A GROUND-WATER MANAGEMENT MODEL FOR THE ELK CITY AQUIFER IN WASHITA, BECKHAM, CUSTER AND ROGER MILLS COUNTIES, OKLAHOMA

By

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PREFACE

Geologic and hydrogeologic properties of the Elk City Sandstone and the overlying unconsolidated sediments are evaluated and used in a ground-water management model. The primary objective of this study is to determine the maximum annual yield and corresponding annual pumping allocation for the Elk City Sandstone Aquifer in accordance with Oklahoma ground-water law. The computer model is used to determine the maximum annual yield based on predicted changes in the potentiometric surface (water table) caused by pumpage prior to July 1, 1973, and subsequent allocated pumpage until July 1, 1993.

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CHAPTER I

ABSTRACT

The Elk City Aquifer supplies water for irrigation, domestic, municipal, and industrial use for rural communities and their residents in Beckham and Washita Counties. The aquifer's areal boundary is defined by the continuous outcrop of the Elk City Sandstone. The ground-water aquifer is bounded vertically by the water table above, and the impermeable Doxey Shale below. The study area is divided into two smaller areas labeled A and B.

The purpose of the study is to determine relationships within the aquifer and determine a legal annual allocation for the Elk City Aquifer as stated under Oklahoma Law. In order to achieve these goals, a geological and a hydrogeological investigation was conducted.

The data was collected from previous reports and records, and from field work. Assumption of the relationships within the aquifer were made from the interpreted data. These assumptions were used to develop the appropriate maps and parameters of the aquifer, and were then put into computer format. Computer runs, using the Trescott-Pinder model, were first run on one-year periods to calibrate the aquifer into a recharge-discharge equilibrium. After calibration was completed, 20-year simulations were run to determine a mass balance relationship and legal annual allocation for the aquifer. An annual allocation of 0.91 acre foot/acre was established for the Elk City Aquifer.

CHAPTER II

INTRODUCTION

General

The Elk City Sandstone and the overlying unconsolidated material represent an aquifer which is being used as a water supply for the western part of Washita County and the eastern part of Beckham County. The aquifer supplies domestic and irrigation water for rural residents and communities.

Under Oklahoma Statute No.'s 82 § 1020.4 and 82 § 1020.5, the Oklahoma Water Resources Board is responsible for completing hydrology surveys of fresh ground-water basins or subbasins within the state of Oklahoma and for determining a maximum annual safe yield which will provide a 20-year minimum life for each basin or subbasin.

Oklahoma Statue No. 82 § 1020.5 states the following:

> After making the hydrologic survey, the Board shall make a determination of the maximum annual yield of fresh water to be produced from each ground-water basin or subbasin. Such determination must be based upon the following:
>
> 1. The total land area overlying the basin or subbasin;
> 2. The amount of water in storage in the basin or subbasin;
> 3. The rate of natural recharge to the basin or subbasin and total discharge from the basin or subbasin;
> 4. Transmissivity of the basin or subbasin; and
> 5. The possibility of pollution of the basin or subbasin from natural sources.
>
> The maximum annual yield of each fresh ground-water basin or subbasin shall be based upon a minimum basin or subbasin life of twenty (20) years from the effective date of this act. An

annual allocation in terms of acre feet per acre per year is to be determined based on the maximum annual yield and used as a basis for issuing permits to owners whose land is located within the aquifer area. (OWRB Rules and Regulations, 665.2)

Objectives

The main objective of this study is to determine the maximum annual yield and a corresponding pumping rate allocation of fresh ground water that can be pumped from the Elk City Aquifer during a 20-year period between July 1, 1973 and July 1, 1993. In order to achieve this goal, the following factors must be determined:

1. To interpret the geology with respect to its structure and lithologic characteristics.
2. To relate geologic factors with well data to interpret the hydrogeologic parameters of the aquifer.
3. To determine the recharge-discharge relationship within the aquifer.

After these qualitative factors are known, quantitative values may be assigned with reference to well data and other hydrogeologic information.

These quantitative values are used in a mathematical model to predict changes in the potentiometric head within the Elk City Aquifer over a 20-year period. A flow chart showing these steps is shown in Figure 1.

Location

The area of study is located mainly in Beckham and Washita Counties, with a small portion found in Roger Mills and Custer Counties (Fig. 2). The exact location of the Aquifer as to township and range is shown in Figure 3. The total surface area of the aquifer is approximately 256

