wells near the boundaries with a grid with higher saturated thickness, then the well or wells of that marginal grid were assigned to the nearest grid with a greater saturated thickness. This situation resulted from using one average value of saturated thickness and aquifer parameters for the entire grid subregion. Also, due to the relatively complex shape of the Pawnee Valley, the approximation of that geometry by the finite-difference grid resulted in some small parts of the Valley being located outside the model grid area. In that case, if wells existed in the part of the Valley near the grid boundary, they were assigned to the nearest grid node. The resulting distribution of the appropriated pumpage is indicated in Figure 27. Because the wells in the valley are not water-metered and the farmers' water-use reports are incomplete (not all irrigating farmers submit such reports), the pumpage data used in the model are the amounts appropriated by the Water Resources Division. In cases of overlapping water rights, it is assumed that all overlapping wells are pumping simultaneously over each time step period and that the amount they pump is the average value derived by dividing the maximum amount of pumpage assigned to the water right divided by the total number of overlapping wells. A complete listing of all registered wells in the alluvial aquifer and their appropriated pumpages in the Pawnee Valley portions of Pawnee, Hodgeman, and Ness counties is included in Appendix A.

The present computer model, however, operates on net pumpage values--that is, amounts of gross pumpage minus any amounts of irrigation return flow and natural recharge with no water gain or loss occurring through the base of the aquifer. Since it is assumed that approximately 10% of the amount of water pumped returns as deep percolation to the water table, all amounts of pumpage are adjusted accordingly (H. Dickey, 1979, oral communication). Also, as described in the first part of this report, the average natural recharge over the area is approximately 0.5 inches per year and all amounts of pumpage are adjusted accordingly.

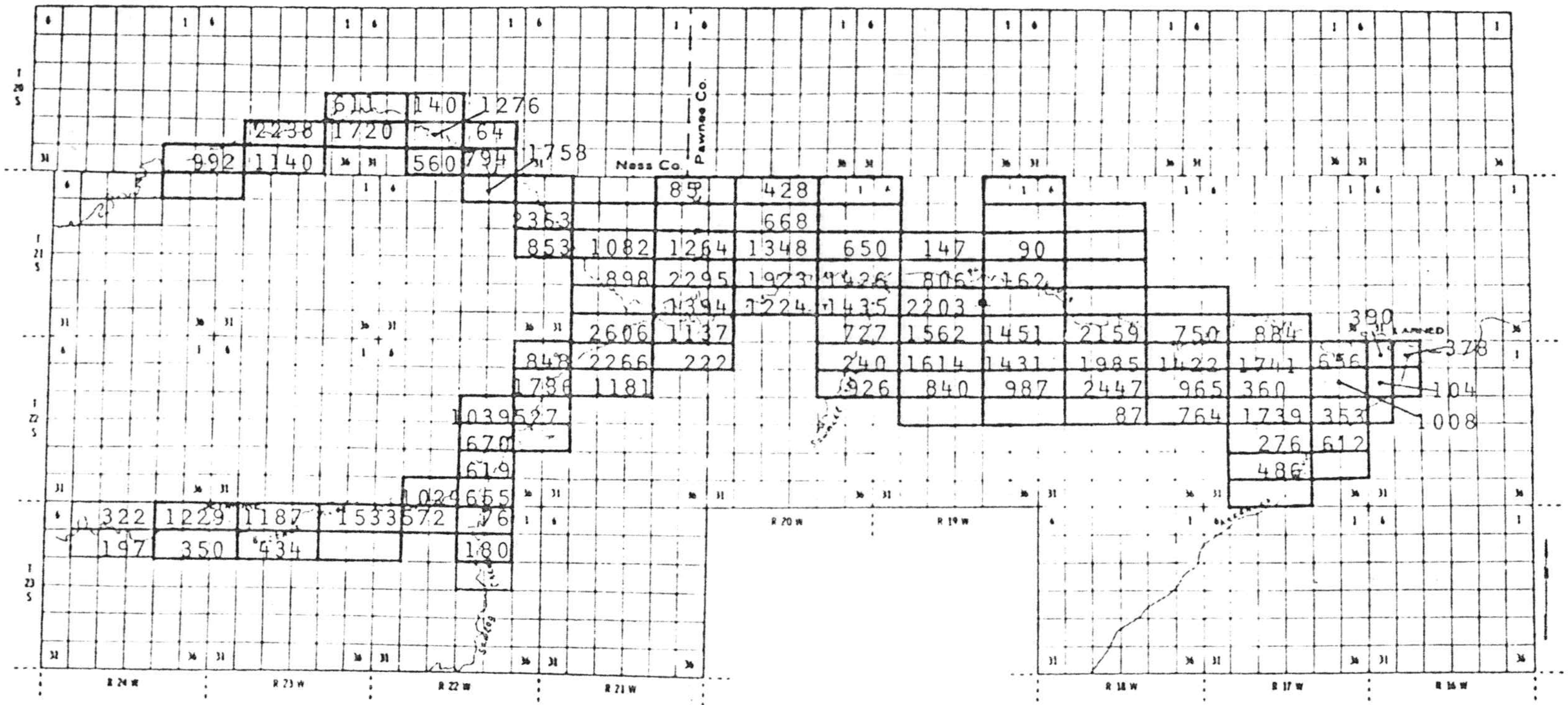


Figure 27. Total amount of groundwater (in acre-feet) appropriated per year to wells in the area of each block.

SOME MODEL FEATURES DESIGNED FOR THE PAWNEE VALLEY

The computer program, as modified for the present study, determines if heads have fallen below the bottom of the aquifer. If so, those heads are set equal to the bottom elevation plus 0.01 foot. Thus, the aquifer transmissivity always has some positive value, allowing re-filling of the aquifer if the opportunity ever occurs.

There are many alternatives available if a well runs dry, e.g., turning the pump off, reducing the pumpage to match the aquifer capabilities, shifting pumpage to other wells, or using some combination of these. There are a few empirically derived formulas relating the reduction of pumpage to the saturated thickness and other aquifer parameters (Lappala, 1978) but these relationships are for thick and relatively deep aquifers as opposed to the thin, shallow Pawnee Valley alluvial aquifer. Besides, no data were available to empirically derive a similar relationship for Pawnee Valley. For these reasons, as an option, it is conservatively and arbitrarily assumed that the wells are able to pump their original appropriation until the saturated thickness declines down to eight feet or less at which time the well is shut down; but the same well does not resume pumping until the saturated thickness is built up to 15 feet or more. Another option employed consists of allowing the well to deplete not more than 40% of the initial saturated thickness, at which time the well is shut down; the same well is assumed to resume pumping when the saturated thickness is built up to 62% or more of the original saturated thickness. Some further model modifications are discussed later in the section on projected water-level declines.

PARAMETER ESTIMATION OR MODEL CALIBRATION

INTRODUCTION

Before an appropriate model can be used as a predictive or problem-solving device for the area of interest, it must be "calibrated" by using data from the physical system to be simulated. The two primary objectives of calibration are 1) to adjust the model's input data (such as aquifer properties, sources and sinks, boundary, and initial conditions) to best approximate the physical system and screen erroneous data; and 2) to determine the sensitivity of the model to the input variables (Huntoon, 1974). In practice, the calibration of a ground-water model is frequently accomplished through a trial-and-error adjustment of the model's input data to modify the model's output. Because a large number of related factors affect the output, this may become a highly subjective procedure. Recent advances in parameter estimation procedures (Seinfeld and Lapidus, 1974) help eliminate some of the subjectivity in model calibration.

The application of a computer model requires that certain terms be known for each node. These include the elevation of the base of the aquifer, initial water-table elevation, net withdrawal values, hydraulic conductivity, and storativity. Elevation of aquifer base and initial water-table may be obtained using physical measurements for each node. The values of hydraulic conductivity and storativity as well as net withdrawal values are much harder to determine. Many methods have been developed to determine values for the aquifer parameters but most of these provide estimates for only a relatively small area.

Parameter estimation procedures provide a tool for determining aquifer parameters for a set of points in an aquifer by treating initial estimates of those parameters as terms to be adjusted on the basis of some criterion of "goodness of fit." The key point in the adjustment of parameters is the determination of the computer-model sensitivity to changes of the parameters. The sensitivity is indicated by the extent the simulated water levels react to a change in an aquifer parameter. A change in the simulated water level will occur not only for the node at which the change in the parameter occurred, but also for the water level of the surrounding nodes. A change in a parameter for any one node will affect the head of all other nodes in the system.

PARAMETER ADJUSTMENT PROCEDURE

The procedure used for adjusting the aquifer parameters is the method of steepest descent, also known as the method of gradients (Knowles and others, 1972). This procedure obtains the minimum of a function by determining the changes of the independent parameters that will result in the greatest rate of reduction of the function. The function to be minimized is the difference between the simulated and measured water levels. The independent parameters are the hydraulic conductivity, storativity and net withdrawal rates or fluxes.

The parameter adjustment procedure is as follows. First, the water levels for the year or years during which measured water levels are available are simulated. The measured water levels are used as starting points for each year's simulation, and the original estimates of hydraulic conductivity, storativity, and net withdrawal rates are used for each node. Second, the values of the coefficients and constants for all the sensitivity equations are determined. The sensitivity of any node's simulated water level with respect to one of the parameters may be expressed by the partial derivative expression of water level with respect to the parameter of interest. For further details on the derivation and application of the equations involved in such sensitivity analysis, see Knowles and others (1972).

Third, the aquifer parameters are adjusted according to the steepest descent algorithm (Vemuri and Karplus, 1969)

$$\phi^{m+1} = \phi^{m} - \lambda(\partial H/\partial \phi)$$

where ϕ is an aquifer parameter (hydraulic conductivity, storativity or net withdrawal value)

$\partial H/\partial \phi$ is the sensitivity of the water level with respect to parameter ϕ

λ is a scalar such that $\lambda > 0$

and m is an iteration index.

The order of nodal adjustment was based on the decreasing size of the simulation error, that is, the difference between the simulated water-table elevation and the measured water-table elevation. The node with the largest simulation error was adjusted first, the node with the second largest error was adjusted second, and so on. The adjustment procedure was terminated when the simulation error of any node was less than 0.5 foot. This termination criterion reduced the execution time of the computer program; also, a simulation error of that size was not considered significant.

Once a node was chosen for adjustment, the sensitivities based on a specified number of nodes surrounding the chosen node were calculated. Although a change of a parameter for any node will theoretically affect the simulated water level for all other nodes in the system, the effect on distant nodes will be slight. This fact suggests that acceptable results could be obtained by a procedure that differentiates only the equations of the nodes most affected by a change at node i,j. Knowles and others (1972) tried several arrangements involving 48, 24, and 12 nodes surrounding node i,j, which were within three or two tiers of that node. They found that the 12 node arrangement surrounding the node of interest i,j (Fig. 28) was not only much more economical to solve but also accurate enough, as the values of the partial derivatives for the nodes in the corners of the region were very small, resulting in a very small change in the simulated head value.

After the parameters had been adjusted, the simulation errors for the twelve adjoining nodes were changed to reflect the expected change in the simulated water level for the center node. The water levels for the surrounding nodes will also change since they are functions of the water level of the adjusted node. The procedure was then repeated, beginning with the simulation of new water levels, until the simulated errors were so small that additional iterations were not justified.

IMPLEMENTATION OF THE PARAMETER ADJUSTMENT PROCEDURE

The water-table configuration served as the basis for evaluating goodness of fit with respect to adjustments of hydraulic conductivity, storativity, and boundary fluxes. Initial estimates of these parameters were used in the calibration of the model. These were adjusted between successive simulations with the objective of minimizing the differences between observed and computed water-table elevations in the study area. In order to avoid the uncertainties related to the amount of net pumpage

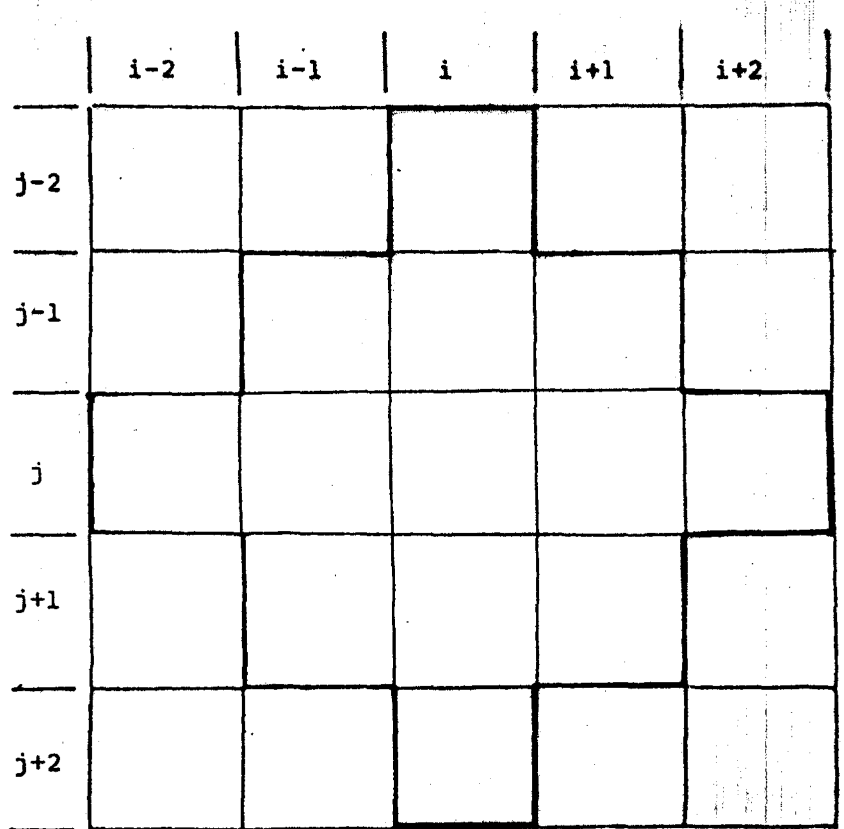


Figure 28. 12-node arrangement surrounding the central node i,j used in calculating the sensitivities of a node.

in calibrating the model, water-level measurements taken during the 1945-47 period were used. It is assumed that the water-table configuration then was closer to equilibrium conditions than it is today and that whatever groundwater was pumped out of the aquifer was approximately replenished by natural recharge. Therefore, starting with that initial water-table surface, the present model was employed to calculate which distribution of aquifer parameters and boundary fluxes would keep that surface nearly constant. By minimizing the simulation errors, this procedure resulted in the distribution of aquifer parameters referred to below. It should be noted that if the pumpage distribution and water levels for several years had been available in adequate detail, this calibration procedure would have been more effective because data of several years would have been averaged, resulting in a better approximation of the aquifer parameters.

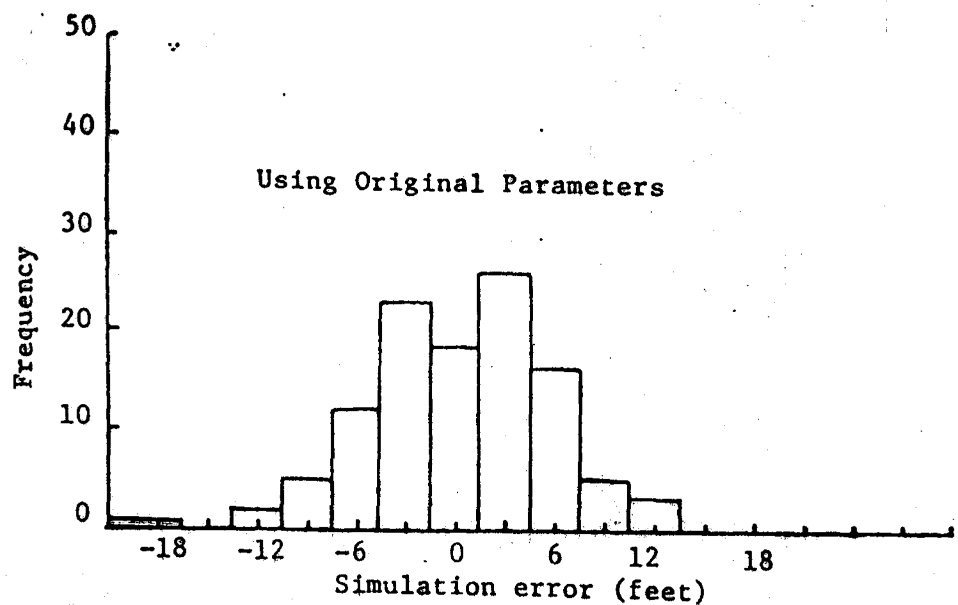
The parameters for all nodes were adjusted by the steepest descent procedure mentioned previously, using constraints on storativity, hydraulic conductivity, and fluxes. The two constraints applicable to the storativity were minimum and maximum allowable values of 0.05 and 0.25. The allowable limits for hydraulic conductivity were 0.03 and 14.0 acre-feet per square foot per year, which correspond approximately to the range from 25 to almost 12,500 gallons per day per square foot. The maximum change allowed in boundary fluxes was one acre-foot per acre per year, which, for a 3x1 square mile area, represents 1,920 acre-feet per year. All the above figures are based on the types of sediments in Pawnee Valley and reflect the great variability of rocks in that Valley.

Table 14 shows the results of the parameter adjustment on the simulation errors for the 1945-47 calibration period. Figure 29 gives a

TABLE 14

Comparison of Frequency of Errors During Parameter Adjustment for 1945-47

Range of Errors	Original Values	After Two Iterations	After Four Iterations	Final Values (After 11 Iterations)
>16.5	1	1	0	0
-16.5 to -13.5	0	0	0	0
-13.5 to -10.5	2	0	0	0
-10.5 to -7.5	5	0	0	0
-7.5 to -4.5	12	3	0	0
-4.5 to -1.5	23	10	6	0
-1.5 to 1.5	18	79	99	107
1.5 to 4.5	26	13	4	3
4.5 to 7.5	16	1	1	0
7.5 to 10.5	5	3	0	0
10.5 to 13.5	3	1	1	1
Sum of Error Squared (ft^2)	3,380	1,976	257	161
Reduction of original Error Squared		42%	92%	95%



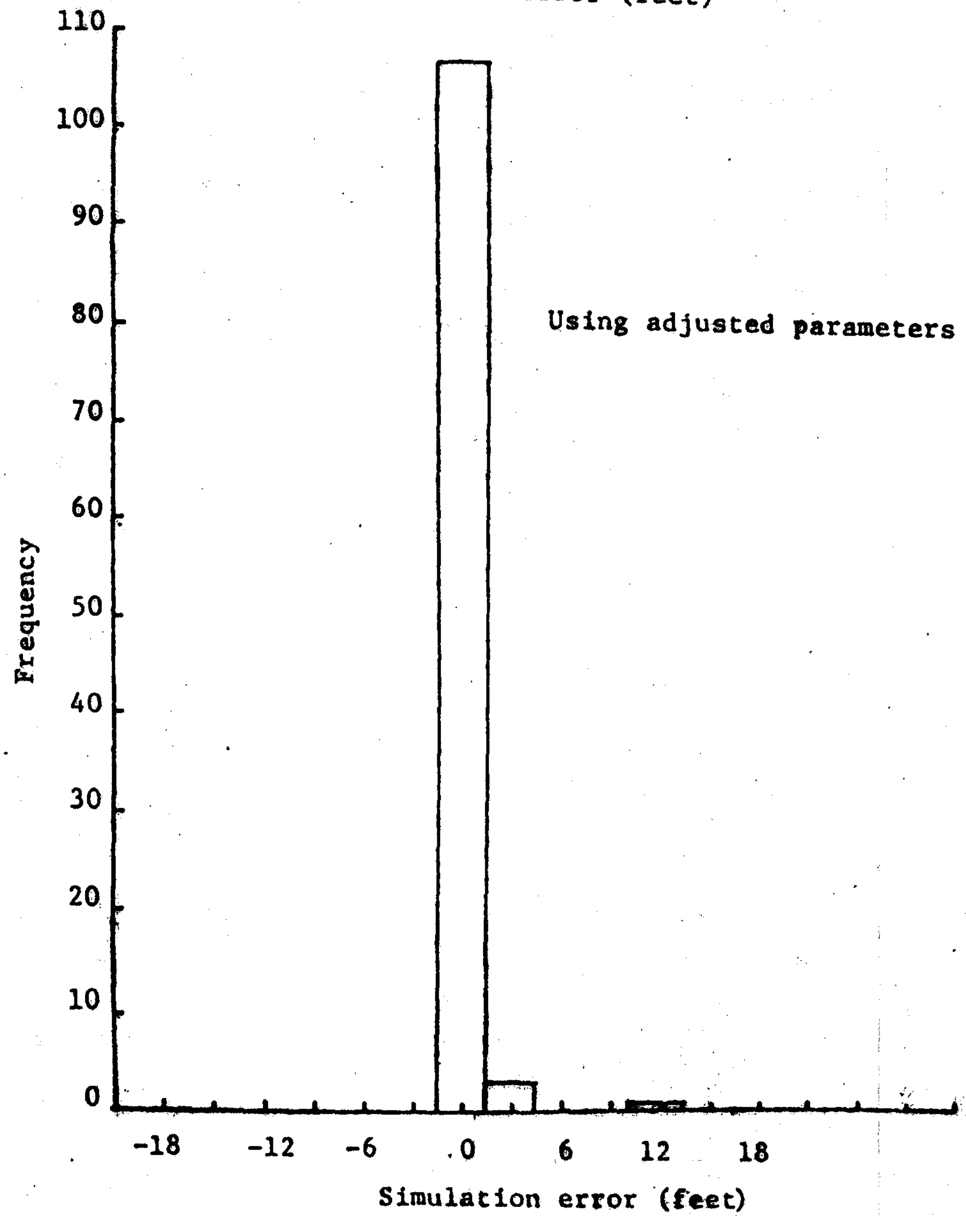


Figure 29. Histogram for the 1945-47 simulation errors

graphical representation of the reduction of the simulation errors by using the adjusted values. As shown in Figure 30, the sum of the errors squared between observed and calculated water levels decreased as successive simulation tests were made. This figure indicates that the parameter adjustment procedure effectively reduced the magnitude of the error. After about ten tests, additional adjustments produced only very small improvements in the fit between observed and computed water levels.