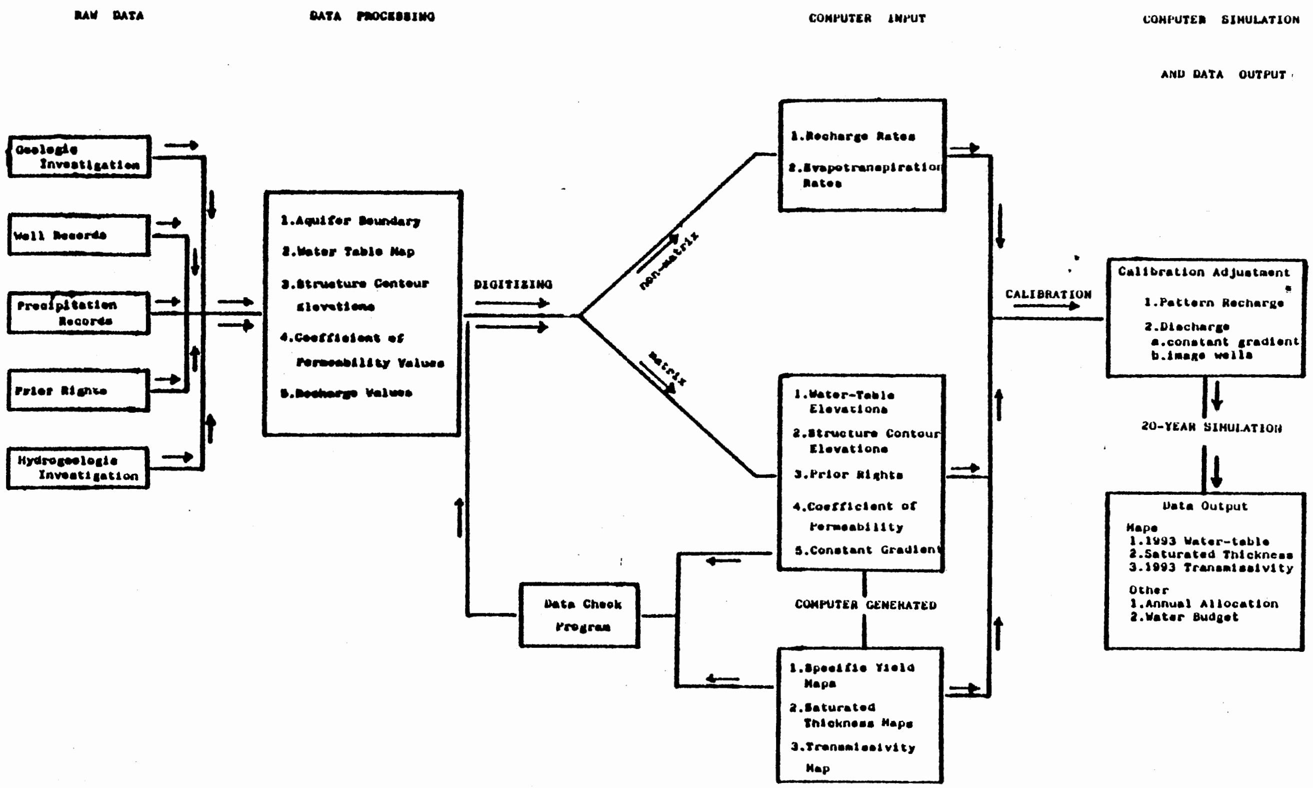


Fig. 1--Flow chart of computer modeling

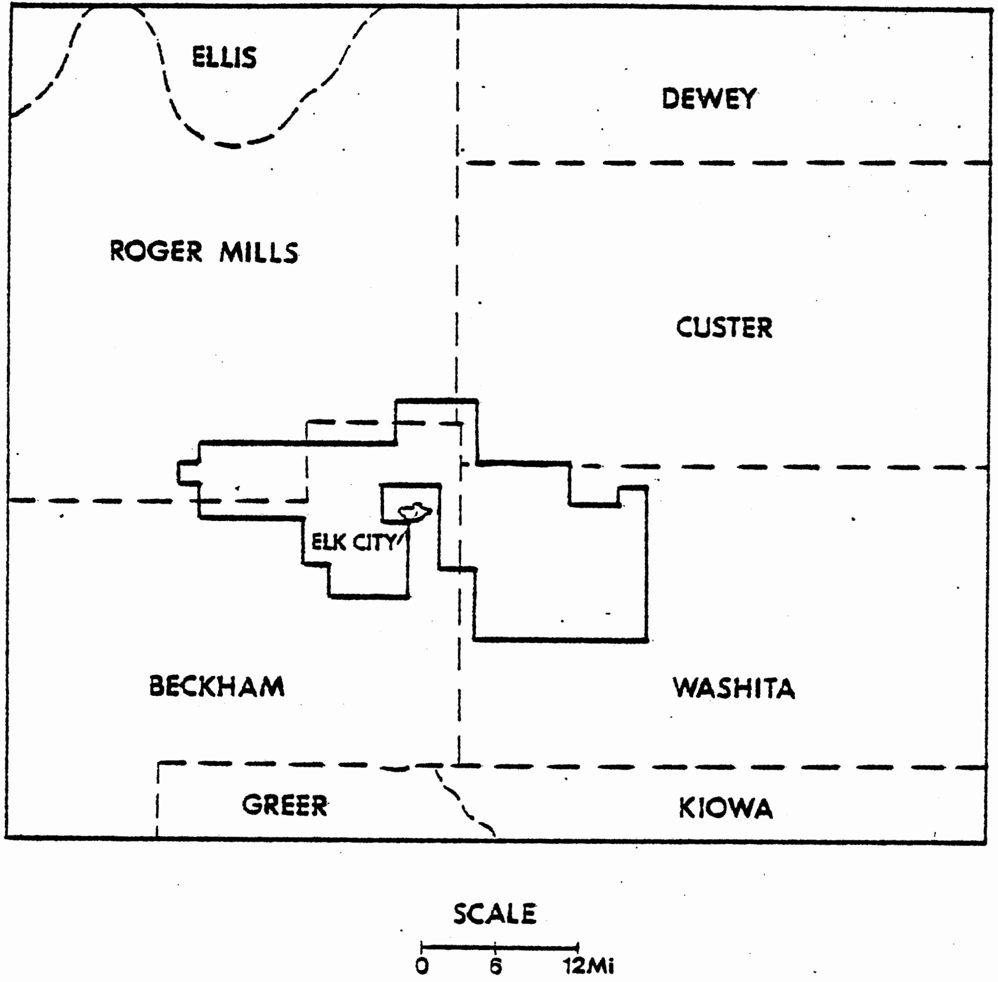


Fig. 2--Location of study area by counties.

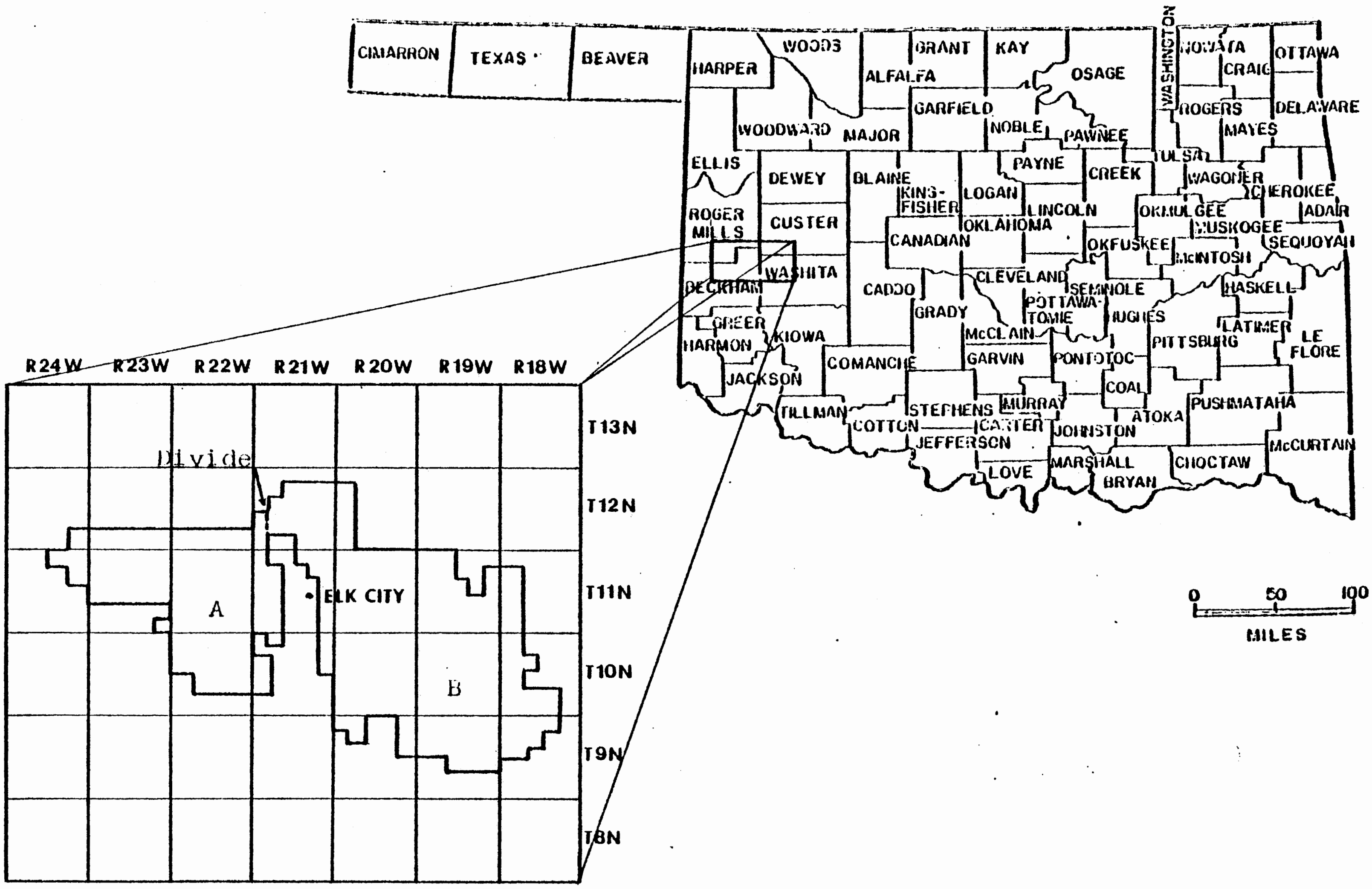


Fig. 3--Location of study area by township and range.

square miles. The aquifer has been divided into the two subareas, A and B, as shown in Figure 3. The natural drainage has nearly severed the Elk City Sandstone exposing the underlying Doxey Shale.

The study area is defined by the continuous outcrop of the Elk City Sandstone in western Oklahoma. A few outliers of the Elk City, west of the study area, were not considered to be part of the Elk City Aquifer. The edge boundary of the aquifer is surrounded by the underlying Doxey Shale except where the Ogallala Formation outcrops at the northwestern edge of the study area.

Previous Work

Freie (1930) studied the sedimentation in the Anadarko Basin. His work was largely a petrologic study on mineralogy, grain size and sphericity, and roundness of sedimentary rocks found in the Anadarko Basin, which includes the Elk City Sandstone. Hills (1942) studied the paleogeographic extent of marine seas at different periods in the Permian and determined the cyclic nature and gradual retreat of the sea during this time. In 1967, McKee and Maclahlam related the tectonic history with sedimentation in Permian time. By studying the type and thickness of sedimentary rocks deposited, they described the tectonic activity which occurred during the Permian.

Smith (1964) mapped parts of Beckham and Roger Mills Counties around Elk City. His thesis was mainly a stratigraphic investigation which included mapping the area. The mapped area represents the western half of the area in this investigation.

Richardson (1970) studied the effects of the solution of the Yellow Salt in western Washita County. He also produced a geological map of the area. His thesis area corresponds to the eastern half of the study area. Zabawa (1976) studied the surficial structural geology of western Washita and eastern Beckham Counties. Her area encompasses most of the area in this report. The main purpose of her thesis was to show that many of the solution collapse features found in the area are related more to major subsurface faults rather than to the solution collapse exclusively. The relative age and mapping of these surficial faults were determined from geologic data.

In 1964, Palmquist and Koofman investigated the occurrence and availability of ground water in northwestern Washita County. The purpose of their study was to determine if a capable water supply could be established for the Clinton-Sherman Air Force Base. Their study corresponds to the eastern half of the study area. Much of the data from their report was used in modeling the Elk City Aquifer.

Kent (1978, 1980) studied the alluvium and terrace deposits along the North Fork of the Red River for water supply capability. Kent used the 1974 computer model version developed by the U.S. Geological Survey to determine maximum annual yield and annual allocation of those aquifers. Many of the hydrogeologic and modeling techniques used by Kent (1980) were used in this investigation.

Bredhoeft and Pinder (1970) and Pinder (1970) designed a basic mathematic model to simulate two-dimensional aquifer problems. This model has been modified several times. Witz (1978) modified the model for a multilayered system and developed new input-output options for the IBM 370-158. The 1974 version of this model developed by the U.S. Geological Survey plus the later modifications was used in this study.

CHAPTER III

GEOLOGY

General

The study area is located along the Permian axis of the Anadarko Basin. The Anadarko Basin is asymmetrical, and its axis parallels and lies north of the Amarillo-Wichita uplift. This basin has a thick sequence of sedimentary rocks dating back to the Cambrian period. A general stratigraphic chart for the central Anadarko Basin is shown in Figure 4.

Much of the sedimentation which occurred in the Anadarko Basin was tectonically controlled by faults and from subsidence of the basin. Deposition began in an intercratonic sag that developed upon the granitic basement floor and initiated the South Oklahoma Aulacogen in early Cambrian time (Zabawa, 1976). Deposition continued until Pennsylvanian time where an orogeny occurred. Subsequently, the basin deepended rapidly, and a thick sequence of Pennsylvanian sediments was deposited. Most of the detrital sediments in the Pennsylvanian were derived from the Amarillo-Wichita Uplift which was active at the time. Continuing deformation occurred along the same zones of weakness that were initiated during the formation of the aulacogen (Zabawa, 1976). This deformation lasted into early Permian time. Carbonates, evaporites and detrital sediments were deposited which filled the rest of the basin during Permian time.

AGE	UNIT	THICKNESS IN FEET
Mississippian	Springer Sand Chester Shale	1,000 3,000
Silurian	Meramec Lime	1,000
Silurian-Ordovician	Hunton Lime	700
Ordovician	Simpson Sand Middle and Upper Arbuckle	1,500 3,000
Late Cambrian	Lower Arbuckle Group Honey Creek Limestone Reagan Sandstone	450 200 75-90
Middle Cambrian(?)	Wichita Granite Group Carlton Rhyolite Group	sills 600-1,500 4,500
Early Cambrian(?)	Raggedy Mountain Gabbro Group Navajoe Mountain Basalt-Spilite Group	10,000 1,050
Late Precambrian or Early Cambrian	Tillman Sedimentary Group	15,000
Precambrian	Eastern Arbuckle Province	

Fig. 4--Generalized stratigraphic chart for central Anadarko Basin (After Zabowa, 1976).