If water-level data are available for N years, each year will result in a new set of parameters. These parameters are therefore N approximations to the actual values of the parameters, and the averages of the N values obtained are assumed to provide good estimates of their true value at each node. To reflect the continuity in space of the parameters, the values of hydraulic conductivity and storativity obtained at each node by this method were averaged with the corresponding values at surrounding nodes. Referring to Figure 28, the values of the average parameter, ϕ, were determined by the following formula:

$$\phi_{i,j} = \frac{1}{16} (\phi_{i-1,j-1} + 2\phi_{i,j-1} + \phi_{i+1,j-1} + 2\phi_{i-1,j} + 4\phi_{i,j} + 2\phi_{i+1,j} + \phi_{i-1,j+1} + 2\phi_{i,j+1} + \phi_{i+1,j+1})$$

The resulting distributions of the average hydraulic conductivity and storativity are shown in Figures 31 and 32 respectively.

Another objective of the calibration procedure is to determine the sensitivity of the model to factors that affect groundwater flow. Evaluating the importance of each factor helps determine which data must be defined more accurately and which data are already adequate or require only minimal definition. If additional data cannot be collected, then the sensitivity tests can help to assess the reliability of the

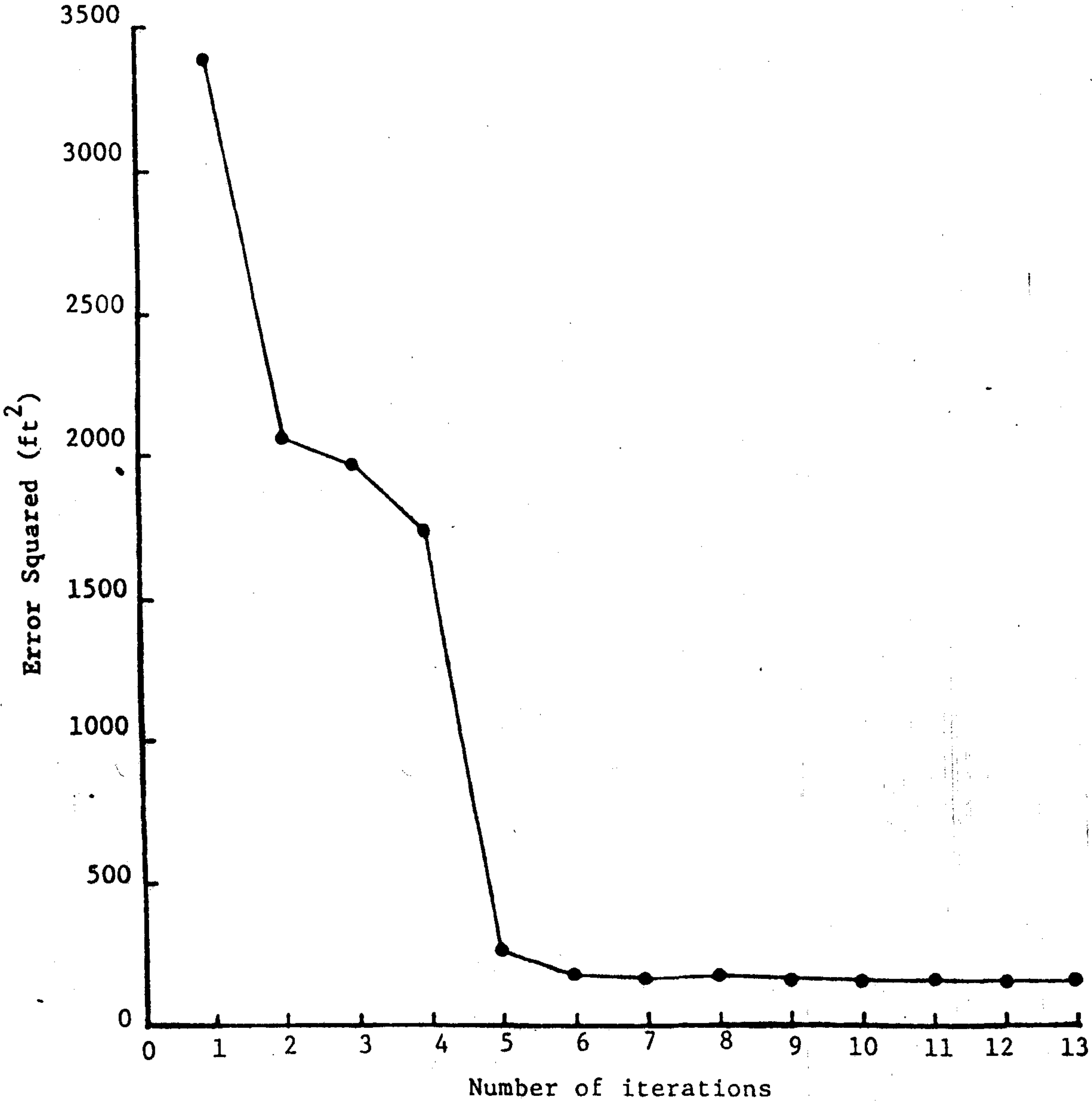
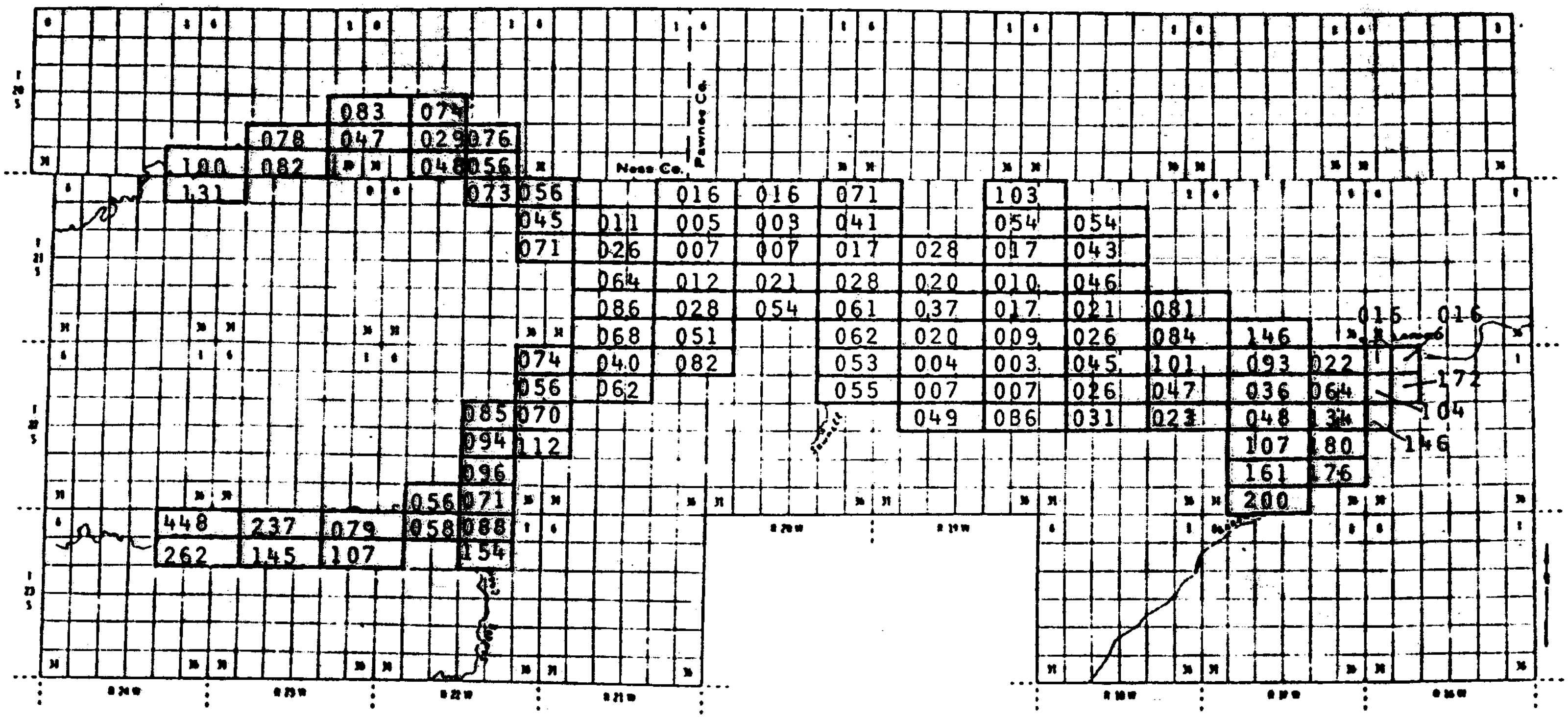


Figure 30. Plot of sum of error squared versus number of iterations.

Distribution of
Average hydraulic conductivity (aft/ft^2/yr
based on parameter adjustment
(last two digits are decimals, i.e., 131 = 1.31)

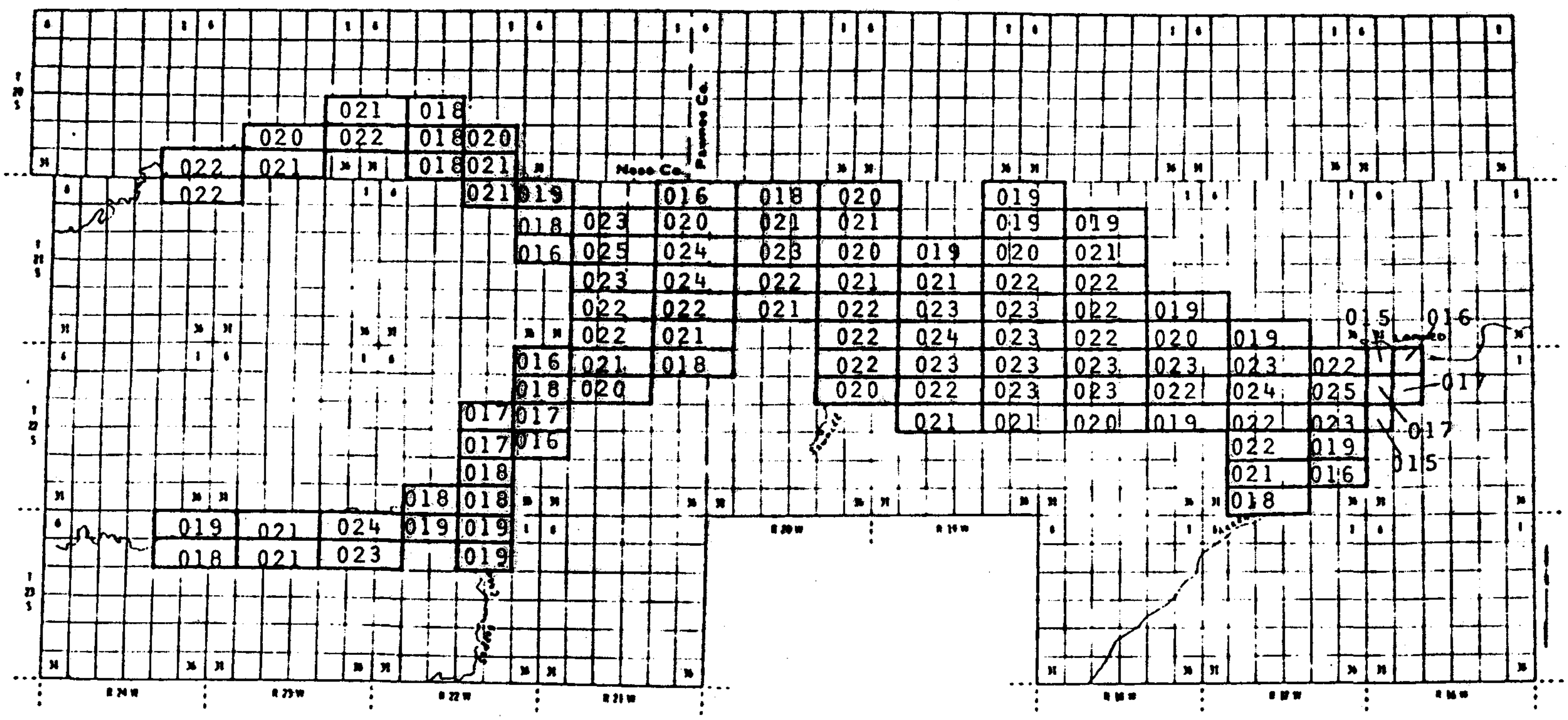


Approximate scale
1:125,000

Figure 31

[redacted]

Distribution of
Average Specific Yield (S_y)
based on parameter adjustment
(last two digits are decimals, i.e., 131 = 1.31)



Approximate scale
1:125,000

Figure 32

model by demonstrating the effect of a given range of uncertainty or error in the input data on the output of the model. The relative sensitivities of the parameters that affect flow will vary from problem to problem. Figures 33, 34, and 35 show the effects of changes of hydraulic conductivity, storativity, and fluxes on the simulated water levels at a randomly selected node at column 12, row 9 of the nodal grid system near Rozel (Fig. 26). From these figures it is concluded that the computed head is more sensitive to values of storativity and fluxes (both vertical and lateral) than to hydraulic conductivity values. The high sensitivity of computed hydraulic head to storativity is important because this property is the least well known at a given point in space and time. While the sensitivity of hydraulic head to fluxes is constant (linear), the sensitivity to hydraulic conductivity decreases with increasing hydraulic conductivity (Figs. 34 and 33).

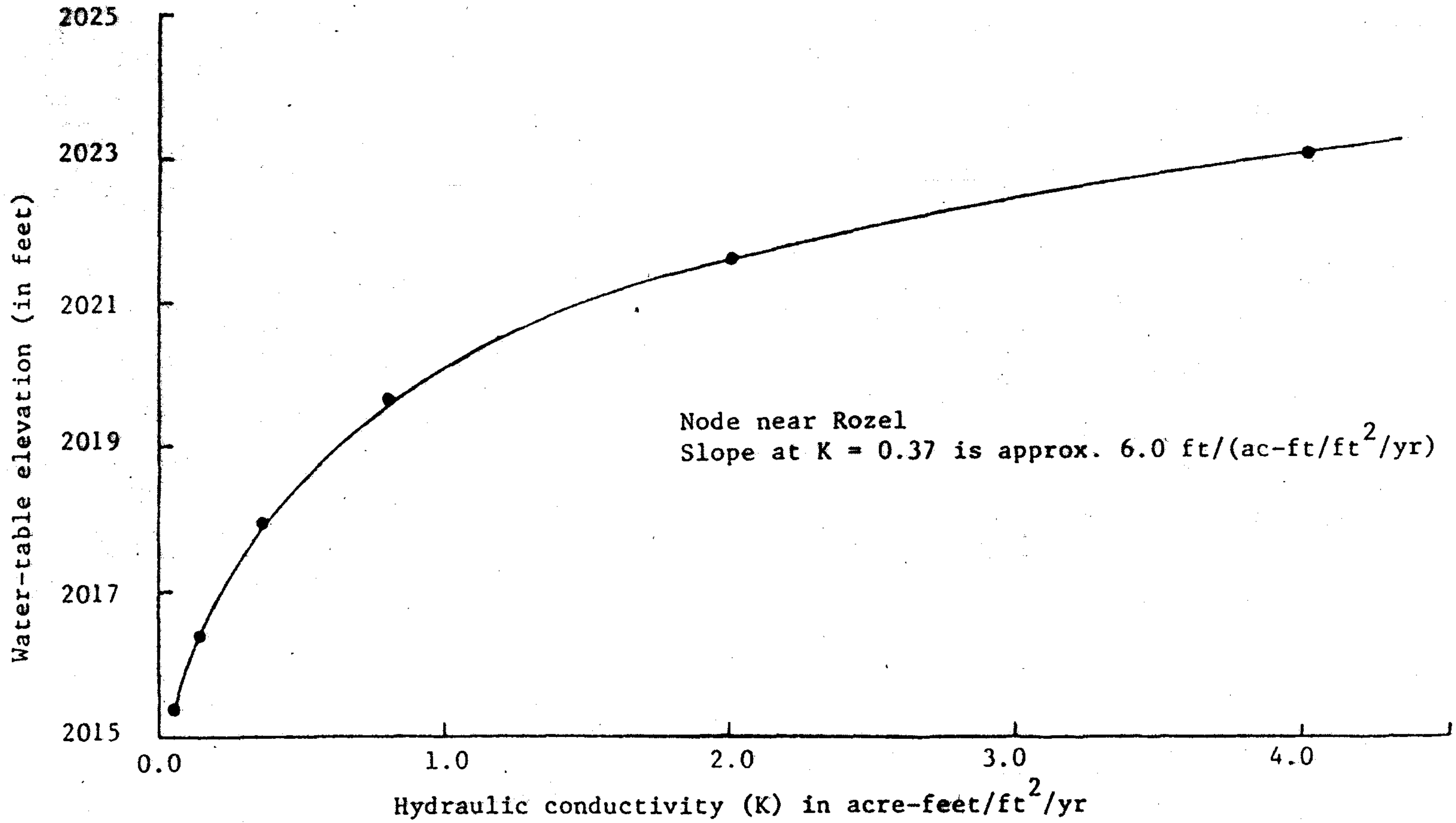


Figure 33. Effect of changes in hydraulic conductivity on simulated water level of a node.

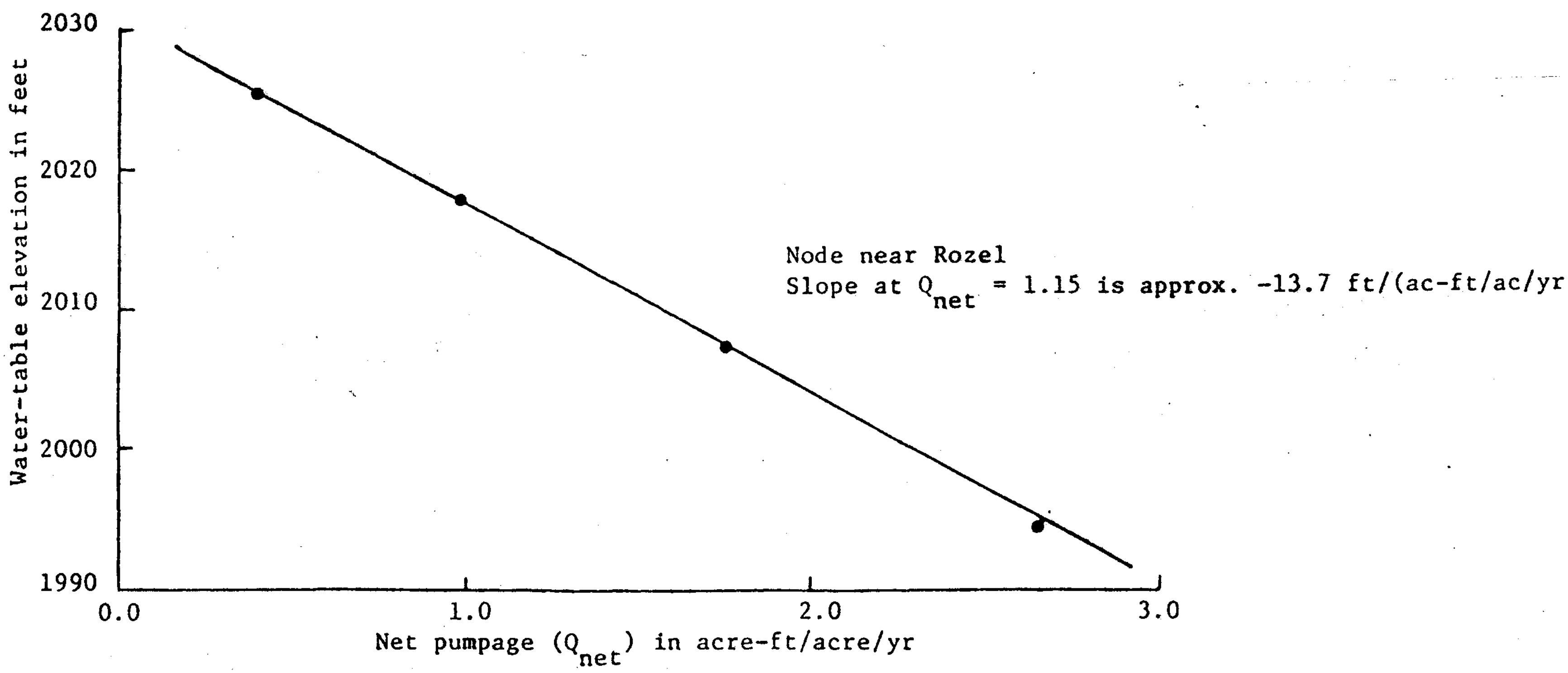


Figure 34. Effect of changes in net pumpage on simulated water level of a node.

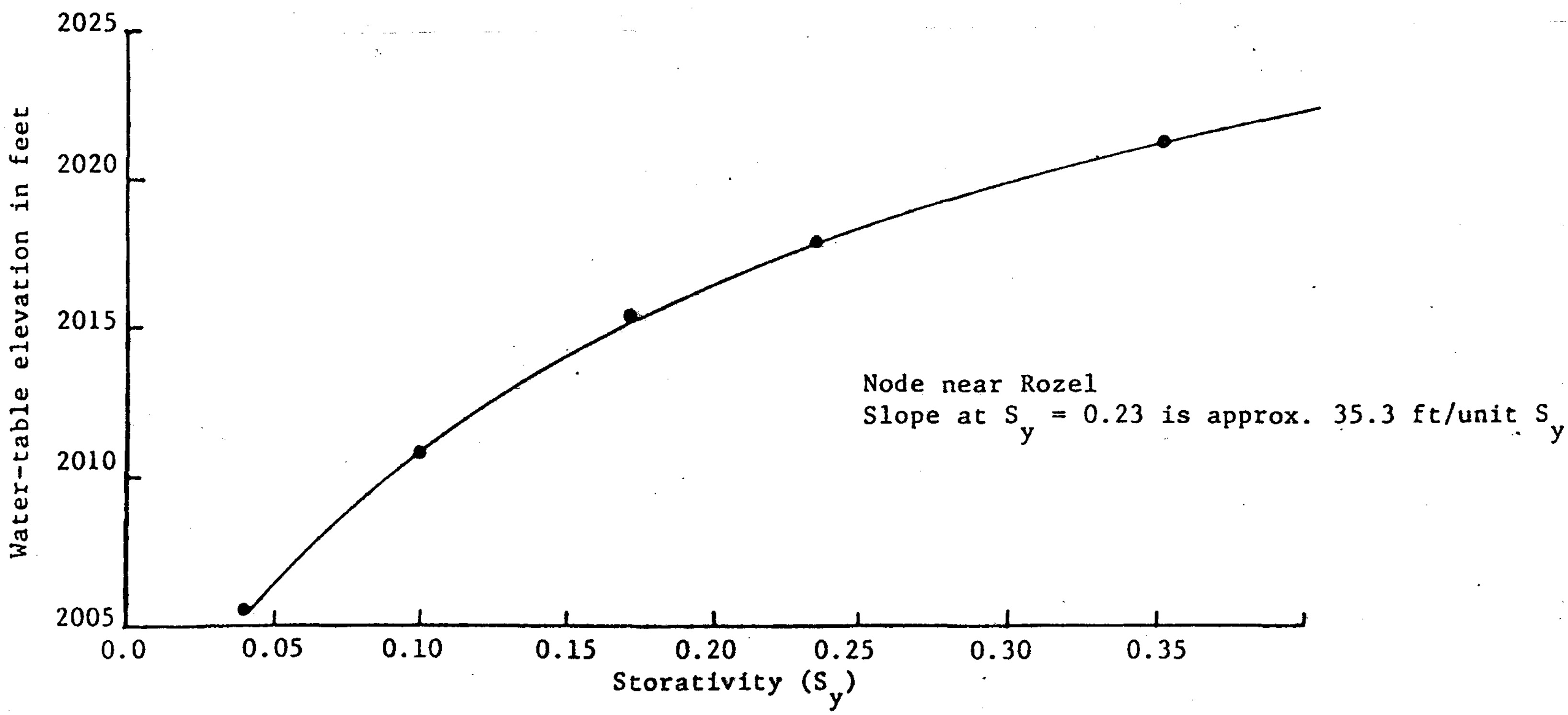


Figure 35. Effect of changes in storativity on simulated water level of a node.

PREDICTED WATER-LEVEL DECLINES - MANAGEMENT OPTIONS

INTRODUCTION

The main purpose of this report is to evaluate the impacts of present and future groundwater withdrawals in the region. The calibration procedure, consisting of the automated parameter estimation technique described previously, resulted in a very satisfactory match between observed and simulated water-level data. Therefore, the present model is considered an acceptable representation of the hydrogeologic system in the study area within the limitations of data inadequacies as discussed in previous sections of this report. This model can be used to predict the effect of any management scheme on the groundwater levels. This report, however, describes only six predictive simulations or management options. In all options the period 1979-1980 was chosen as initial condition for the predictive simulations because it is the only recent period for which detailed data on water levels are available. The predictive simulations were designed to terminate 20 years in the future. Results obtained by applying each option are presented every ten years for a 20-year period. The results displayed consist of the following two items: 1) predicted average water-level declines for each grid subregion, 2) subregions where the saturated thickness dropped below a specified lower limit; pumpage in these grid subregions cannot be supported and thus all wells within that area will have to shut down. It should be noted that such wells may resume pumping once the saturated thickness is built up to a specified level. The significant reduction in pumpage due to the shut-down of such wells provides such an opportunity, as may be seen by comparing the tenth and twentieth-year projected declines for some subregions.

MANAGEMENT OPTIONS

The following six options were considered.

Option 1: All registered wells (as of 1979) are assumed to pump the appropriated amount of water on a yearly basis for the next 20 years. They continue to do so until the saturated thickness in the vicinity of the wells drops to eight feet or less, at which time they are shut down. These wells do not resume pumping until the saturated thickness is built up to at least 15 feet. Average climatic conditions are assumed.

Option 2: All registered wells (as of 1979) are assumed to pump the appropriated amount of water on a yearly basis for the next 20 years. They continue to do so until the saturated thickness in the vicinity of the wells is reduced by 40% of the initial (1979) saturated thickness, at which time they are shut down. These wells do not resume pumping until the saturated thickness is built up to at least 62% of the initial saturated thickness. Average climatic conditions are assumed.

Option 3: All registered wells (as of 1979) are assumed to increase their appropriated pumpage by 20% and keep it constant on a yearly basis for the next 20 years. Otherwise Option 3 is the same as Option 1.

Option 4: All registered wells (as of 1979) are assumed to reduce their appropriated pumpage by 20% and keep it constant on a yearly basis for the next 20 years. Otherwise Option 4 is the same as Option 1.

Option 5: A five-year wet period is assumed to occur just before the middle of the 20-year projection period. All registered wells reduce their appropriated pumpage in half, while the amount of natural recharge doubles during that period. Otherwise Option 5 is the same as Option 1.

Option 6: A five-year dry period is assumed to occur just before the middle of the 20-year projection period. All registered wells double their appropriated pumpage while the amount of natural recharge is reduced by half during that period. Otherwise Option 6 is the same as Option 1.

PROJECTED WATER-LEVEL DECLINES

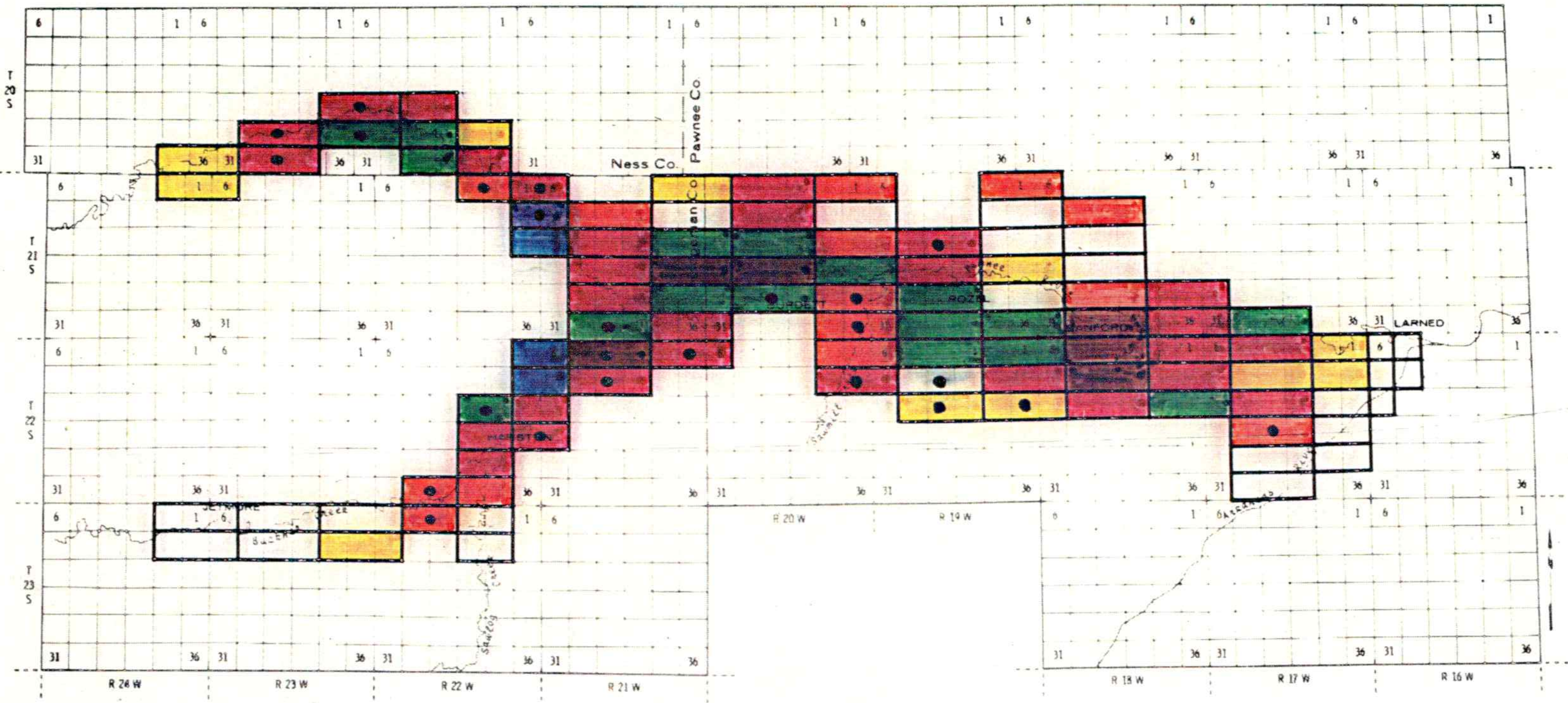
Option 1: This management option assumes no more development after 1979. The critical question asked in this situation is whether, after an initial adjustment, the water levels will stabilize to the existing pumping regime if no additional wells are installed. Figures 36 and 37* summarize the results of the simulation and illustrate that water levels will continue to decline despite a cessation of development in 1979. This simulation indicates that by the year 2000 most of the central part of the valley will experience more than 30 feet of water-level decline, with portions south, west, and around Sanford; north and west of Burdett; and the area around Rozel experiencing more than 50 feet of declines. However, the areas around the Arkansas River in Pawnee County and the Jetmore area in Hodgeman County will not experience any water-level declines according to this simulation. In a great number of subregions, as can be seen in Figure 37, pumpage will be stopped due to drastic reductions in saturated thickness.

Option 2: This management option of allowing only 40% saturated-thickness reduction for the next 20 years produces the least amount of water-level decline in 20 years of all options considered. However, the

*Appendix B contains the actual values of water-level declines for each grid of the model area for all options considered.

Figure 36

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1989-1990 UNDER OPTION 1



EXPLANATION

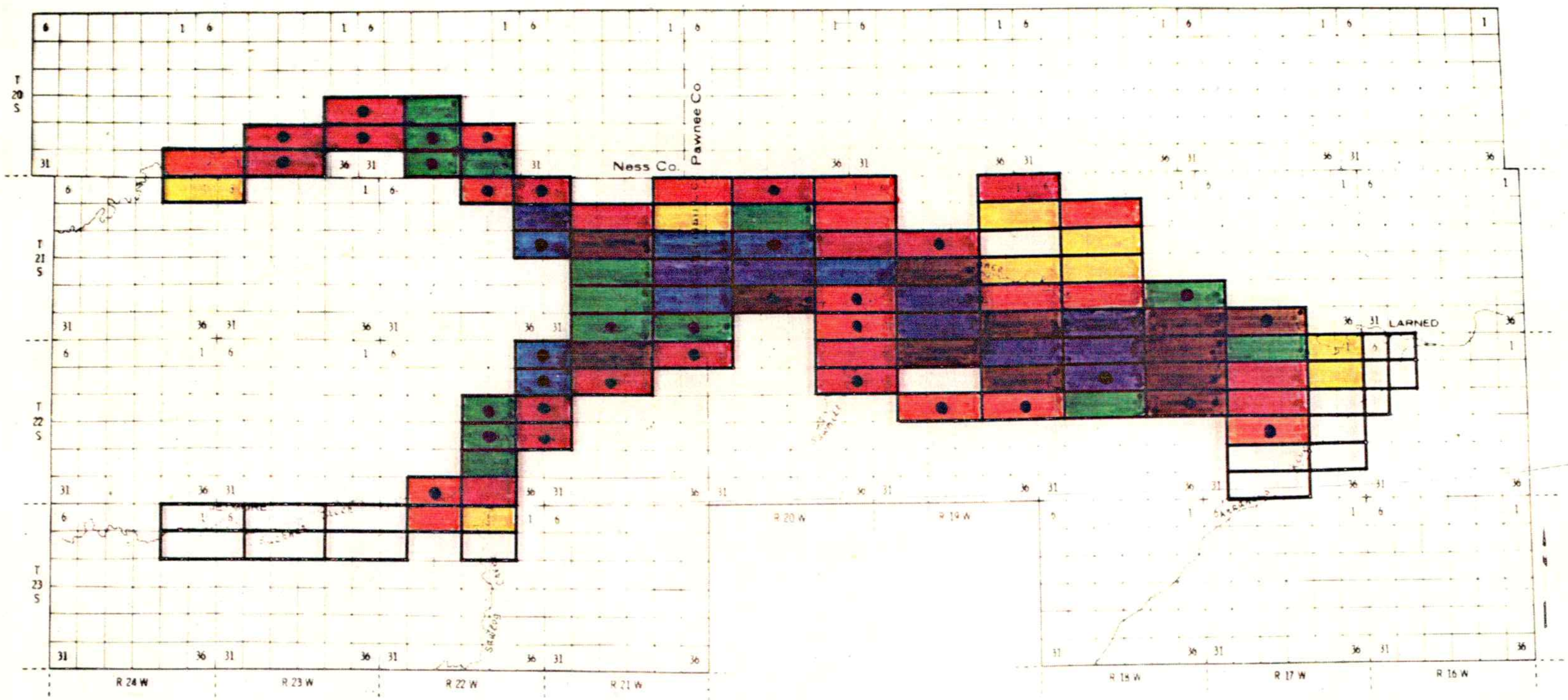
<1.0	1.0 - 4.9	5.0 - 9.9	10.0 - 19.9
20.0 - 29.9	30.0 - 39.9	40.0 - 50.0	>50.0

● Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 37
PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1999-2000
UNDER OPTION 1



EXPLANATION

<1.0 | 1.0 - 4.9 | 5.0 - 9.9 | 10.0 - 19.9
20.0 - 29.9 | 30.0 - 39.9 | 40.0 - 50.0 | >50.0

• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

number of grid subregions where the saturated thickness is reduced to that level, causing closure of wells in those areas, is so numerous that irrigated agriculture in most of the Pawnee Valley would have to cease by the year 2000. Figures 38 and 39 detail the above observations. However, for the next decade, this policy will not result in such a prohibitive situation for the Pawnee County as may be seen in Figure 38. Therefore, the beneficial results from this policy for the next decade should be carefully considered in any management decision.

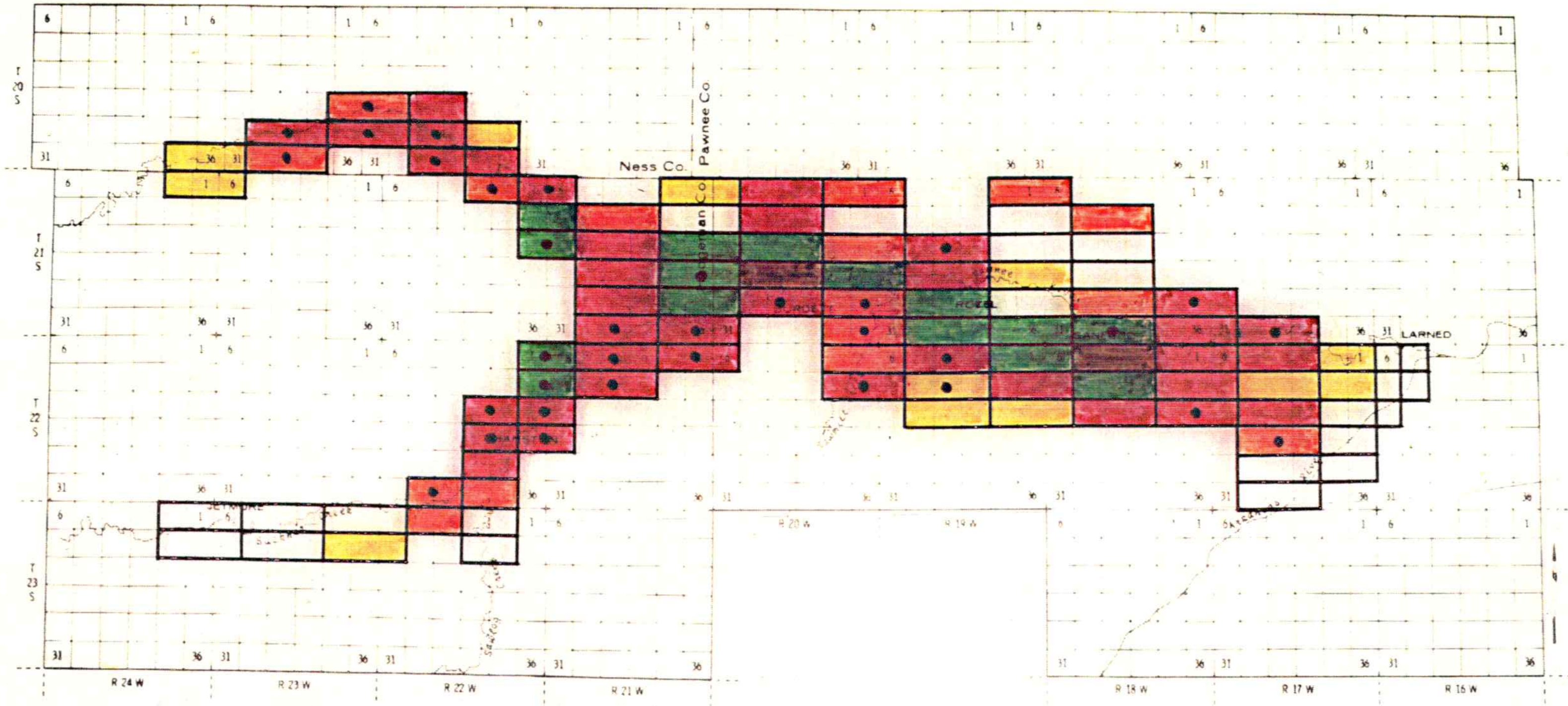
Option 3: This management option allows for an immediate 20% increase in the amount of present (1979) groundwater pumpage followed by no further development. The results of this simulation are indicated in Figures 40 and 41. As expected, more serious declines, compared to Option 1, are observed.

Option 4: This option is the opposite of Option 3 in that it calls for an immediate 20% reduction in the amount of present groundwater pumpage followed by no further development. The simulated improvement in water-level declines is indicated in Figures 42 and 43. Compared to Option 1, a number of regions - as those around Sanford, Burdett, and Rozel - will experience between 10 and more than 17 foot recovery in water levels. A greater number of regions will have between five and 10 foot recovery by the year 2000.

Options 5 and 6: These two options are introduced to answer the question on the effects of droughts or wet periods on water levels. In the case of an extended drought in the area, heavy demand would be made on the groundwater system. Similarly, in the case of a period of unusually wet years, the rate of groundwater withdrawals would be substantially reduced and have a positive effect on water levels. In order to

Figure 38

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1989-1990
UNDER OPTION 2



EXPLANATION

<1.0

1.0 - 4.9

5.0 - 9.9

10.0 - 19.9

20.0 - 29.9

30.0 - 39.9

40.0 - 50.0

>50.0

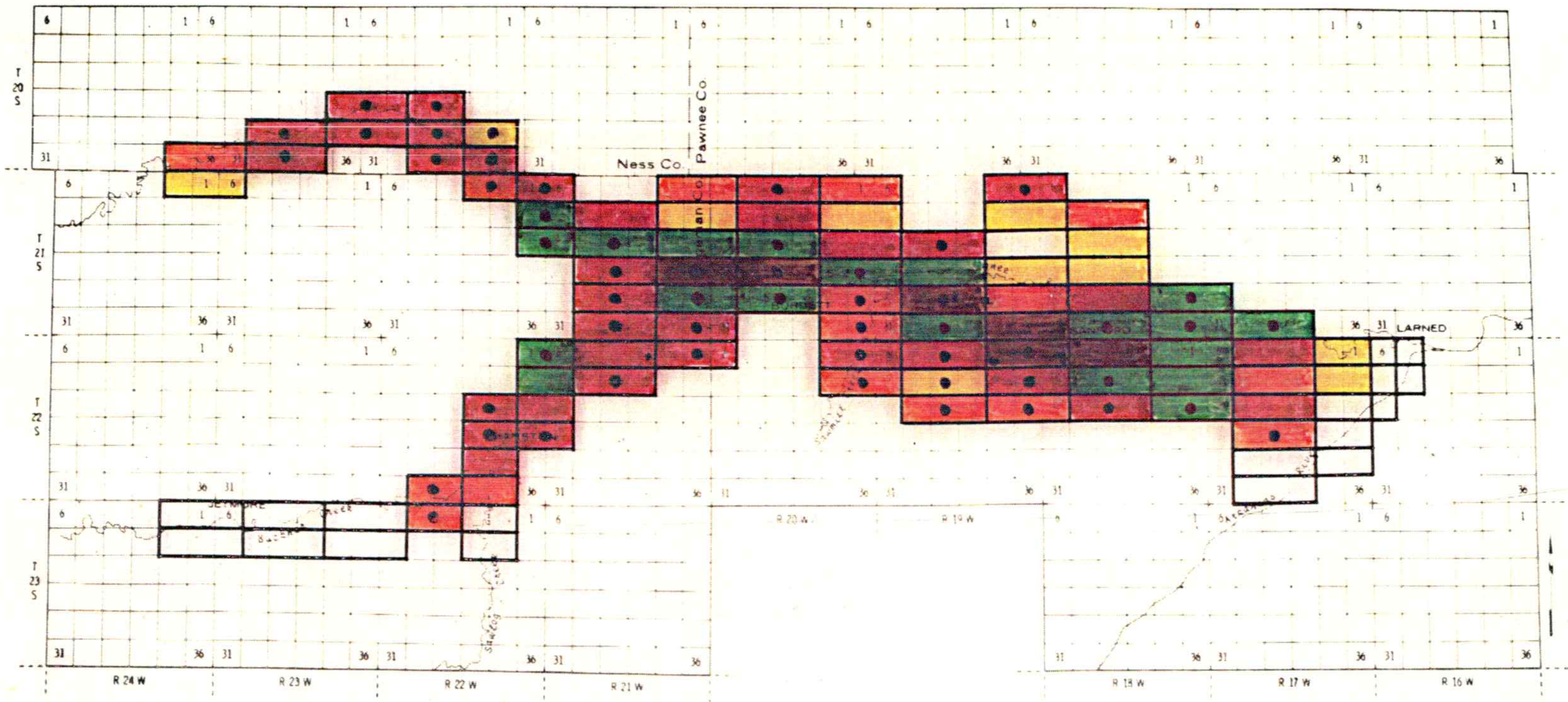
• Saturated thickness 8 feet or less;
pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 39