AGE	UNIT	THICKNESS IN FEET
Quaternary	Alluvium Deposits Terrace Deposits Undivided Silt Terrace Deposits Sand Terrace Deposits Dune Sand Washita River Deposits Deposits Possibly Kansan or Illinoisan in Age	variable up to 50
Tertiary	Undivided Deposits Possible Pliocene Deposits	variable up to 150
Cretaceous	Deposits of Questionable Age Kiowa Formation Undivided Deposits	outliers-thickness variable
Permian	Elk City Sandstone	0-260
	Doxey Shale	160-195
	Cloud Chief Formation	365-458
	Rush Springs Sandstone	300-430
	Whitehorse Group	387
	Flowerpot Shale	2,700
	Wellington Anhydrite	1,200
	Brown Dolomite	2,200
Pennsylvanian	Virgilian Limes	2,000
	Douglas Group	1,000
	Tonkawa Sands	200
	Hogshooter Limestone	100
	Clareland and Checkerboard Sands	500
	Cherokee Group	1,000
	Krebs Group	500
	Morrow Formation	4,500

Fig. 4--(Continued).

Little is known about the Mesozoic environment because sedimentary rocks are absent. Only a few outliers of Cretaceous sediments are found in the central Anadarko Basin.

The Ogallala Formation represents piedmont sediments derived from an uplifted area to the west which was caused by the Laramide Orogeny. This formation is a large remnant of a large alluvial apron of late Tertiary age. Many geologists believe that the Ogallala once extended over much of Oklahoma.

Since Tertiary time, erosion has been the dominant geologic activity in Oklahoma. However, thick terrace deposits and floodplain deposits exist along present-day rivers. The great thickness of these terrace deposits resulted from the large water supply and sediment load which were derived from the Rocky Mountains during the cyclic glacial and interglacial periods in North America.

Surficial Geology

The Elk City Aquifer is defined by the continuous outcrop of the Elk City Sandstone in western Oklahoma. The initial geologic map used in this study was a combination of maps by Smith (1964) and Richardson (1970). Modification of these maps were based on field work and on soils maps of Washita and Beckham Counties. The natural and computer boundaries of the Elk City Aquifer are shown on Plate 1.

The Elk City and Doxey Formations were originally combined into the Quartermaster Formation by Gould in 1902. The Quartermaster Formation was later divided on a lithological basis (Fig. 5).

The Doxey Shale underlies the Elk City Sandstone. It consists of blocky, maroon shale and maroon siltstone. The resistant siltstone caps

Fig. 5--Contact of the Elk City Sandstone (above) and the Doxey Shale (below) in Sec. 3, T11N, R22W.

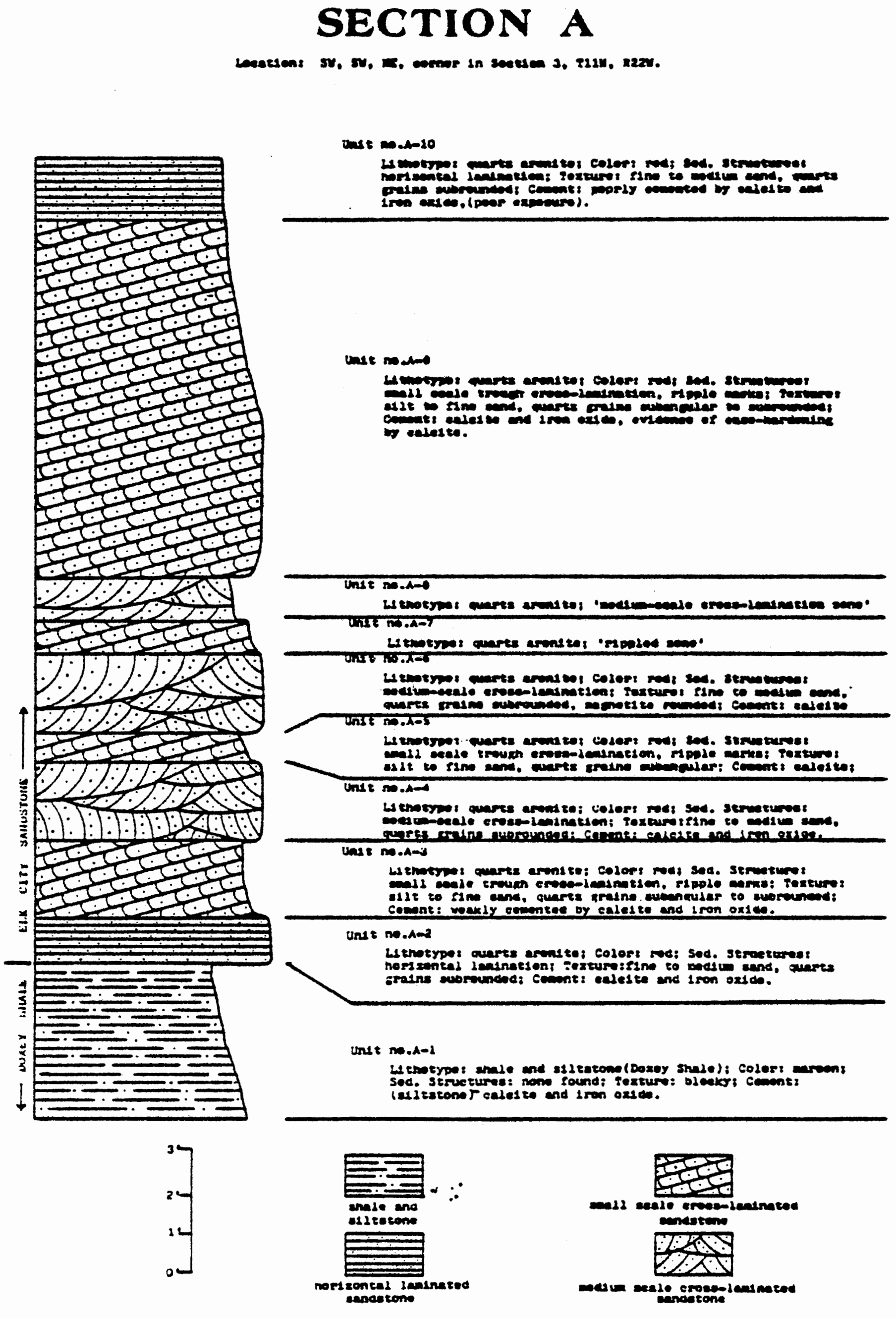
hills which form an undulating topography where the Doxey Shale outcrops. The thickness of the formation ranges from 160 to 195 ft.