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1999-2000 UNDER OPTION 2



EXPLANATION

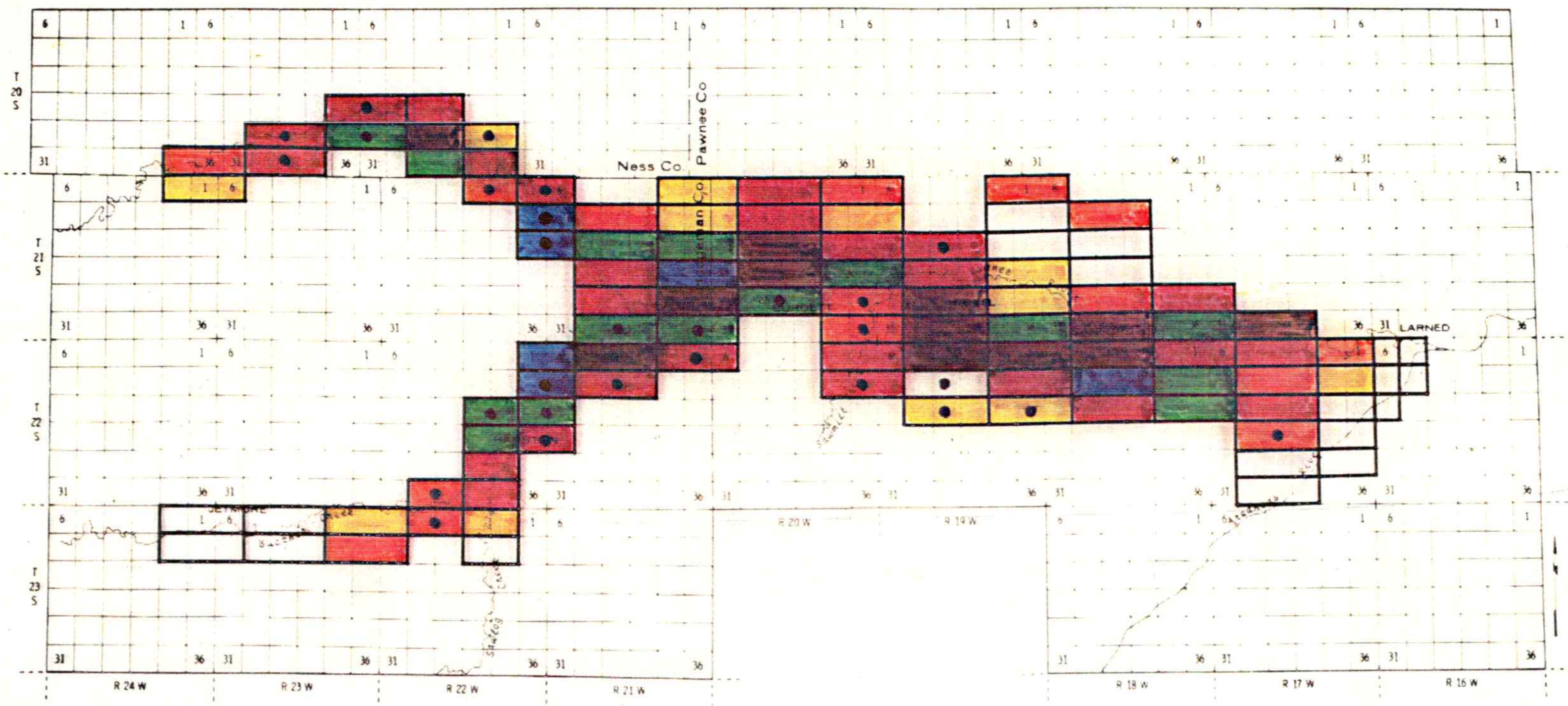
<1.0	1.0 - 4.9	5.0 - 9.9	10.0 - 19.9
20.0 - 29.9	30.0 - 39.9	40.0 - 50.0	>50.0

• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale 1:125,000

Figure 40

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1989-90
UNDER OPTION 3



EXPLANATION

White	<1.0
Yellow	1.0 - 4.9
Orange-red	5.0 - 9.9
Red	10.0 - 19.9
Green	20.0 - 29.9
Brown	30.0 - 39.9
Blue	40.0 - 50.0
Purple	>50.0

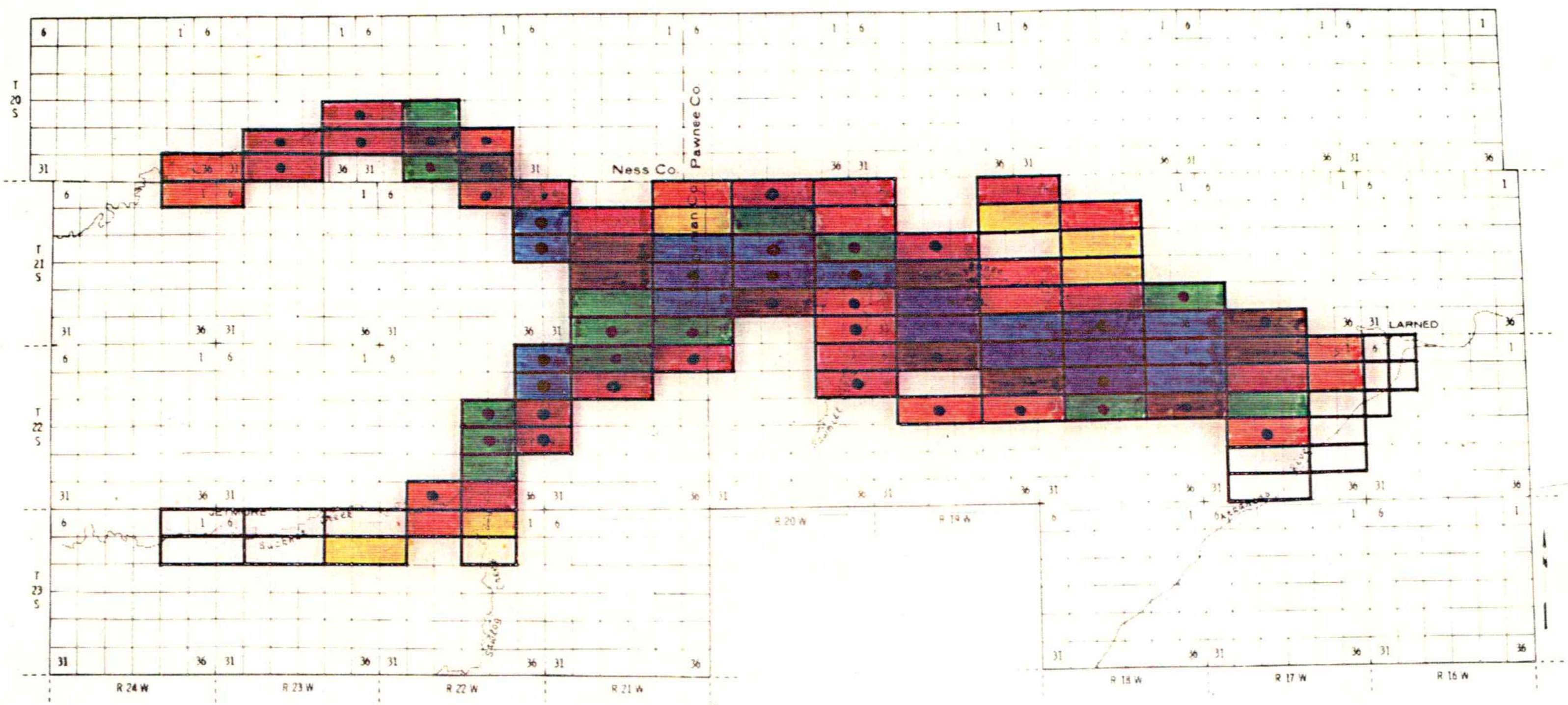
• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 41

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1999-2000 UNDER OPTION 3



EXPLANATION

White	<1.0
Yellow	1.0 - 4.9
Orange	5.0 - 9.9
Red	10.0 - 19.9
Green	20.0 - 29.9
Brown	30.0 - 39.9
Blue	40.0 - 50.0
Purple	>50.0

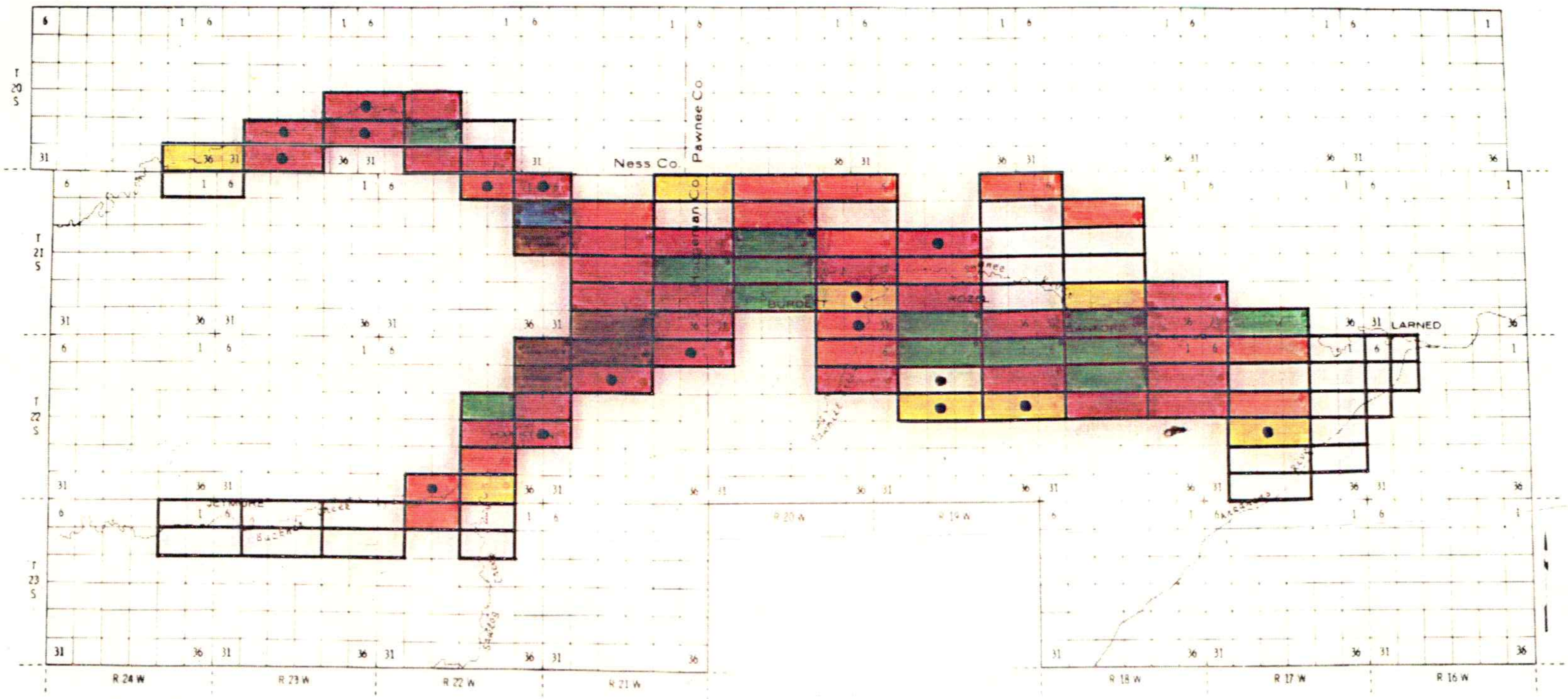
• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 42

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1989-1990 UNDER OPTION 4



EXPLANATION

White	<1.0
Yellow	1.0 - 4.9
Orange	5.0 - 9.9
Red	10.0 - 19.9
Green	20.0 - 29.9
Brown	30.0 - 39.9
Blue	40.0 - 50.0
Purple	>50.0

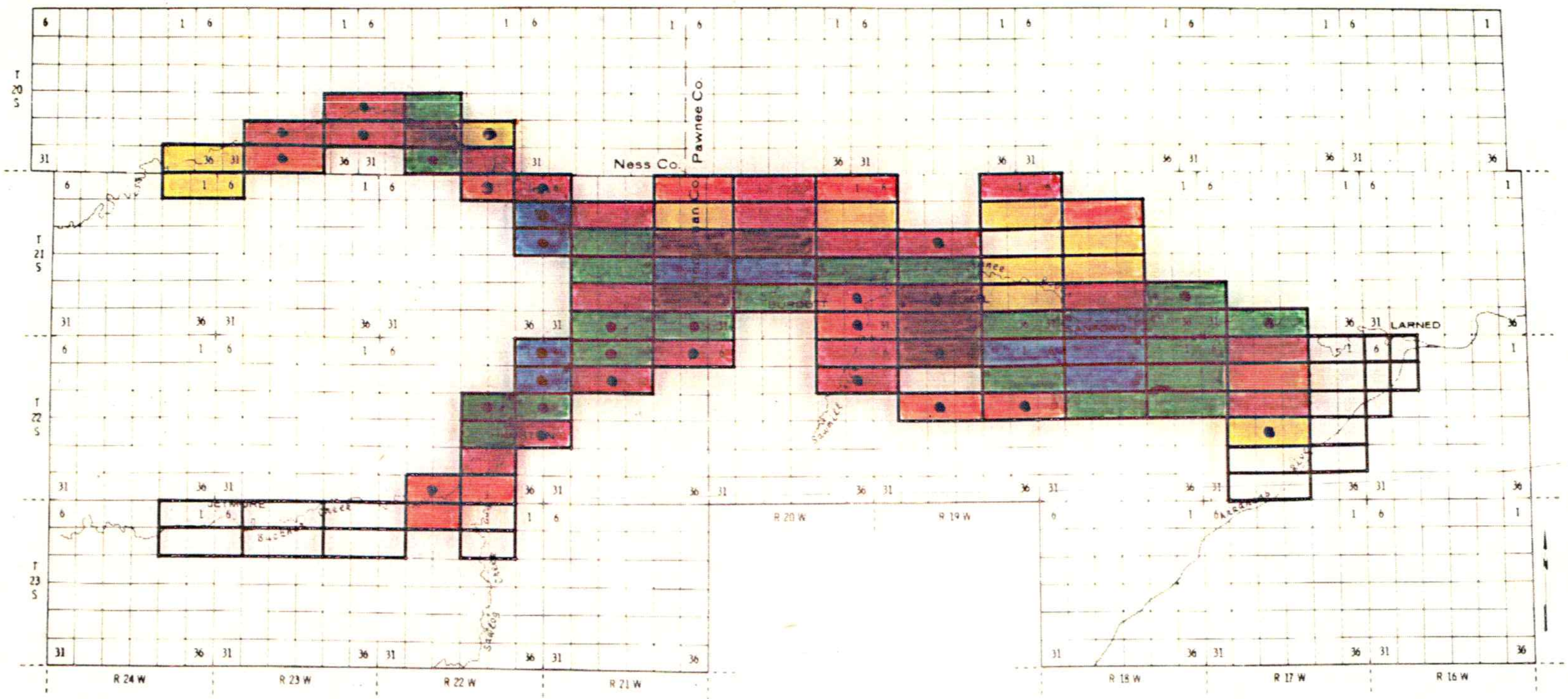
• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

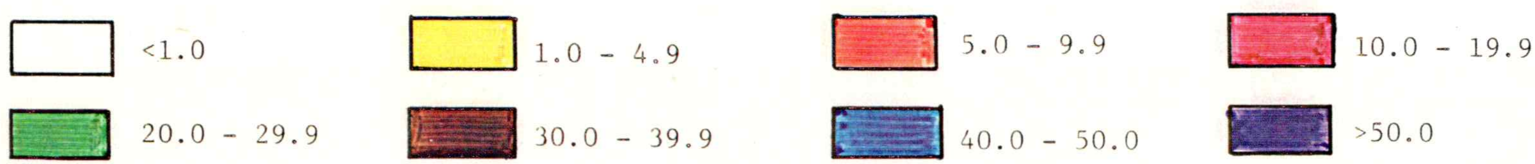
1:125,000

Figure 43

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1999-2000 UNDER OPTION 4



EXPLANATION



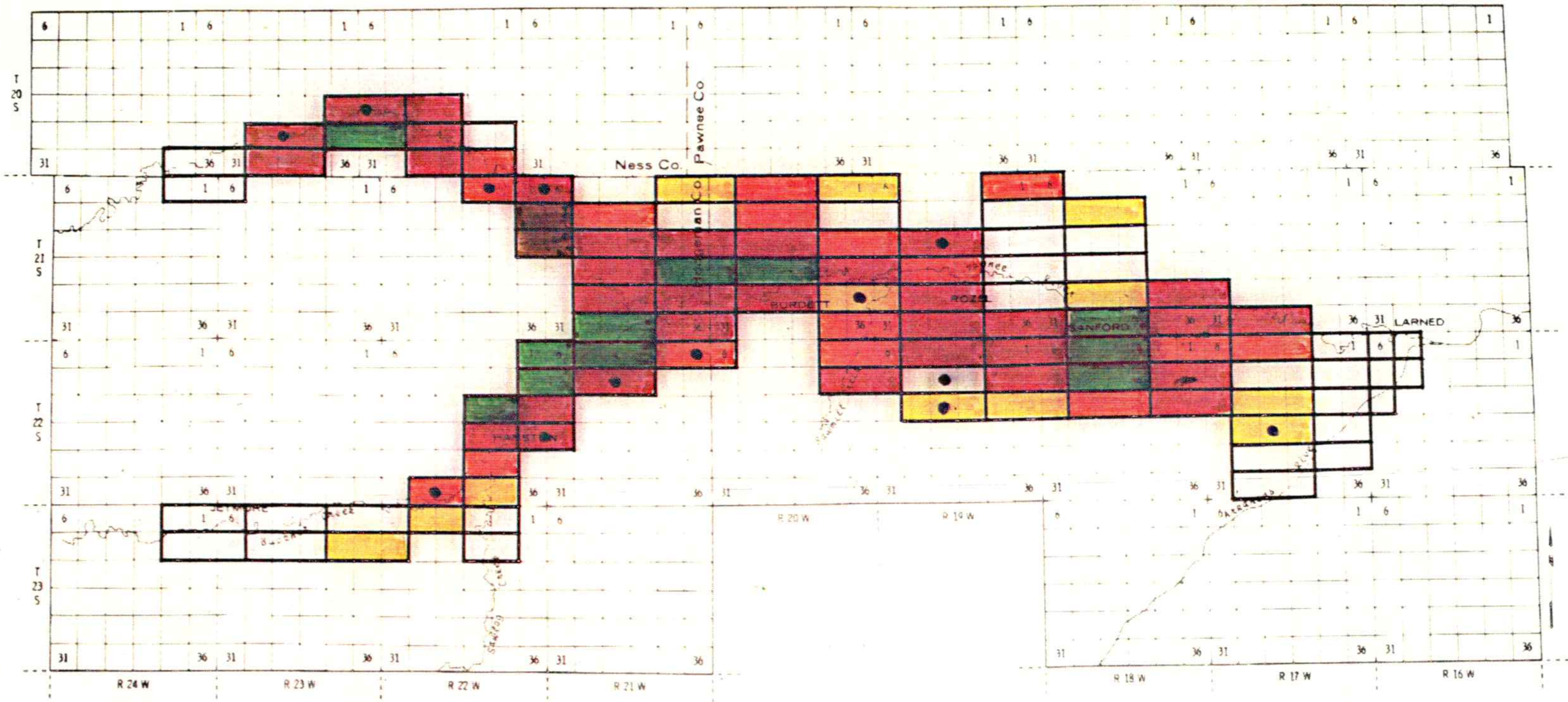
• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 44

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1989-1990 UNDER OPTION 5



EXPLANATION

<1.0

1.0 - 4.9

5.0 - 9.9

10.0 - 19.9

20.0 - 29.9

30.0 - 39.9

40.0 - 50.0

>50.0

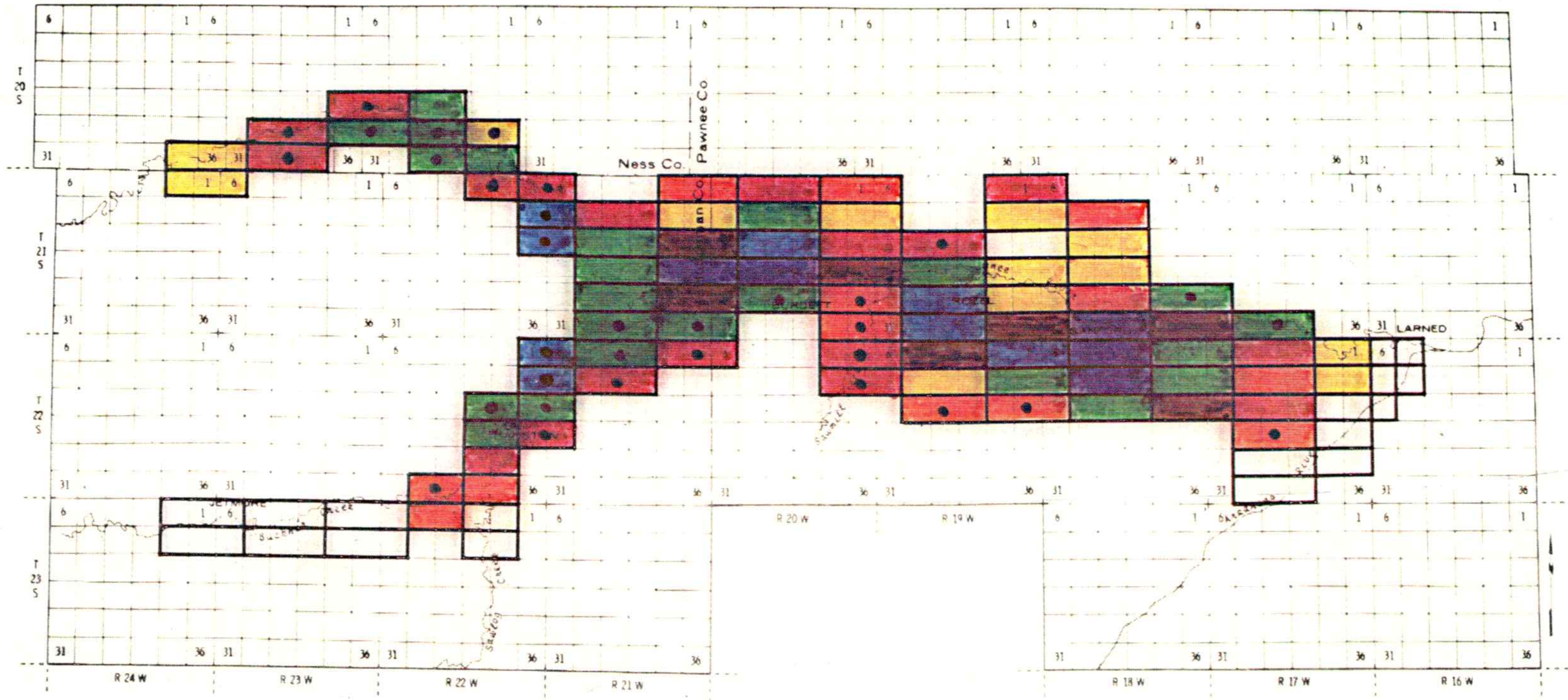
• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 45

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1999-2000
UNDER OPTION 5



EXPLANATION

<1.0	white
1.0 - 4.9	yellow
5.0 - 9.9	orange
10.0 - 19.9	red
20.0 - 29.9	green
30.0 - 39.9	brown
40.0 - 50.0	blue
>50.0	purple

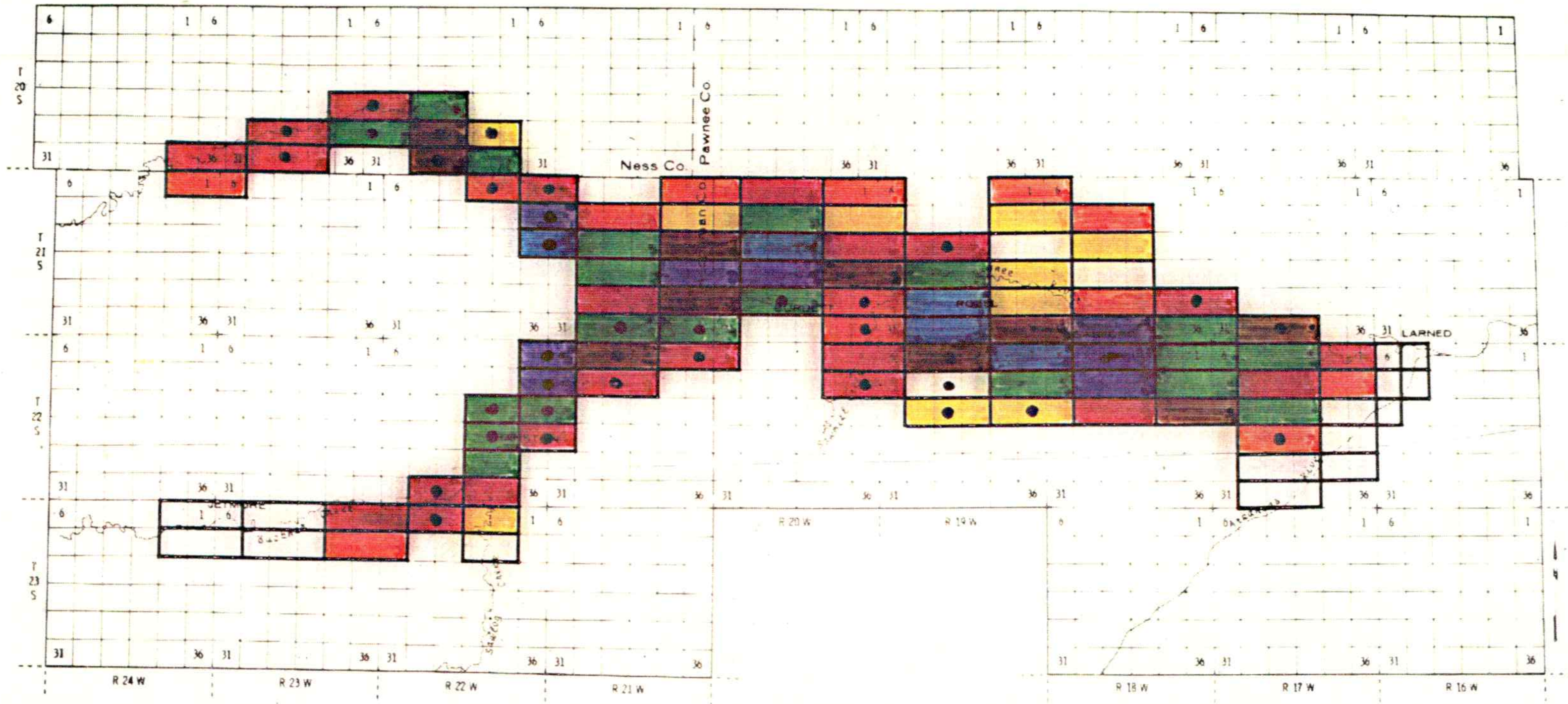
• Saturated thickness 8 feet or less;
pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 46

PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1989-1990 UNDER OPTION 6



EXPLANATION

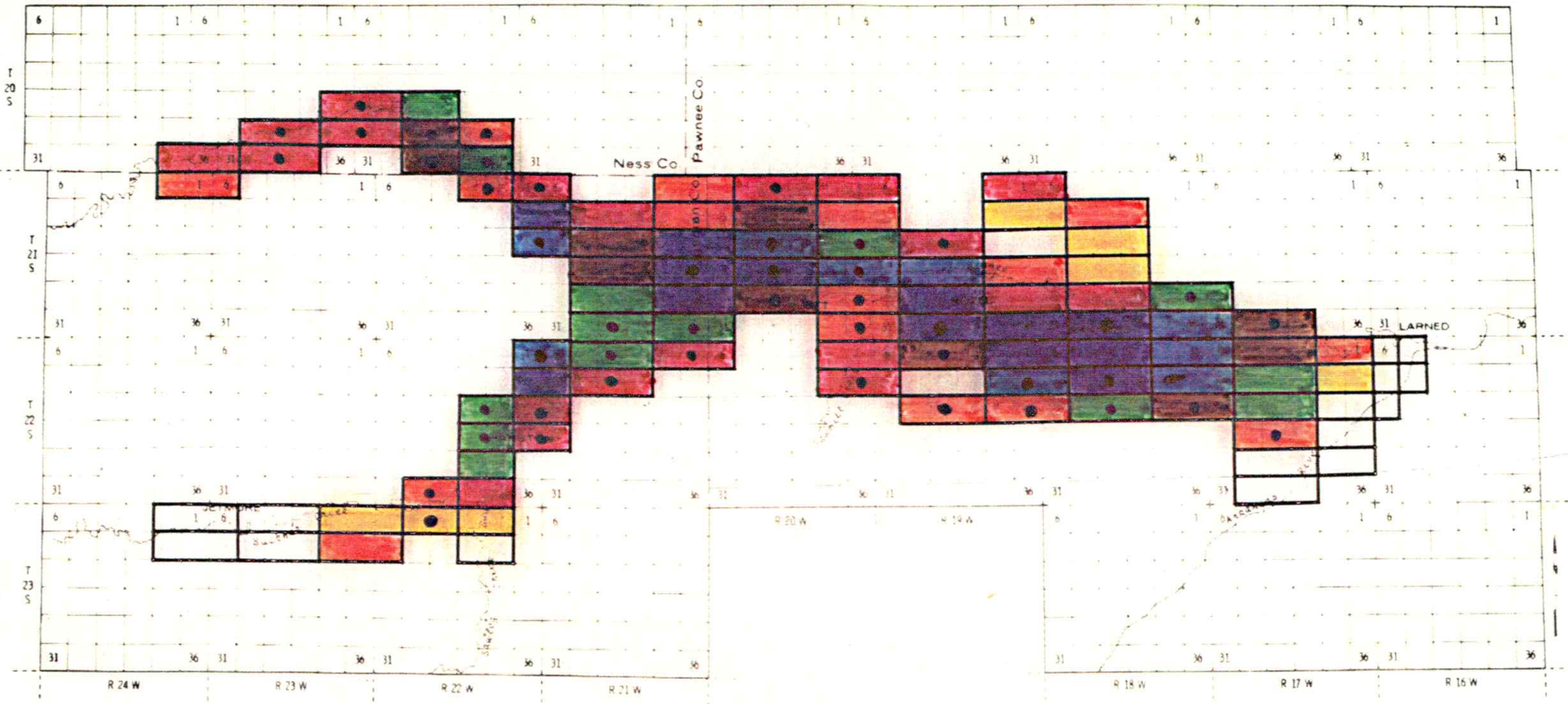
White	<1.0
Yellow	1.0 - 4.9
Orange	5.0 - 9.9
Red	10.0 - 19.9
Green	20.0 - 29.9
Brown	30.0 - 39.9
Blue	40.0 - 50.0
Purple	>50.0

● Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

Figure 47
PROJECTED AVERAGE WATER-LEVEL DECLINES, IN FEET, FROM 1979-80 TO 1999-2000
UNDER OPTION 6



EXPLANATION

<1.0
1.0 - 4.9
5.0 - 9.9
10.0 - 19.9
20.0 - 29.9
30.0 - 39.9
40.0 - 50.0
>50.0

• Saturated thickness 8 feet or less; pumpage cannot be supported at these nodes

Approximate scale

1:125,000

examine the behavior of the aquifer under sustained periods of extreme climatic conditions, both a five-year wet period (Option 5) and a five-year drought period (Option 6) were simulated.

The wet period was simulated between the beginning of 1986 and the end of 1990 by reducing by half the appropriated pumpage from the wells; at the same time natural groundwater recharge was doubled uniformly over the region. The five-year drought period was simulated between the beginning of 1986 and the end of 1990 by uniformly decreasing by half natural recharge throughout the region while pumpage from wells was doubled. Figures 44 and 45 summarize the results of the wet period, and Figures 46 and 47 summarize the results of the drought period. While the effects of the wet periods are temporary (compare Figs. 44 and 45) the effects of an extended drought are very severe (compare Figs. 47 and 45). Under the drought option, the areas between Frizell and Rozel as well as some areas around the Hodgeman-Pawnee County line will experience by the year 2000 more than 10 to 19 feet of groundwater declines over those of Option 1. The benefits from an extended wet period, as in Option 5, would result in holding water-level declines to 5 to 10 feet above those of Option 1 by the year 2000.

It should be recognized that these predictions represent general regional trends in water levels and not necessarily detailed, point-accurate, and definitive projections. Much more data, as mentioned in the first part of the report, and even more elaborate models are required for such a purpose. Such sophisticated models would have to encompass surface and subsurface water interactions and saturated-unsaturated flow mechanisms. Although the detailed water-level distribution may change as a result of these models, the general trends as predicted by the present basic model would not change at all.

CONCLUSIONS AND RECOMMENDATIONS

Groundwater withdrawals in the Pawnee Valley are currently of such magnitude that even without any additional development, water-level declines will continue indefinitely, exceeding 40 to 50 feet in many parts of the valley by the year 2000.

Wet periods, which reduce the pumpage demand and increase the rate of natural recharge, would benefit the groundwater system; however, even extremely wet periods would not reverse water-level declines resulting from any anticipated level of development. Even if no further development occurs, the beneficial effects of such wet periods would be felt mainly during those periods or shortly thereafter; in other words, they would be temporary.

Data presented in this report indicate a rather bleak future for groundwater supplies in a large part of the study area unless the groundwater management districts of the area soon make important decisions regarding their water supply. One option for consideration is to prolong the life of the groundwater resource through concerted efforts to reduce water wasting and to increase efficiency of water use. However, such practices alone will not solve the problem because the current level of development is such that the water supply eventually will approach exhaustion. As mentioned above, even if no new wells were to be drilled, eventual stabilization of water levels cannot be assured under the current rate of withdrawals. Development of artificial recharge systems in addition to concerted efforts to conserve water and to increase the efficiency of water use provides an option which may prolong the life of the groundwater reserves.

The cost of an adequate recharge scheme would probably be tremendous and presumably would increase with time. The surficial materials between the land surface and water-table in large parts of the Pawnee Valley are not well suited for artificial recharge through recharge basins, seepage canals, or surface-spreading systems. More expensive means such as recharge wells may offer better opportunities for success in many areas. Detailed studies of the availability of adequate water supplies and of recharge potential over the valley may provide an estimate as to the feasibility of such endeavor. It should be kept in mind, however, that water is not plentiful in the area, and that the amounts of estimated natural groundwater recharge are very small. In the meantime, the benefits resulting from putting a freeze on new irrigation wells and the implementation of Option 2 (i.e., 40% saturated-thickness depletion allowance) for this new decade should be rigorously pursued, encompassing both old and new wells.

The option of foregoing any effort to manage the groundwater resource and allowing the number of wells to increase along with increases in the total rate of withdrawals until virtual depletion of the resource and return to dryland farming is not considered in this report. The very establishment of the groundwater management districts demonstrates that residents of the area reject this "do-nothing" approach.

All users of water, both surface and groundwater, should be informed of the fact that they are contributing to the regional decline of groundwater levels and to the depletion of streamflow. If they recognize the problem, they may become supportive participants in regional efforts to stabilize water supplies.

ACKNOWLEDGEMENTS

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APPENDIX A

Legend for Figure 48.

(a)	(b)	(b')
NNS	NSA*(B,C,D)	NNH
NSS	SSA*(B,C,D)	NSH
NES	ESA*(B,C,D)	NEH
NWS	WSA*(B,C,D)	NWH
Near E*(W,N,S) side	E*(W,N,S) side of A*(B,C,D)	Near center of E*(W,N,S)

(c)	(d)
NHA*(B,C,D)	NAX
SHA*(B,C,D)	NBX
EHA*(B,C,D)	NCX
WHA*(B,C,D)	NDX
E*(W,N,S) half of A*(B,C,D)	Near center of A*(B,C,D)

(1) Groups (a) through (d) describe well location in decreasing order of acreage for a given section.

(2) Groups (b) and (b') describe the same location.

(3) Any letter in parenthesis can be substituted for the one with an asterisk right before it.

(4) The letter X following any <u>two</u> letters from the group (A,B,C,D) is considered blank.

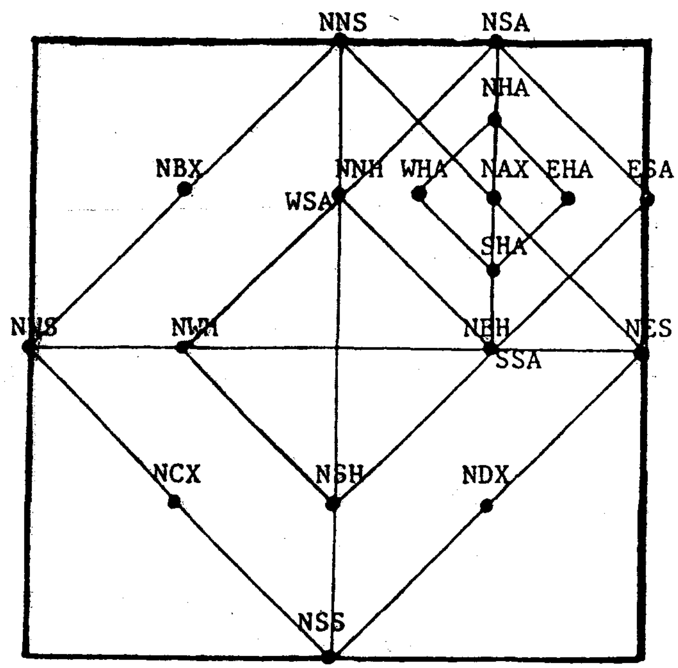


Figure 48. Well description format for Pawnee County.

Pumping Wells

PAWNEE COUNTY+

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
2872	21	16	29 AAX	185
26,461	21	16	32 CDA	185
2872	21	16	33 CBX	185
2872	21	16	33 BDX	185
26,461	21	16	33 ACB	185
26,461	21	16	33 ACC	185
7,652	21	16	33 BAX	80
VR 627	21	16	33 BCX	22
26,461	21	16	33 CCD	185
26,461	21	16	33 CDA	185
26,461	21	16	33 CDD	185
11340	21	16	33 DBD	95
11339	21	16	33 DBD	95
7633	21	16	33 DBD	95
8705	21	16	33 DBD	95
9320	21	17	27 CDX	60
12,898	21	17	31 BDA	294
10,886	21	17	31 DCC	158
10,886	21	17	31 DCD	158
18,065	21	17	32 DCD	684
31,121	21	17	33 NAD	140
19,378	21	17	36 CCC	81
30,896	21	18	31 ADC	133
30,896	21	18	31 BAD	133

Explanation: *Designates the maximum pumpage a single well can pump or a member of a group of overlapping wells can individually pump provided that the group of overlapping wells pump simultaneously.

+For an explanation of well location designations for Pawnee County refer to Figure 48.

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location			Pumpage (AcFt)
	Township	Range	Section	
30,896	21	18	31 BCB	133
VR 6213	21	18	31 CAX	230
24,228	21	18	31 DDA	114
24,229	21	18	32 BBA	176
VR 6215	21	18	32 CCC	218
VR 6214	21	18	32 DCB	210
13,010	21	18	33 ACA	196
13,010	21	18	33 ABD	196
28,494	21	18	33 BCB	36
21,559	21	18	33 CBB	141
21,559	21	18	33 CBC	141
19,990	21	18	33 DCB	404
4,935	21	18	33 NAX	300
7168	21	18	33 S½ S½ B	47
11,227	21	18	33 S½ S½ B	47
21,559	21	18	33 S½ S½ B	47
VR 6219	21	18	35 CBX	140
2506	21	19	14 BBD	90
15211	21	19	16 CBA	147
21,243	21	19	18 ADD	240
8,143	21	19	19 CXX	64
5324	21	19	19 NDX	300
VR 6223	21	19	20 CCC	122
10,161	21	19	20 CCC	122
10,161	21	19	20 CDC	122

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
12,515	21	19	21 ACA	110
680	21	19	21 CCB	190
3,323	21	19	21 DCA	140
2,823	21	19	23 BAB	40.5
4,945	21	19	23 BAB	40.5
4,945	21	19	23 NED	81
VR 6225	21	19	27 CCX	152
10,160	21	19	27 CCX	152
24,430	21	19	27 DBC	153
12,296	21	19	28 ABC	177
31,723	21	19	28 BCC	240
5,169	21	19	28 DBC	120
VR 6226	21	19	28 DBX	46
20,099	21	19	28 DDA	67
5,275	21	19	29 ADB	281
6,132	21	19	29 BCB	338
9,964	21	19	29 CBB	238.5
9964	21	19	29 CDD	119.25
VR 6227	21	19	29 CDD	119.25
26,364	21	19	30 DBA	99
26,364	21	19	30 DCB	99
5,323	21	19	30 AXX	300
26,364	21	19	30 CCD	49.5
8,142	21	19	30 CCD	49.5
24,840	21	19	30 NBX	209

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
8142	21	19	30 SHA	99
13,925	21	19	31 AAB	407
11,041	21	19	31 BAX	320
10,606	21	19	32 DBX	497
16,788	21	19	33 ABC	106.5
5,229	21	19	33 ABX	106.5
VR 6,228	21	19	33 BBB	150
3,858	21	19	33 CBC	150
24,971	21	19	33 CCB	105
30,325	21	19	33 CCB	105
16,708	21	19	33 DAA	192
9011	21	19	33 CDB	150
VR 6229	21	19	36 ACX	117.5
7803	21	19	36 BCC	117.5
6,097	21	19	36 BDX	157.7
VR 6230	21	19	36 DBX	157.7
9,388	21	19	36 WCC	157.7
25,600	21	20	4 BDD	71.4
25,600	21	20	4 DBB	71.4
25,600	21	20	4 DDD	71.4
14,954	21	20	4 DDD	71.4
10,338	21	20	4 DDD	71.4
10,338	21	20	4 DDD	71.4
12,849	21	20	8 CDX	382

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location: Township	Range	Section	Pumpage (AcFt)
10,338	21	20	9 DAA	71.4
14,954	21	20	9 DAAA	71.4
10,339	21	20	9 DAAA	71.4
25,600	21	20	9 DAAA	71.4
19,558	21	20	13 DCA	240
27,369	21	20	14 CCB	85
27,369	21	20	14 CCC	85
28,526	21	20	15 CCD	240
14,203	21	20	15 DBC	85
VR 6232	21	20	15 DBX	85
15,014	21	20	16 DBB	95
5166	21	20	16 DBB	95
5166	21	20	16 DBB	95
15020	21	20	16 NCX	120
15013	21	20	17 BDA	377
13709	21	20	17 CDC	52
VR 6233	21	20	17 CDX	52
16,343	21	20	17 DCC	52
28196	21	20	18 CCD	347(overlaps with #10,3 (Hodg. Co.))
27,366	21	20	18 DCC	120
27,366	21	20	18 DDD	120
4454	21	20	19 AAX	240
8732	21	20	19 CBB	236
14,453	21	20	19 DAX	240
VR 6235	21	20	20 ABC	52