The Elk City Sandstone represents the uppermost Permian unit in the Anadarko Basin, and is the main lithologic unit of the aquifer under study. Earlier reports have indicated a maximum thickness of 220 ft. for the Elk City Sandstone. A maximum thickness of 260 ft. was noted in the northeast part of the study area using well data.

The Elk City Sandstone ranges in grain size from clay to cobble size, with fine-grained sand dominating most of the lithological units in the formation. The detrital grains are predominantly quartz, with small amounts of zircon, garnet, tourmaline, rutile, mica, and magnetite. Cobble-size intraformational clay clasts have been found in some of the basal units of the sandstone.

The Elk City is a very friable sandstone, being lightly cemented by clay, calcite, gypsum and/or iron oxide. The iron oxide gives the formation a reddish color. Due to its friable property, the sandstone is very erodable; thus, only a few good outcrops of the sandstone can be found.

In order to typify the petrologic characteristics and to interpret the environment of deposition of the Elk City, two closely spaced stratigraphic sections are described. These stratigraphic sections are used to show areal and vertical relationships within the sandstone. The area of the described sections is located in a roadcut in the SW¼ SW¼ NE¼ of Section 3, T11N and R22W. The measured sections are shown in Figures 6 and 7. They are approximately 120 ft. apart and both represent the basal units of the Elk City Sandstone. The lithologies and sedimentary structures are quite different in the sections of A and B.



SECTION A

Location: SW, SW, NE, corner in Section 3, T11N, R22W.

Unit no.A-10

Lithotype: quartz arenite; Color: red; Sed. Structures: horizontal lamination; Texture: fine to medium sand, quartz grains subrounded; Cement: poorly cemented by calcite and iron oxide,(poor exposure).

Unit no.A-9

Lithotype: quartz arenite; Color: red; Sed. Structures: small scale trough cross-lamination, ripple marks; Texture: silt to fine sand, quartz grains subangular to subrounded; Cement: calcite and iron oxide, evidence of case-hardening by calcite.

Unit no.A-8

Lithotype: quartz arenite; 'medium-scale cross-lamination zone'

Unit no.A-7

Lithotype: quartz arenite; 'rippled zone'

Unit no.A-6

Lithotype: quartz arenite; Color: red; Sed. Structures: medium-scale cross-lamination; Texture: fine to medium sand, quartz grains subrounded, magnetite rounded; Cement: calcite

Unit no.A-5

Lithotype: quartz arenite; Color: red; Sed. Structures: small scale trough cross-lamination, ripple marks; Texture: silt to fine sand, quartz grains subangular; Cement: calcite;

Unit no.A-4

Lithotype: quartz arenite; Color: red; Sed. Structures: medium-scale cross-lamination; Texture:fine to medium sand, quartz grains subrounded; Cement: calcite and iron oxide.

Unit no.A-3

Lithotype: quartz arenite; Color: red; Sed. Structure: small scale trough cross-lamination, ripple marks; Texture: silt to fine sand, quartz grains subangular to subrounded; Cement: weakly cemented by calcite and iron oxide.

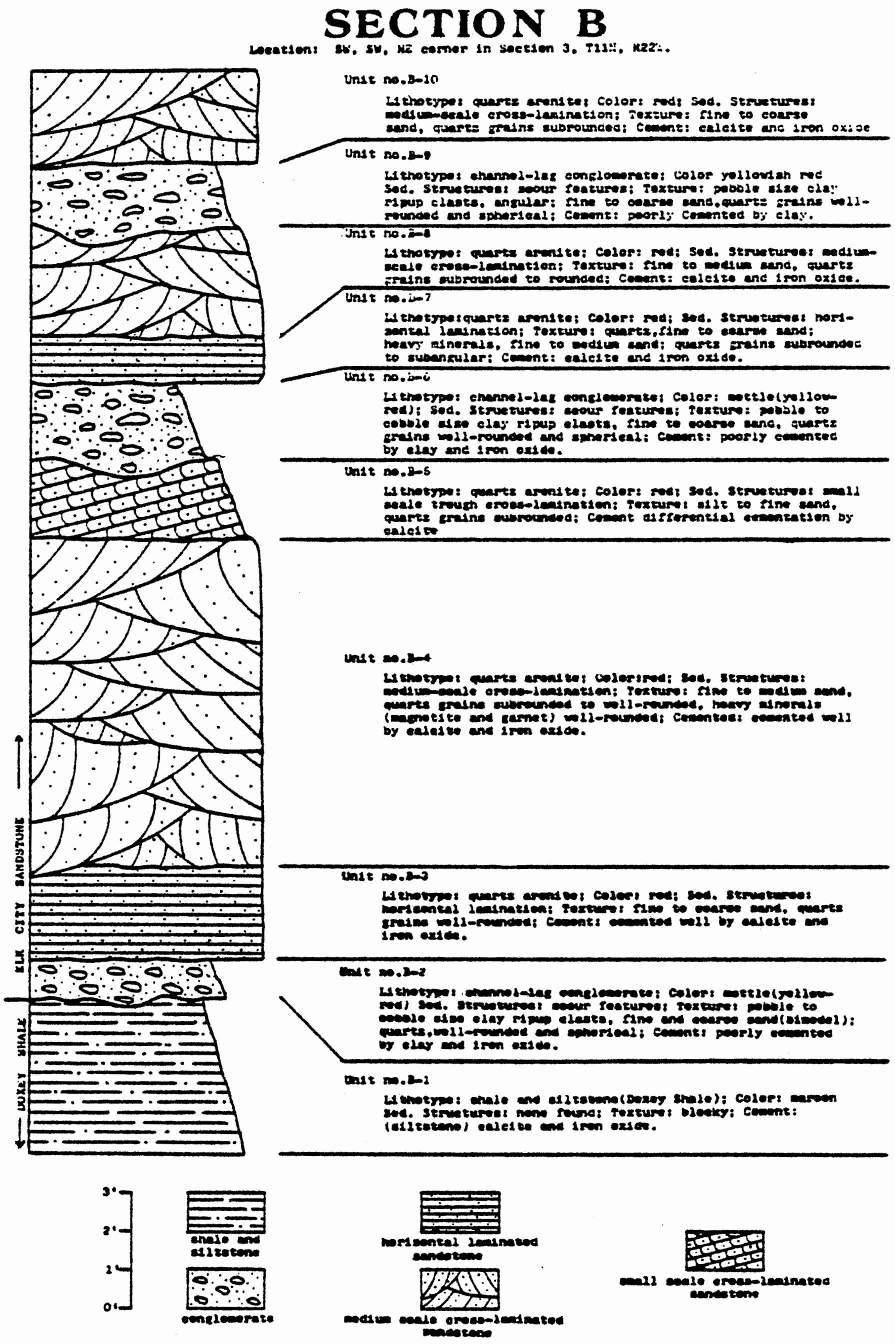
Unit no.A-2

Lithotype: quartz arenite; Color: red; Sed. Structures: horizontal lamination; Texture:fine to medium sand, quartz grains subrounded; Cement: calcite and iron oxide.