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
5,444	21	20	20 ABC	52
VR 6234	21	20	20 BAX	180
VR 6236	21	20	20 DDX	60
3990	21	20	21 BBX	111
7677	21	20	21 BXX	111
VR 6237	21	20	21 CBX	180
17,417	21	20	21 DCB	201
20,802	21	20	22 ABB	138
VR 6239	21	20	22 CDC	350
9,846	21	20	22 CDC	350
20,802	21	20	22 NEH	138
27,368	21	20	23 AAC	42
27,370	21	20	23 AAC	42
27,368	21	20	23 ACD	84
12,969	21	20	23 CBX	197
26,363	21	20	23 CDX	157
→ 9129	21	20	23 NBD	300
VR 6240	21	20	24 ACX	240
18,657	21	20	26 ABB	80
VR 6242	21	20	26 ABX	80
16,190	21	20	26 BBB	240
VR 6241	21	20	26 DAX	50
18,657	21	20	26 NNA	80
8,413	21	20	28 AXX	180

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
8,388	21	20	28 BBB	140
10,376	21	20	28 CAA	168
8,413	21	20	28 NHD	180
26,208	21	20	29 BAA	69.5
VR 6243	21	20	29 BAX	69.5
26,208	21	20	29 BBB	139
26,208	21	20	29 BCB	69.5
VR 6243	21	20	29 BCX	69.5
26,208	21	20	29 NNB	139
31,751	21	20	30 AAB	115
25984	21	20	39 ABX	43.5
29,057	21	20	30 ABX	43.5
28,579	21	20	30 ABX	43.5
29,057	21	20	30 BBB	130.5
19,016	21	20	30 CBC	65.3
29,057	21	20	30 CBC	65.4
5,228	21	20	30 DAA	174
29057	21	20	30 NNH	130.5
VR 6247	22	16	4 BAX	40
16,948	22	16	4 BBD	131
9,475	22	16	4 CBX	15
VR 6248	22	16	4 WBB	75
VR 6249	22	16	5 CDX	8
2,872	22	16	5 AAX	185
26,126	22	16	6 ACA	150
4,615	22	16	6 CCC	240
10,184	22	16	7 DBD	104
20,085	22	16	8 NDX	234
15,287	22	17	1 ACA	55.5
15,287	22	17	1 ACC	55.5
19,387	22	17	1 BBB	81
16,734	22	17	1 DCA	140
19,378	22	17	2 ABC	81

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
VR 6276	22	17	2 DCA	40.5
19,378	22	17	2 DCA	40.5
19,378	22	17	2 DCD	81
19,103	22	17	3 DCC	309
25,331	22	17	4 BBB	120
5,017	22	17	4 EHB	160
18,550	22	17	5 BBB	96
4,939	22	17	5 BBB	96
6,991	22	17	5 BBB	96
13,318	22	17	5 BDA	144
18,550	22	17	5 BDA	144
18,550	22	17	5 CBB	72
4,940	22	17	5 CBB	72
6,991	22	17	5 CBB	72
13,318	22	17	5 CBB	72
18,550	22	17	5 DAD	288
23,519	22	17	6 ACC	240
26,683	22	17	10 EHC	360
5,704	22	17	11 BCX	490
15,217	22	17	12 ABB	300
14,690	22	17	12 CBB	168
VR 6254	22	17	12 CCX	50
15,530	22	17	14 CDA	213
22,261	22	17	14 NAX	140
7,430	22	17	15 XXX	1040

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location: Township	Range	Section	Pumpage (AcFt)
15,225	22	17	16 NBX	234
30,491	22	17	16 CAD	112.5
30,491	22	17	16 CDD	112.5
15,226	22	17	17 BAA	240
3430	22	17	18 AAX	120
VR 6255	22	17	18 AAX	120
6817	22	17	22 CDD	156
6599	22	17	22 SHA	120
16,789	22	17	24 CBC	372
21,999	22	17	24 NAX	240
26,072	22	17	27 ABD	156
26,340	22	17	28 NDX	330
10,065	22	18	1 BCC	160.6
6,558	22	18	1 BCC	160.7
19,110	22	18	1 BCC	160.7
28,028	22	18	1 DCB	203
3,105	22	18	SHA	105
31,688	22	18	1 SHA	105
9473	22	18	2 CBC	53.5
7745	22	18	2 CBC	53.5
3,635	22	18	2 DCX	180
5719	22	18	3 BCX	
14,545	22	18	3 NAX	
9,471	22	18	3 NWC	
5,748	22	18	3 NWC	
5,748A	22	18	3 NWD	320
9,472	22	18	3 NWD	
7745	22	18	3 WSC	
7745	22	18	3 WSD	
10,066	22	18	3 WCB	
9,135	22	18	4 ACC	120
8,311	22	18	4 ACC	120
8,311	22	18	4 BCC	80

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location			Pumpage (AcFt)
	Township	Range	Section	
7,565	22	18	4 BCC	80
9,135	22	18	4 BCC	80
VR 6257	22	18	4 CBX	99
5242	22	18	4 CBA	99
16,003	22	18	4 NDX	237
VR 6258	22	18	5 DBB	270
13,599	22	18	5 NBX	480
VR 6260	22	18	6 AAX	100
VR 6259	22	18	6 BBX	120
15,386	22	18	7 AAB	111
16,049	22	18	8 ABB	162
29,065	22	18	8 BCD	145
VR 6261	22	18	8 BCB	145
22,389	22	18	8 DBB	145
30,891	22	18	8 NHB	162
VR 6263	22	18	9 BBX	116
5269	22	18	9 BBX	116
VR 6264	22	18	9 CBX	168
10,750	22	18	9 CBX	168
11,602	22	18	9 NWA	310
7369	22	18	10 BBX	60
VR 6266	22	18	10 BBX	60
15,314	22	18	10 CBB	90
VR 6265	22	18	10 CBB	90
15,314	22	18	10 CCC	180
15,323	22	18	10 NSA	147
15,324	22	18	10 SSA	183
8199	22	18	11 ABX	240
15,735	22	18	11 BCC	234
15,806	22	18	11 CAA	117
VR 6267	22	18	11 CDB	60
28,602	22	18	11 CDB	60

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
4,406	22	18	12 ABX	254
30,351	22	18	13 DBB	118.5
30,351	22	18	13 NSD	118.5
VR 6268	22	18	14 ABX	97
11,472	22	18	14 BCX	190
VR 6269	22	18	15 ABX	87
3138	22	19	1 ABX	140
7340	22	19	1 ABX	121
13,437	22	19	1 BCC	234
22,914	22	19	1 CCC	238
15,931	22	19	2 CAB	120
15,931	22	19	2 CBA	120
28,921	22	19	2 DAB	238
16,252	22	19	3 BAB	317
10,766	22	19	3 BDD	158.5
10,765	22	19	3 BDD	158.5
10,766	22	19	3 NAX	158.5
10,765	22	19	3 NAX	158.5
11,097	22	19	4 AAB	234
28,696	22	19	4 BAB	75
20,252	22	19	4 BCD	75
28,696	22	19	4 CAC	120
28,696	22	19	4 CAC	120
22,225	22	19	4 DAA	115.5
29,235	22	19	5 BDB	240

Pumping Wells

PAWNEE COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
27,053	22	19	6 NDX	240
20,237	22	19	7 DDA	240
16,838	22	19	8 ACD	240
22,769	22	19	8 BAC	240
26,122	22	19	8 CCX	120
17,340	22	19	8 DBC	120
24,231	22	19	8 DDD	120
30,892	22	19	12 ABA	290
18,369	22	19	12 BAA	146.5
11,001	22	19	12 BAA	146.5
18,369	22	19	12 BBD	293
14,221	22	20	11 DBD	57.7
14,221	22	20	11 DCC	57.7
18,668	22	20	12 BCC	63
14,221	22	20	14 BAD	57.7
10,643	22	20	11 DCC	150
10,643	22	20	11 DBD	150
10,643	22	20	14 BAD	150

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)#	Location Township	Location Range	Location Section	Pumpage (AcFt)
*951	21	21W	6 W½ SW	180
(15,487)	21	21	6 (approx. 350' N of SW corner of SW)	320+
	21	21	2 SW corner SE SW	
1306	21	21	6 SE SW	30
*25,759	21	21	23 NW NE SE	280+
(30,427)	21	21	23 NW NE SE	144
23,926	21	21	23 NE NE NW	278
12,519	21	21	24 SW NE NE	320
6093	21	21	25 E½ NE NE	173
25,494	21	21	24 SE NE NW	160
VR 5	21	21	21 NW SE	320
4947	21	21	14 NW SW SW	330
VR 77	21	21	17 NW SW	140
27,435	21	21	16 NW NW SW	640
10,337	21	21	17 NW SE	302
6632	21	21	18 W½ E½	240
VR 2	21	21	18 NE NE	130
30,427	21	21	23 NW NE SE	144
4353	21	21	24 N½ SW	397
VR 8	21	21	25 NW SW	270
VR 7	21	21	25 NW SE	140

<u>Explanation</u>: *Designates well overlap(s) with one or more wells right below it in parenthesis.
+Indicates the maximum assigned pumpage value, all the overlapping wells can pump simultaneously.
#VR = vested right <u>or</u> file number

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
8084	21	21	33 NE SE NE	224
8698	21	21	33 SW SW SE	273
*15,985	21	21	33 SW SW SE	916+
	22	21	4 NW NE NE	
	22	21	4 SW NE NE	
	22	21	4 SE SW NE	
(VR 10)	21	21	33 SW SW SE	402
	21	21	33 NW NE NE	
	22	21	4 NE NE	
(8698)	21	21	33 SW SW SE	400
(6661)	22	21	4 SE SW NE	277
*10,331	21	21	13 SE Corner	694+
(28,196)Pawnee Co.	21	20	18 SE SW SW	450
*27,554	21	21	21 SE NW SW	578+
	21	21	21 NW SE SW	
(VR 6)	21	21	21 SW SW NW	440
	21	21	21 NC N½ NW NW	
*2800	21	21	7 S½ SW	200
	21	21	7 S½ SW	
(9168)	21	21	7 SW (Pawnee Creek)	16
(VR 3)	21	21	18 NW NW	460
(8820)	21	21	7 SW NW NE	952
(15,613)	21	21	7 SW NW NE	1200+
	21	21	7 NE NW SE	
(7138)	21	21	7 SW NW NE	433
*VR 11	21	21	34 SW SW NE	470
	21	21	34 SW SW SW	
	21	21	34 NW NW SE	
(10,018)	21	21	34 SW SW NE	1104+
	21	21	34 SW SW SW	
	21	21	34 NW NW SE	
(14,138)	21	21	34 SW SW NE	746
	21	21	34 SW SW SW	
	21	21	34 NW NW SE	

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
*10,017	21 21	21 21	34 NW NW NE 34 NW NE NW	598+
(2945)	21 21	21 21	34 NW NW NE 34 NW NE NW	260
6108	21	21	35 (Nr.Ctr. S of NW NE SE)	28
*19,641	21	21	36 (Nr.Ctr. of W side of NW)	296
(4618)	21	21	35 NW SW NW	400+
(578)	21	21	35 NW NE NW	279.2
5194	21 21	21 21	36 SE SW SW 1 NE NW NW	170
VR 12	21	21	35 SW SW	194
VR 15	21	21	36 NW NE	310
VR 14	21	21	36 NW SE	120
VR 16	21	22	1 SE NE	60
VR 17	21	22	1 NW SE	150
11,318	21	22	1 SE NE SE	38
VR 76	21	22	1 SW NW	120
15,883	21	22	1 NW SW	320
*VR 20	21	22	2 SE NW NE	80
(16,099)	21	22	2 SE NW NE	154+
*VR 18	21	22	2 NW NW	106
(14,201)	21 21	22 22	2 SE NW NW 2 (Nr.Ctr. of W side of SW NW)	290+
17,281	21	22	2 SW NW NE	320
*9151	21	22	3 SW NW NW	240
(17,450)	21	22	3 SW NW NW	242+

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
*313	21	22	11 NW NW NE	240
(23,674)	21	22	11 SW NW NE	312+
*VR 22	21	22	12 (16' from original well SW NW)	260+
(8424)	21	22	12 NE NW NW	160
VR 23	21	22	12 NW SE	124
14,522	21	22	12 SE SE	152
*VR 21	21	22	12 NW NW SE	100
(5368)	21	22	12 NW NW SW	200+
*28,991	21	22	13 NE NE NE	312
(8,507)	21	22	13 NE NE NE	312+
9356	22	21	2 NW NW	222
VR 27	22 22	21 21	3 NW NE 3 NW SE	144
VR 26	22	21	3 NW SW NW	220
9991	22	21	4 SW NW SW	226+
(VR 28)	22	21	4 SW NW SW	60
25,354	22	21	4 NW SW SW	92
6,185	22	21	5 SW SE SE	290
*30,244	22	21	5 SE SW NW	308+
(31,625)	22	21	5 Nr.Ctr. W of SW NW	200
21,808	22 22	21 21	5 (N.Ctr. W side of Lot 2, NW NE) 5 SW SW NE	320
14,771	22	21	6 SW SW SE	312
14,932	22	21	6 NW SE SW	536
14,122	22	21	7 SE SW SE	122
11,865	22	21	7 SE SE	124
VR 30	22	21	7 SE NE	110
30,924	22	21	7 SE SE SE	124

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
*11,316	22	21	7 Nr.Ct. S of NW NW	516+
	22	21	7 NW SW	
	22	21	7 NW SW SW	
(VR 34)	22	21	7 NW SW SW	54
6595	22	21	8 NW SW NE	244
*14,124	22	21	8 SE SE SW	360
	22	21	8 Nr.Ctr. NW SW	
(23,638)	22	21	8 Nr.Ctr. SW SW	276
	22	21	8 SE SE SW	
(8825)	22	21	8 SE SE SW	360+
(6153)	22	21	8 SE SE SW	172
*VR 35	22	21	8 NW NW NW	140
(19,201)	22	21	5 SW NW SW	314+
*28,164	22	21	9 NE NE NW	260
(5931)	22	21	9 SE NW SW	220
(VR 36)	22	21	9 NW SE SW	420+
	22	21	9 SW SW SW	
18,320	22	22	11 NE NE SW	254
	22	22	11 Nr.Ctr. SW SW	
28,587	22	22	11 Nr.Ctr. W of NW NW	85
28,088	22	22	11 SE SE NE	310
VR 40	22	22	12 NW SE	430
	22	22	12 SW SE	
	22	22	12 SW SW	
VR 42	22	22	13 NW SE	202
*VR 43	22	22	13 SW NW	100
(28,061)	22	22	13 Nr.Ctr. NW NE	325+
5665	22	22	14 SE	380
*15,255	22	22	14 Nr.Ctr. of NW	316
(16,577)	22	22	15 NE SE NE	320+
32,092	22	22	22 SE NE	38.4

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)	Location: Township	Range	Section	Pumpage (AcFt)
VR 44	22	22	23 NE corner of SE SE	120
934	22	22	23 SE	114
VR 46	22	22	23 NE NE	214
20,062	22	22	23 SE SE SE	64
*175	22	22	23 NW SW NW	120+
(26,876)	22	22	23 NW SE NW	64
(26,877)	22	22	23 Nr.Ctr. W of NW NW	52
*7626	22	22	26 SW NW SW	170
(25,698)	22	22	26 SW NW SW	202+
	22	22	26 SE NE SW	
*12,011	22	22	27 SW NW SE	282+
(32,079)	22	22	27 SW SW SE	140
(VR 48)	22	22	27 SW SW SW	230
	22	22	27 NE NE SW	
1449	22	22	28 NE NE	135
VR 50	22	22	31 SW SW SE	200
	22	22	31 SW SW SE	
*19,130	22	22	31 SW SE SW	768+
	23	22	6 NW NE NW	
(vr 51)	22	22	31 NW NW SW	106
(VR 65)	23	22	6 NW NE NW	177
(28,176)	23	22	6 NW NE NE	284
27,815	22	22	32 Nr.Ctr.E½ of W½ SE	128
*4114	22	22	32 (Nr.Ctr.S of SE SW SW)	100
	22	22	32 Nr.Ctr.SW corner SW	
(8781)	22	22	32 SE SW SW	255+
	22	22	32 Nr.Ctr.SW Corner SW	
VR 53	22	22	33 SW SW	110
19669	22	22	33 SE SW SE	235.8
28,099	22	22	33 NW NW SE	48

Pumping Wells

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
*23,665	22	22	33 SE NE NE	255
(3240)	22	22	33 SE SE NE	155
(VR 57)	22	22	34 (Nr.Ctr.N½ of NW SW NW)	160
*VR 58	22	22	34 SW NW NE	120
(10,954)	22	22	34 SW NW NE	176+
	22	22	34 SE SW NE	
26,274	22	22	34 SW NW SE	246
	22	22	34 NW SW SE	
VR 59	22	22	35 SW SW	36
*VR 61	22	23	35 SE SE SE	94
(11,730)	22	23	35 SE SE	220+
	23	23	1 SW NE NW	
(17,819)	23	23	1 NE NE SW	80
VR 62	22	23	35 NW SE	200
	22	23	35 SW NE	
17,105	22	23	35 NW NW SE	150
	22	23	35 SW NW SE	
	22	23	35 NE SW SE	
8407	22	23	36 SE	120
VR 71	22	23	35 SE SE SW	130
	23	23	2 NE NW	
VR 63	23	22	3 CS SW SE	76
27,063	23	22	5 NE NE NE	290
	23	22	5 NE NE NE	
28,188	23	22	5 W½ E½ W½	102
*11,269	23	22	5 NE NW	180+
(VR 64)	23	22	5 SW NE NW	60
VR 66	23	22	11 SW SW SW	180
28,177	23	23	1 SW NE NE	160
*3529	23	23	2 NE NW NE	149
	23	23	2 SE NW NE	
(7032-A)	23	23	2 NE NW NE	230+
	23	23	2 SE NW NE	

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
*VR 72	23	23	3 SW SW NE	50
(28,015)	23 23	23 23	3 SE NW NE 3 SW SW NE	126.6+
13,426	23 23 23	23 23 23	4 NE NW SW 4 NE NW SW 4 NW NE SW	900
*848	23	23	4 Nr.Ctr. SE SE	45
(15,437)	23 23 23	23 23 23	3 NW NW NW 3 NW NW NW 4 Nr.Ctr. SE NE	160+
(847)	23	23	3 NW NW NW	69
*VR 1	23	23	6 SE NW SW	99
(1787)	23	23	6 NW NE SW	235
(28,266)	23 23	24 23	1 SW SW NE 6 NW NE SW	291.4+
5432	23	23	6 SE SW SW	40
*2018	23	23	6 SW SW SE	20
(11,259)	23 23	23 23	6 SW NE SE 6 NW SE SE	208+
*9854	23 23	23 23	8 SE NW NW 8 NW NE NW	114+
(29,062)	23	23	8 NW NE NE	88
13,413	23	23	9 Nr.Ctr. of NW	320
*5853	23	24	1 NW SW SW	114
(15,765)	23 23 23 23	24 24 24 24	1 Nr.Ctr. NE SW 1 NW SE SW 1 NW SE SW 1 NW SW SW	246
(22821)	23 23 23 23 23	24 24 24 24 24	1 NE SE SW 1 NE NW SW 1 NW SW SW 1 NW SE SW 1 NW SE SW	530+

Pumping Wells

HODGEMAN COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
(4879)	23	24	1 NE SE SW	7
19117	23 23 23	24 24 24	2 NE SE SW 2 NE SE SW 2 NE SW SE	160
*5285 (28,032)	23 23	24 24	4 SE SW SE 4 SW SW SE	68 92 } 126+
*1075 (2674)	23 23 23	24 24 24	5 SW SE SW 5 SW SW SW 5 SW SE SW	60 105+
5824	23	24	5 SE	86
5201	23	24	6 SE SE SE	5
969	23	24	7 NE NW	47
16,152	23	24	8 NW SW NW	40
17,190	23 23	24 24	10 NW NE SE 10 NE NW SE	110
*19,706	23	24	11 NW NW NE	158
(22,933)	23 23 23	24 24 24	11 NW NW NE 11 NE NW NW 11 NW NW NW	192+

Pumping Wells

NESS COUNTY

Water Right Number (VR = vested right)#	Location Township	Range	Section	Pumpage (AcFt)
VR 8	20	22W	19 SW SE SE	60
VR 9	20	22	19 NE SW SW	130
VR 10	20 20 20	20 20 20	20 NE SE SE 20 NE SE SE 20 SW NW SE	250
VR 11	20	22	21 NW NW SE	140
VR 12	20	22	28 NW NW SW	90
VR 13	20	22	28 NW SW SW	102
VR 14	20	22	28 SW SW SW	106
*VR 15	20	22	29 NW SE NW	150
(16,233)	20	22	29 SE SW NE	264+
*VR 16	20	22	30 NE NW SW	59
(130)	20	22	30 NE NW SW	59+
*VR 17	20	22	30 NW NW SE	80
(31,375)	20	22	30 NE NE SE	124+
VR 18	20	22	30 SE SW NW 30 N/C W Side NE	227
VR 19	20	22	32 NE NE NE	38
VR 20	20	22	33 NE NE NE	30
*VR 21	20	22	33 SE NE NE	100+
(30,780)	20	22	33 SE NW NE	76
VR 22	20	22	34 SW SW NW	166
VR 23	20	22W	35 NW SW SW	120
VR 24	20	22	35 NW NW SE	130
VR 25	20	22	35 SW SW NW	120

Explanation: *Designates well overlap(s) with one or more wells right below it in parenthesis.
+Indicates the maximum assigned pumpage value, all the overlapping wells can pump simultaneously.
#VR = vested right or file number