Unit no.A-1

Lithotype: shale and siltstone(Doxey Shale); Color: maroon; Sed. Structures: none found; Texture: blocky; Cement: (siltstone)" calcite and iron oxide.

Fig. 6--Stratigraphic measured section description (section A).



SECTION B

Location: SW, SW, NE corner in Section 3, T11N, R22W.

Unit no.B-10

Lithotype: quartz arenite; Color: red; Sed. Structures: medium-scale cross-lamination; Texture: fine to coarse sand, quartz grains subrounded; Cement: calcite and iron oxide

Unit no.B-9

Lithotype: channel-lag conglomerate; Color yellowish red Sed. Structures: scour features; Texture: pebble size clay ripup clasts, angular; fine to coarse sand, quartz grains well-rounded and spherical; Cement: poorly Cemented by clay.

Unit no.B-8

Lithotype: quartz arenite; Color: red; Sed. Structures: medium-scale cross-lamination; Texture: fine to medium sand, quartz grains subrounded to rounded; Cement: calcite and iron oxide.

Unit no.B-7

Lithotype:quartz arenite; Color: red; Sed. Structures: horizontal lamination; Texture: quartz,fine to coarse sand; heavy minerals, fine to medium sand; quartz grains subrounded to subangular; Cement: calcite and iron oxide.

Unit no.B-6

Lithotype: channel-lag conglomerate; Color: mottle(yellow-red); Sed. Structures: scour features; Texture: pebble to cobble size clay ripup clasts, fine to coarse sand, quartz grains well-rounded and spherical; Cement: poorly cemented by clay and iron oxide.

Unit no.B-5

Lithotype: quartz arenite; Color: red; Sed. Structures: small scale trough cross-lamination; Texture: silt to fine sand, quartz grains subrounded; Cement differential cementation by calcite

Unit no.B-4

Lithotype: quartz arenite; Color:red; Sed. Structures: medium-scale cross-lamination; Texture: fine to medium sand, quartz grains subrounded to well-rounded, heavy minerals (magnetite and garnet) well-rounded; Cementes: cemented well by calcite and iron oxide.

Unit no.B-3

Lithotype: quartz arenite; Color: red; Sed. Structures: horizontal lamination; Texture: fine to coarse sand, quartz grains well-rounded; Cement: cemented well by calcite and iron oxide.

Unit no.B-2

Lithotype: channel-lag conglomerate; Color: mottle(yellow-red) Sed. Structures: scour features; Texture: pebble to cobble size clay ripup clasts, fine and coarse sand(bimodal); quartz,well-rounded and spherical; Cement: poorly cemented by clay and iron oxide.

Unit no.B-1

Lithotype: shale and siltstone(Doxey Shale); Color: maroon Sed. Structures: none found; Texture: blocky; Cement: (siltstone) calcite and iron oxide.

Fig. 7--Stratigraphic measured section description (section B).

Section A is composed mostly of fine sand and silt with very few coarser-grained particles. Ripple marks are the dominant sedimentary structure. Section B is much coarser grained. Cobble-sized clay intraformational clasts and coarse sand are found in the basal unit. The section shows a graded sequence of gradually finer sands toward the top and are truncated by another coarse unit. Scour features and medium-scale crossbedding are the most abundant sedimentary structures.

The main depositional environment of the Elk City Sandstone at this location is an alluvial plain environment. The graded sequence and sedimentary structures generally narrow the choice to either an alluvial plain or tidal flat, but the lack of bioturbation and lack of bimodal crossbedding is an indication of an alluvial rather than tidal environment (Potter, 1967).

A and B represent two types of alluvial plain depositional environments. Section A represents levee deposits with ripple fine-grained material. The coarser-grained sediments in section B represents a point bar sequence. In other areas, the environment of deposition of the Elk City has been interpreted as being of tidal flat and deltaic origin (Al-Shaieb and Shelton, 1976). Clearly the Elk City Sandstone may have been laid down in a variety of environments.

The source of the detrital grains appears to be reworked sedimentary rocks. The clay ripup clasts appear to be derived from the underlying Doxey Shale. Lag deposits of well-rounded, coarse sand grains are found with the ripup clasts in the channel. The fact that the grains are so well rounded indicates a reworking of the sediments. The absence of feldspar grains is further evidence of reworking.

Two types of unconsolidated sediments overlie parts of the Elk City

Sandstone. Sediments of Pliocene age are found in the western half of the study area. In the eastern half (part B), Quaternary terrace deposits and stabilized sand dunes overlie the Elk City Sandstone and have been mapped by Richardson (1970). The Pliocene sediments are composed of sand and weakly cemented sandstone. The maximum thickness of these deposits is approximately 170 ft. The age of these sediments was determined by Kitt (1959) on the basis of correlation with known Pliocene beds and fossil evidence. The deposits are lithological and time-equivalent to the unconsolidated sediments in the Ogallala Formation found northwest of the study area. The terrace sediments include undifferentiated terrace deposits, silt-terrace deposits and sand-terrace deposits. The silt-terrace deposits consist of clay and silt, while the sand terraces are made of multicolored sands and gravels. A remnant of a buried channel exists in the central area (Palmquist, 1964). The buried channel trends south-southeast and is filled with alluvial deposits. The deposits in the buried channel reach a maximum thickness of 65 ft. The overall average thickness of the terrace deposits is between 10 and 15 feet. The sand dunes are stabilized by vegetation and consist of aeolian sand.

In order to describe the boundaries of the aquifer, a structure contour map was mapped at the base of the Elk City Sandstone. Water well data, provided by the Oklahoma Water Resources Board, and a surface structure map by Zabawa (1976) were used to develop the structure contour maps shown in Plate 1.

The evidence given by Zabawa (1976) for the age of faulting in the area is listed in Figure 8. Other evidence that supports a late age of faulting are the inferences drawn from the distribution of structure

AGES OF FAULTING		
AGE	QUALITY OF EVIDENCE	NATURE OF EVIDENCE
Pleistocene	Good	1. Down-dropped block of Pliocene 2. Fractures filled with early Pleistocene material
Tertiary	Good	1. Down-dropped block of Pliocene
Cretaceous	Poor	1. Fractures filled with possible lower Cretaceous material
Permian	Poor	1. Fractures filled with Cloud Chief material

Fig. 8--Ages of faulting of surface beds (Zabawa, 1976).

contours based only on well data. Without using Zabawa's (1976) mapped faults, the structure contour map appeared to represent a series of tight folds; however, when faults are assumed, a gently-plunging faulted syncline is apparent. The structure contour map, which represents the occurrence of faults, appears to fit the generally accepted geology of the area. Therefore, the major faults mapped by Zabawa (1976) were used to construct the structure contour maps at the base of the Elk City Sandstone.

CHAPTER IV

HYDROGEOLOGY

General

The Elk City Aquifer is an unconfined aquifer. The Elk City Sandstone is located in the area along the northwest-trending divide between the Washita and Red River basins, and forms a topographic high. The underlying Doxey Shale serves as an aquiclude; the impermeable nature of the Doxey prevents a downward loss of water and restricts available ground water to the overlying sandstone.

Due to its high topographic position, a series of springs and seeps occur at the contact of the Elk City Sandstone and Doxey Shale. The water lost from seeps and springs reduces the saturated thickness of the Elk City Sandstone around the edge of the aquifer.

Water Table

The upper boundary of the Elk City Aquifer is formed by the water table shown in Plate 2. The water table generally follows the topography of the area. The water table gradient is generally low except near the edges where seeps and springs are associated with steeper gradients.

Climate

The area is characterized by a semi-arid climate. The mean annual temperature at Burns Flat is 58.8°F. and the frost-free period averages about 200 days a year (Palmquist, 1964). Precipitation varies within the study area. Average monthly and yearly precipitation for the cities of Sayre, Elk City, and Clinton are shown in Table I. Precipitation amounts decline westward. The main months of precipitation in the area are May, June, July and October.

Land Use and Irrigation

The upland plains in the study area are used mostly for raising cotton and wheat. The soils covering the edges of the uplands and the dissected lowlands are considerably less productive and are used for pasture (Palmquist, 1964). The few irrigation wells found in the area are mostly used to irrigate cotton in June, July, August and September. Some wells in the study area are used for municipal water supply.

Surface Recharge

The ground-water aquifer is recharged mainly by precipitation in the area. Recharge will vary depending upon many factors which affect rainfall and evapotranspiration: rainfall intensity and duration, vegetation, soil type, permeability of unsaturated zone, temperature, wind, topography and depth to water table. Sandy soil in conjunction with flat topography and poor drainage inhibits runoff and enhances infiltration; therefore, a higher percentage of rainfall recharges the aquifer. The recharge from deep percolation of precipitation is estimated to be 14.1 percent of the total rainfall. The estimate is

TABLE I

AVERAGE MONTHLY AND ANNUAL PRECIPITATION (INCHES) FOR THE CITIES OF SAYRE, ELK CITY, AND CLINTON

Time Unit	Sayre	Elk City	Clinton
January	.64	.73	.80
February	.86	1.00	1.06
March	1.17	1.35	1.52
April	2.11	2.33	2.70
May	4.04	4.65	4.80
June	3.57	3.33	3.81
July	2.33	2.41	2.50
August	1.92	2.10	2.97
September	2.25	2.11	2.69
October	2.34	2.30	2.65
November	.89	1.07	1.26
December	.85	.87	1.04
Annual	22.97	24.25	27.08

based on precipitation frequency-magnitude records for the area (Fig. 9). The calculation of recharge percentage is shown on Table II. The amount of rainfall percolating into the aquifer can be calculated by taking the change in water level from the well hydrographs for each storm, and multiplying the amount of change by specific yield. The percent of rainfall that recharges the ground-water reservoir is calculated by dividing the inches of recharge by total rainfall of each storm. The 14.1 percent recharge rate was determined by averaging the recharge rate of each storm.

Subsurface Recharge

A small additional amount of recharge to the aquifer results from subsurface inflow. The location of the inflow is in the northwest corner of the study area where the Ogallala Formation outcrops and is in hydraulic continuity with the Elk City Sandstone (Plate 2). The amount of subsurface inflow from the Ogallala into the Elk City is 9 acre ft. per year, which is negligible when compared to surface recharge.

Natural Recharge

Natural loss of ground water from the aquifer occurs by discharge to streams, springs, and evapotranspiration. Discharge through springs and seeps occur along the contact between the Elk City Sandstone and Doxey Shale. The flow of the springs ranges from less than 1 gpm to as much as 50 gpm (Palmquist, 1964). The rates will vary seasonally due to fluctuations of the water table caused by precipitation changes. Evaporation and transpiration are important factors to be considered