Pumping Wells

NESS COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
VR 26	20	22	36 SW SW SW	160
*VR 27	20	23	22 SW SW SW	105
(31,679)	20	22	20 NW SW SW	200+
VR 28	20	23	24 SW SW SE	72
VR 29	20	23	25 NW SW NE 25 NE NW SE 25 NW SW SW (2 wells)	400
138	20	23	28 NE SE SE	340
VR 30	20	23	32 N/C SE SW	140
VR 31	20	23	32 SW NW NW	140
*VR 32	20	23	33 NW NE NE	80+
(8011)	20	23	33 NW NE NE	34
*VR 33	20	23	33 (Nr.Ctr.N Side SW NW)	320
(31,362)	20	23	33 SW SW NW	320+
VR 35	20	24	35 SW SW SW	240 (surface & ground water)
*VR 36	20	22	27 NW NW SW	188
(30,838)	20	22	27 SE NW NE 27 Nr.Ctr.S½ SW SE 27 NW NW SW 27 SE SE SW	502+
134	20	23	28 SE SE	170
*484	20	23	26 SE NW	100
(6448)	20	23	26 SE SE NE	150+
	20	23	26 SW SE NW	
529	20	22W	34 SW SW NE	150
5885	20	20W	28 SW SW NW	98
6709	20	23	23 SE SW SW	150
*6710	20	23	26 SW SW SE	240
(24,364)	20	23	26 SW NW SE	270+
*7421	20	22	33 NE NW	38
(30,780)	20	22	33 SE NW NE	76+

Pumping Wells

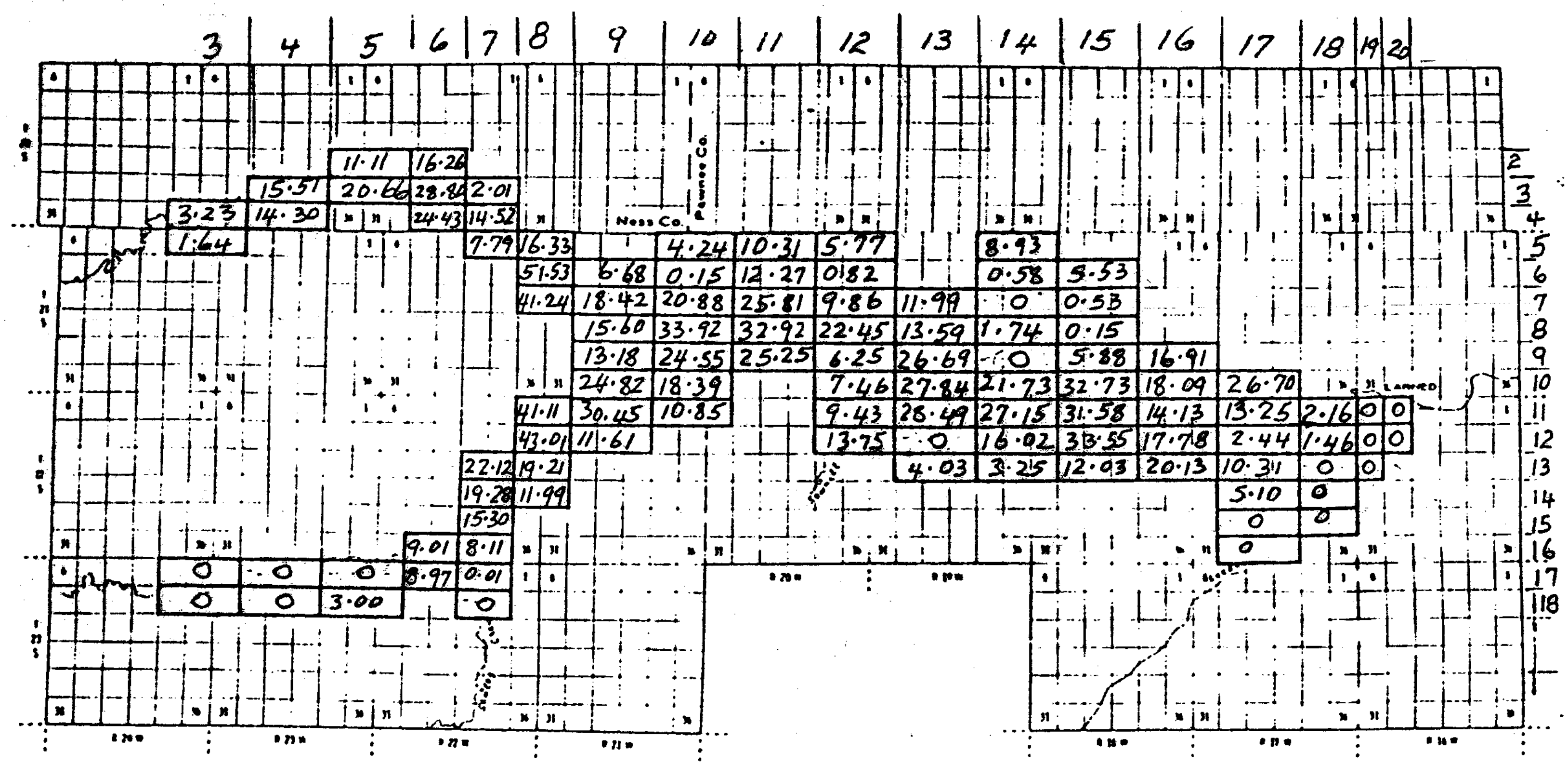
NESS COUNTY

Water Right Number (VR = vested right)	Location Township	Range	Section	Pumpage (AcFt)
*7483	20	23	25 NW	220
(14,464)	20	23	25 NW NE NW	256+
	20	23	25 SW SW NW	
*8184	20	24	36 N½	267
(14,120)	20	24	36 NE SE NW	472+
8402	20	22	27 SW SE	64
31,361	20	23	33 SW NW SW	240
9097	20	23	35 NW NW NW	260
9962	20	22	36 NW SW SE	264
*11,044	20	23	26 E of SW corner	314
(22,991)	20	23	26 SE NW SW	314+
13,350	20	22	27 SE SW NW	100
14,465	20	22	29 NW NW SE	320
14,466	20	22	29 NW NW SW	70
17,406	20	23	27 SE SE NW 27 SE SE NW	444
17,525	20	22	26 SW SW SW	64
17,769	20	23	27 SW SE SE	148
17,770	20	23	27 NW SW SE	152
29,583	20	22	17 NW NW SE	249
29,956	20	23	16 Nr.Ctr.N Side NE	173
31,360	20	23	34 NW NE NW 34 SW NE NW	240
33,070	20	22	28 Nr.Ctr.W Side SE	312

APPENDIX B

OPTION 1

TIME: 10 YRS.



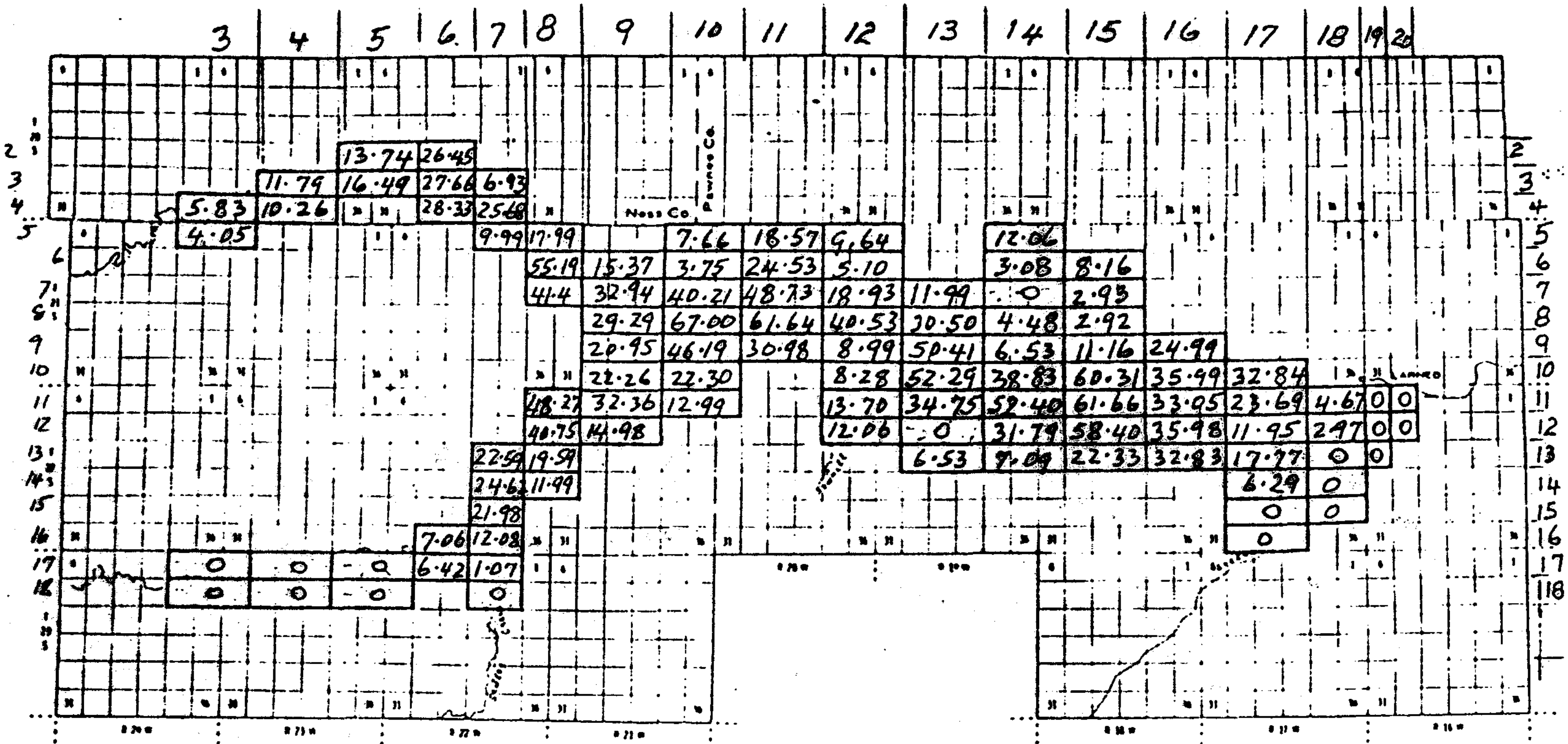
24 nodes reached the minimum allowable saturated thickness.

Approximate scale
1:125,000

[redacted] [redacted]

OPTION 1

TIME: 20 YRS

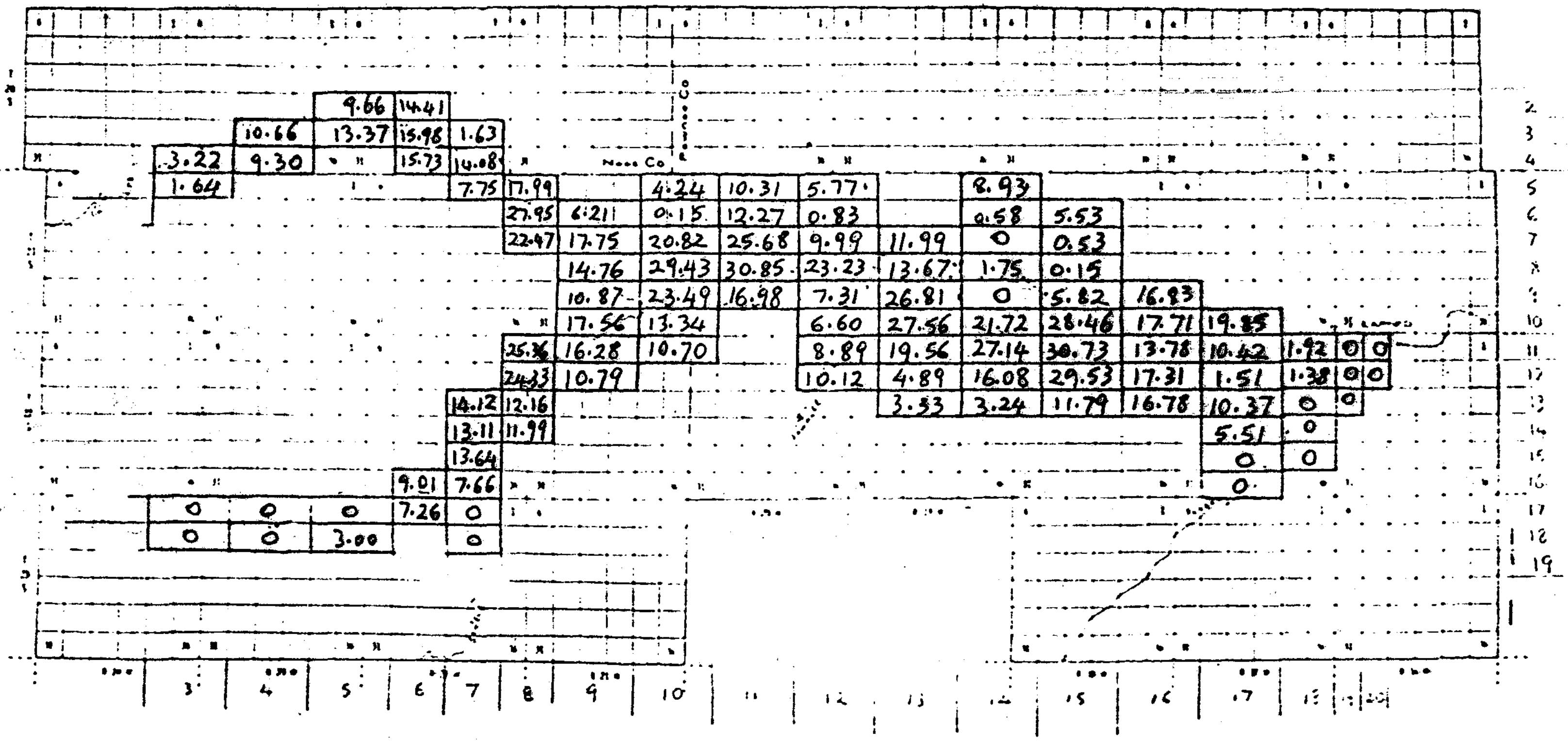


36 nodes reached the minimum allowable sat. thickness

Approximate scale
1:125,000

OPTION 2

TIME : 10 YRS

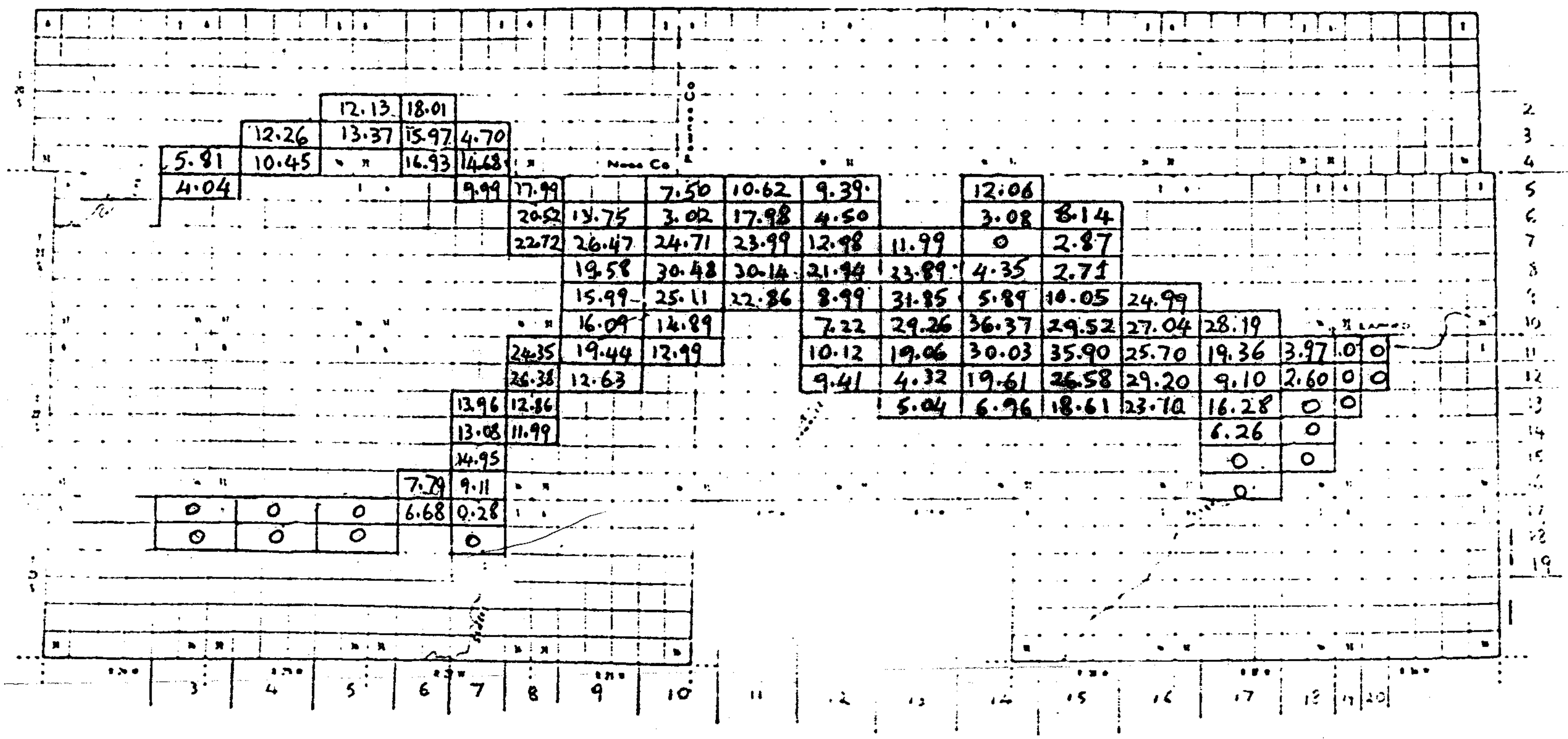


34 nodes reached the minimum allowable saturated thickness

Approx. scale 1: 125,000

OPTION 2

TIME: 20 YRS

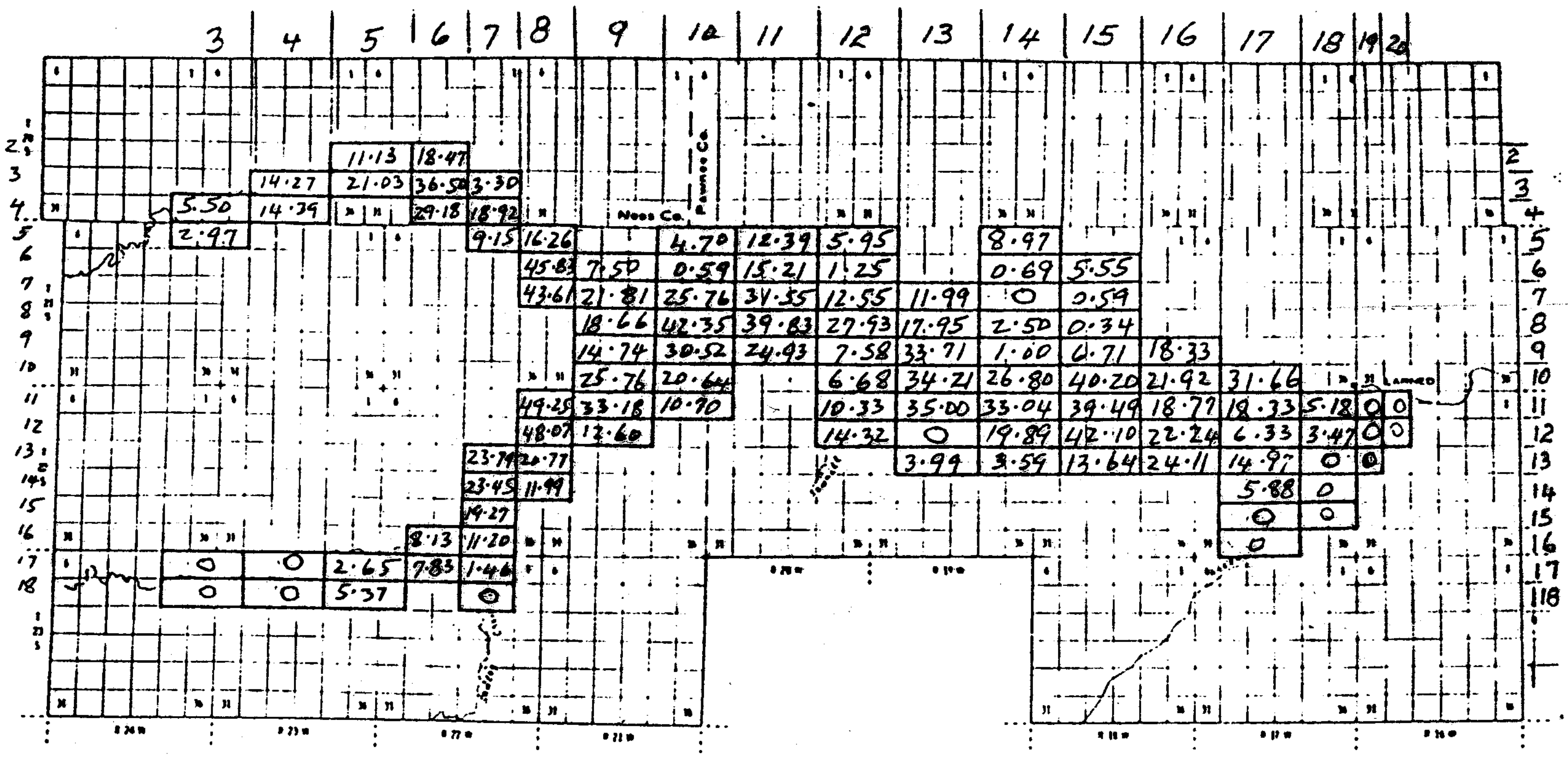


55 nodes reached the minimum allowable saturated thickness.

Approx. scale 1:125,000

[redacted]

OPTION 3
TIME 10 YRS

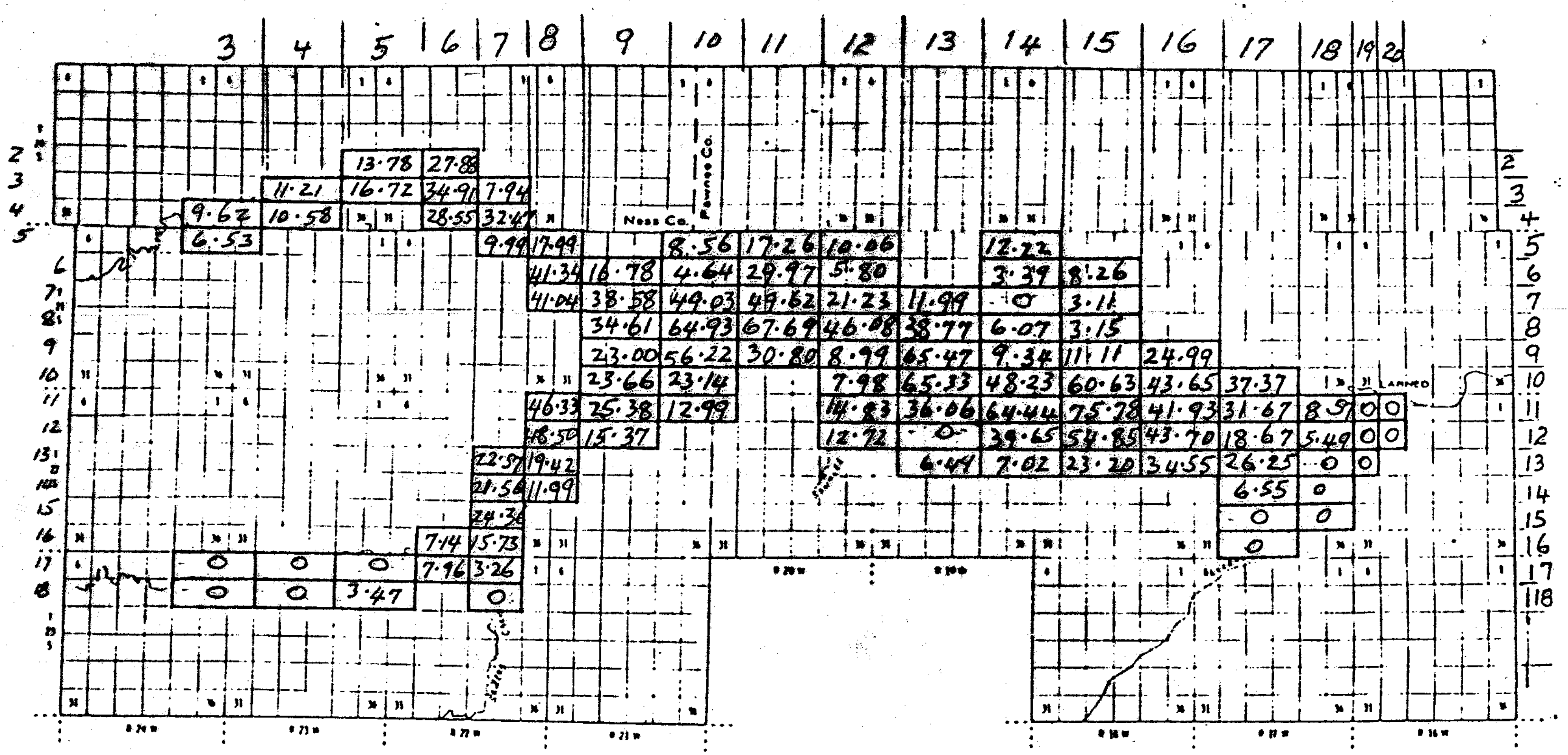


29 nodes reached the minimum allowable sat. thickness

Approximate scale
1:125,000

[redacted]

OPTION 3
TIME: 20 YRS

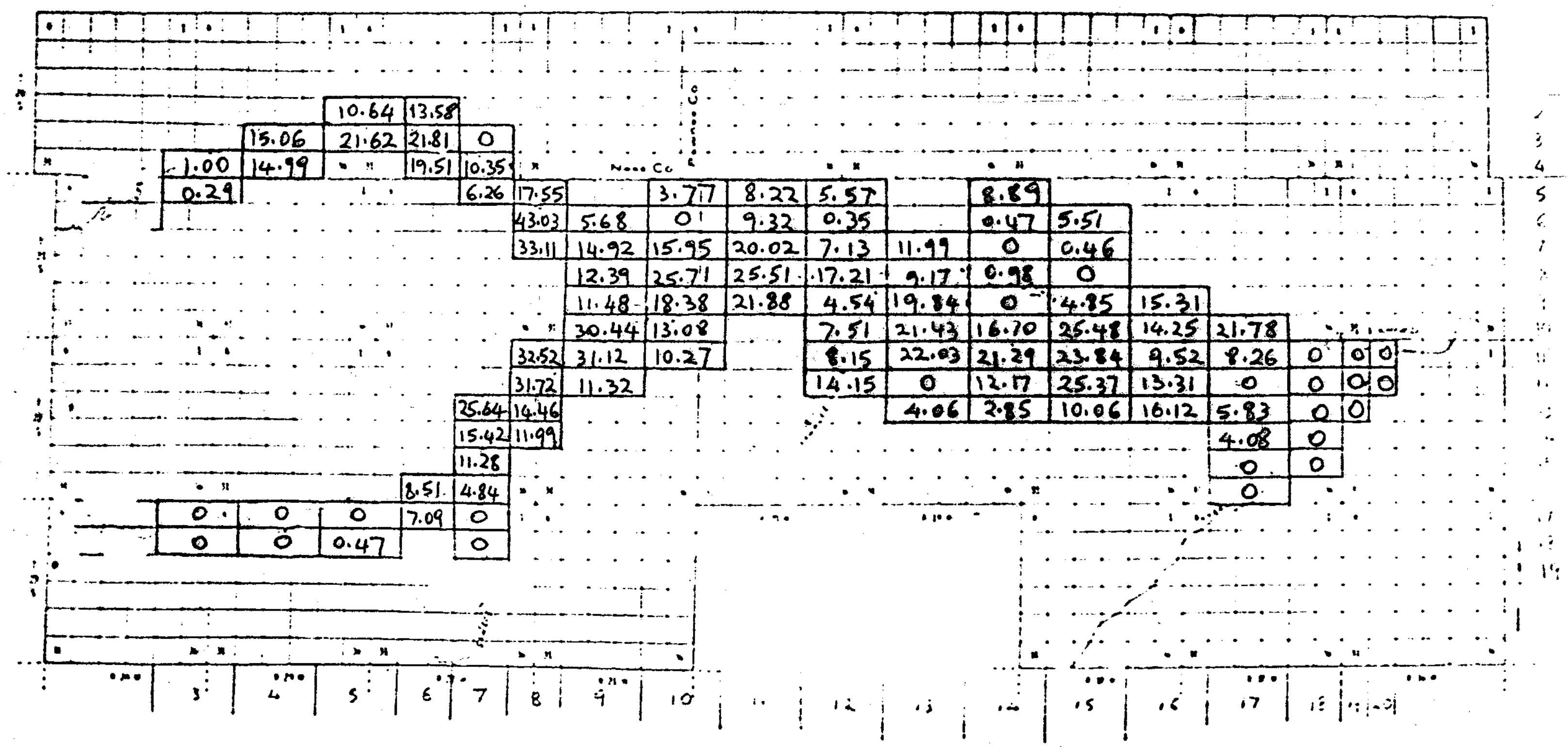


45 nodes reached the minimum allowable sat. thickness

Approximate scale
1:125,000

OPTION 4

TIME 10 YRS

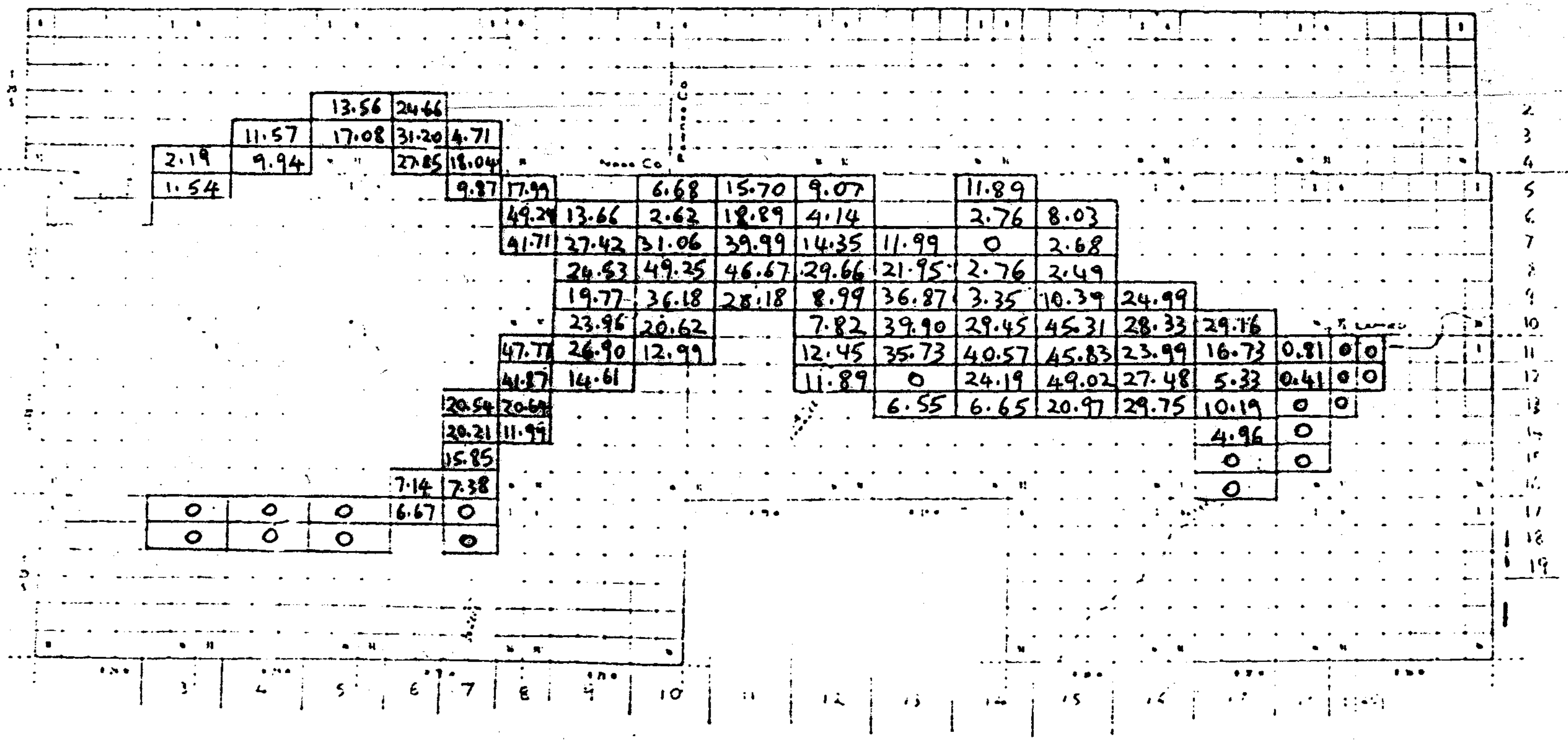


17. nodes reached the minimum allowable sat. thickness

Approx. scale 1:125,000

OPTION 4

TIME: 20 YRS



33 nodes reached the minimum allowable sat. thickness

Approx. scale 1:125,000

[redacted] [redacted]

OPTION 5

TIME: 10 YRS

	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2			10.17	12.61														
3		14.24	21.46	17.73	0													
4	0	14.51		17.21	8.18													
5	0				6.08	17.46		2.44	6.50	4.68		7.86						
6						35.50	5.17	0	7.59	0		0	4.48					
7						30.02	13.04	13.78	17.72	5.28	11.78	0	0					
8							10.89	22.19	22.28	14.35	7.31	0	0					
9							11.04	15.98	19.60	4.26	16.44	0	4.20	14.73				
10							26.15	10.87		7.07	18.88	14.06	21.80	12.41	19.40			
11						29.20	26.88	9.83		7.21	19.45	18.78	20.40	7.20	5.66	0	0	0
12						26.51	10.60			11.86	0	10.10	21.45	11.23	0	0	0	0
13					21.61	12.35					3.17	2.07	9.48	14.19	2.82	0	0	
14					12.78	11.99									3.08	0		
15					8.71										0	0		
16				6.97	2.48										0			
17	0	0	0	4.69	0													
18	0	0	0		0													

13 nodes reached the minimum allowable sat. thickness

Approx. scale: 1:125,000

OPTION 5

TIME: 20 YRS

	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2			13.49	24.67														
3		11.73	20.03	29.75	4.82													
4	3.02	10.93	• •	27.82	20.38													
5	1.65				9.89	17.99		6.00	16.22	8.39		11.02						
6						46.32	13.45	1.94	20.04	3.57		1.88	7.19					
7						41.54	29.33	33.68	43.32	15.31	11.99	0	1.86					
8							26.25	54.81	51.76	32.97	24.25	2.38	1.75					
9							20.17	39.33	28.99	8.99	41.39	3.24	9.86	24.99				
10							24.63	20.79		7.55	43.54	32.33	50.04	30.19	29.76			
11						49.03	28.35	12.99		13.03	34.76	43.97	50.72	26.50	18.97	2.93	0	0
12						43.13	14.10			13.23	1.71	26.07	54.83	29.79	7.08	1.93	0	0
13					20.97	20.13					5.91	6.08	20.80	31.70	12.96	0	0	
14					22.47	11.99									5.28	0		
15					17.85										0	0		
16				6.37	8.72										0			
17	0	0	0	8.06	0													
18	0	0	0		0													

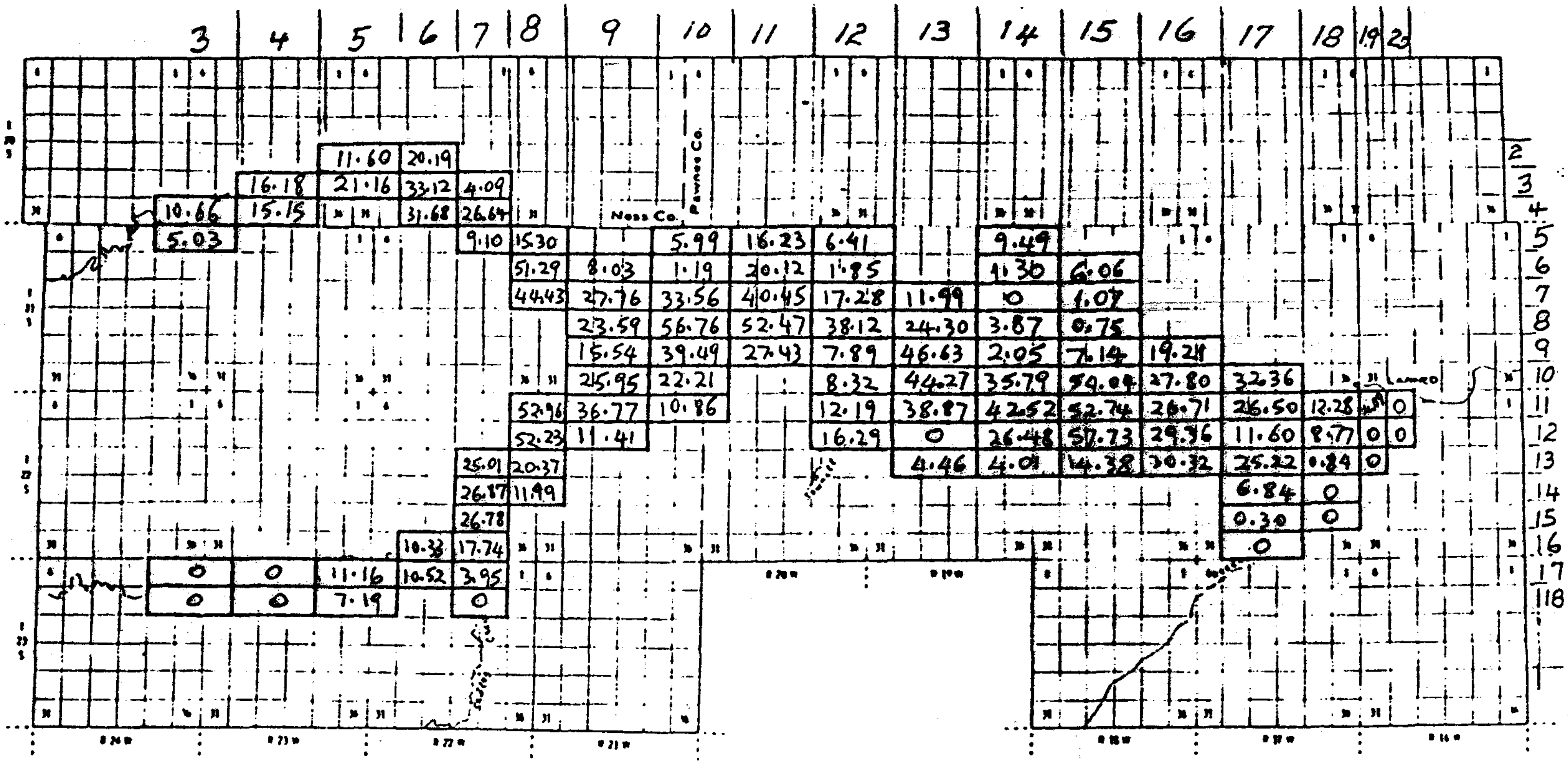
33 nodes reached the minimum allowable sat. thickness

Approx. scale 1:125,000

[redacted] [redacted]

OPTION 6

TIME: 10 YRS



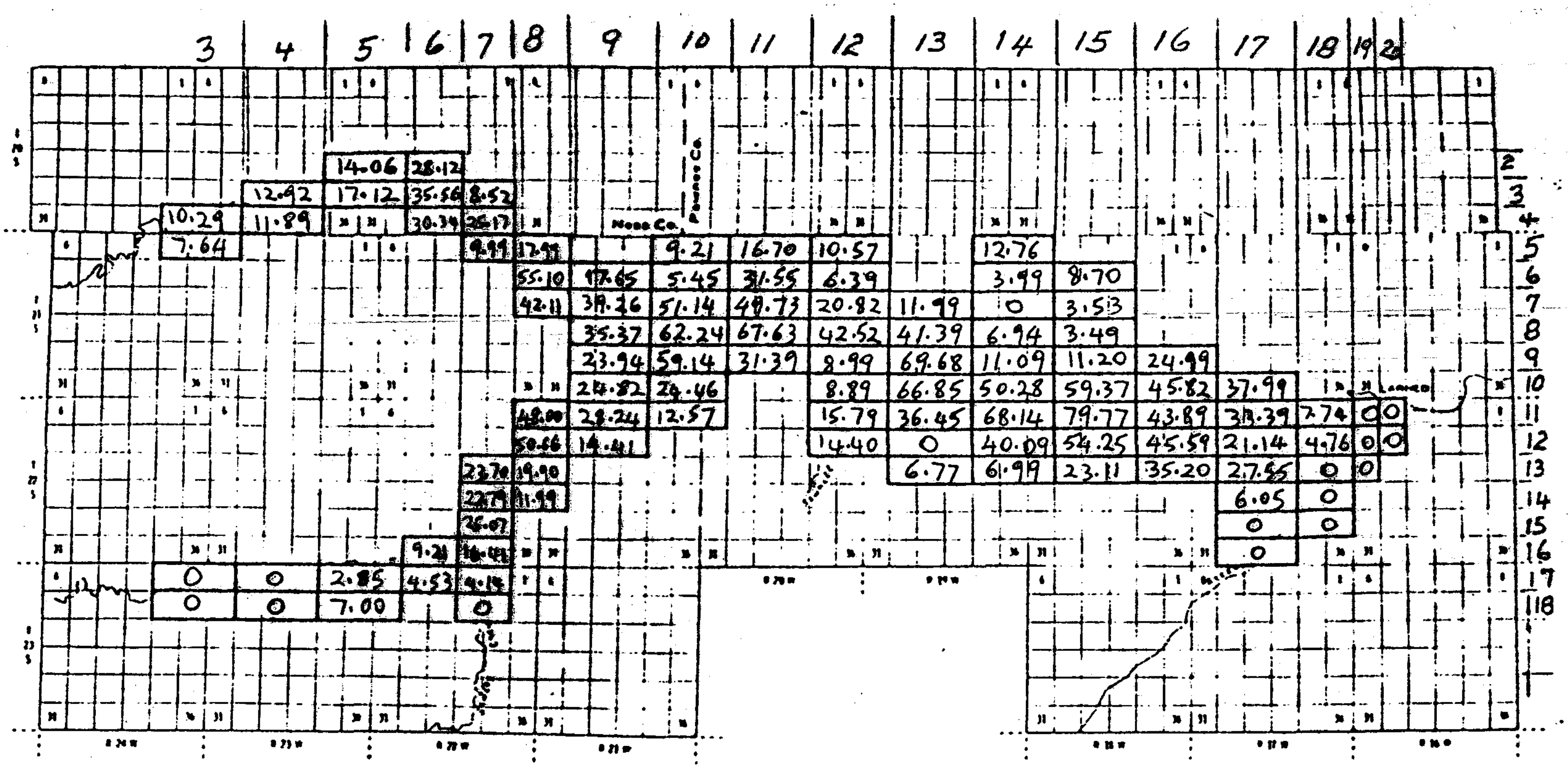
36 nodes reached the minimum allowable sat. thickness

Approximate scale
1:125,000

[redacted] [redacted]

OPTION · 6

TIME: 20 YRS



46 nodes reached the minimum allowable sat. thickness

Approximate scale
1:125,000