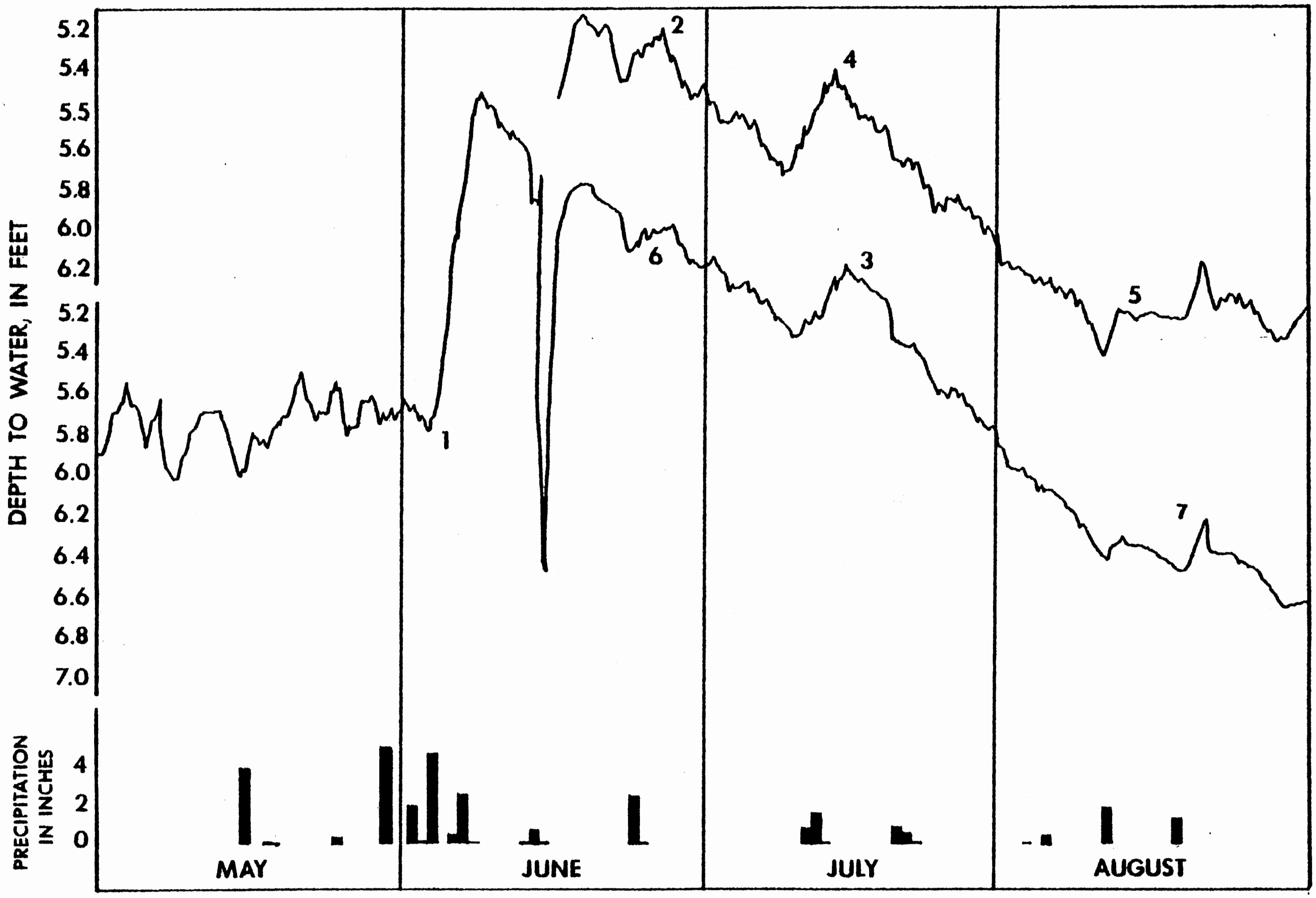


Fig. 9--Precipitation and associated well hydrographs in Sec. 11 and 17, T10N, R19W.

TABLE II

CALCULATION OF THE PERCENT OF RAINFALL THAT GOES TO GROUND-WATER RECHARGE

Storm Event#	Change in Water Table (Inches)		Average Specific Yield (SY)		Gross Inches of Rainfall as Recharge		Total Rainfall of Storm (Inches)		Percent of Rainfall as Recharge
1	18.00	x	.21	=	3.78	÷	15.4	=	24.5%
2	1.32	x	.21	=	.28	÷	2.4	=	11.6%
3	2.4	x	.21	=	.50	÷	3.0	=	16.8%
4	2.64	x	.21	=	.55	÷	3.0	=	18.5%
5	1.44	x	.21	=	.30	÷	3.0	=	10.1%
6	1.08	x	.21	=	.27	÷	3.0	=	7.6%
7	1.08	x	.21	=	.23	÷	2.4	=	9.5%
Mean									14.1%

for a shallow water table aquifer in a semi-arid climate. These two factors have been combined together because of the difficulties in computing transpiration alone. Evapotranspiration will be included in total discharge.

A recharge-discharge equilibrium has been established in the aquifer. In referring to the data on the water table map (Pl. 2), it is noted that a negligible change in water levels has occurred since 1964. When recharge is high due to high rainfall, discharge is increased proportionally along the seeps and springs near the edge of the aquifer. It is assumed that this equilibrium will be maintained unless the aquifer is stressed by pumping. Existing pumping appears to have a negligible affect on the equilibrium.

Permeability

The aquifer includes three major types of lithological units: the Elk City Sandstone, Ogallala sands and gravels, and Quaternary terrace and sand dune deposits. These units have been described in Chapter III.

The Elk City Sandstone composes the major part of the aquifer. This fine-grained sandstone is relatively homogeneous with respect to its grain size. There is a slight variability in its grain size, both vertically and horizontally, in the sandstone. The measured sections in Figures 6 and 7 provide evidence for this variability. The sandstone is primarily friable but some zones are more indurated by calcium carbonate. Laboratory permeabilities range between 0.2 and 24 gpd/ft.^{2}. Field permeabilities were obtained from tests which were conducted by Palmquist (1964). The average field permeability of the Elk City Sandstone is approximately 50 gpd/ft.^{2}. The higher values obtained from the aquifer tests can be explained by the presence of an extensive joint system in the Elk City Sandstone. Jointing can be noted in the sandstone outcrops as shown in Figure 10. The study of the relationship between the concentration of joint patterns and permeability has not been made. Consequently, the Elk City Sandstone is assumed to be a fractured homogeneous aquifer with an average permeability of 50 gpd/ft.^{2}.

The second lithological unit is the Ogallala of Pliocene age and is located in the western half of the study area (Fig. 11). These deposits consist of unconsolidated sand and weakly cemented sandstones. The grain sizes range from fine sand to cobbles. The mean grain size of the deposit is estimated to be medium to coarse sand. The deposits appear to be heterogenous with respect to permeability because of the varying degree of cementation. Permeameter measurements by DeVries and Kent (1973) for the Ogallala Formation in Texas County indicate a range between 150 gpd/ft.^{2} to 835 gpd/ft.^{2}. The U.S. Geological Survey studied similar deposits of the Ogallala Formation in Texas County, Oklahoma. Hydraulic conductivity values for Texas County used by the U.S.G.S. study were determined by Hart, Hoffman, and Gaemaat (1976) and based on aquifer tests and used in a model study of Texas County (Morton, 1980). An average of 750 gpd/ft.^{2} was used in Morton's report and is assumed for the Ogallala occurring in the study area.

The third lithological unit are the Quaternary deposits located in the eastern half of the study area. Most of these deposits are less than 15 ft. thick and are not located in the saturated zone of the aquifer. The only Quaternary deposits found in the saturated zone are the sediments in a buried river channel (Fig. 12). The alluvial deposits in the buried channel consist mostly of unconsolidated sand and silt.

Fig. 10--Jointing found in Elk City Sandstone Sec. 3, T11N R22W.

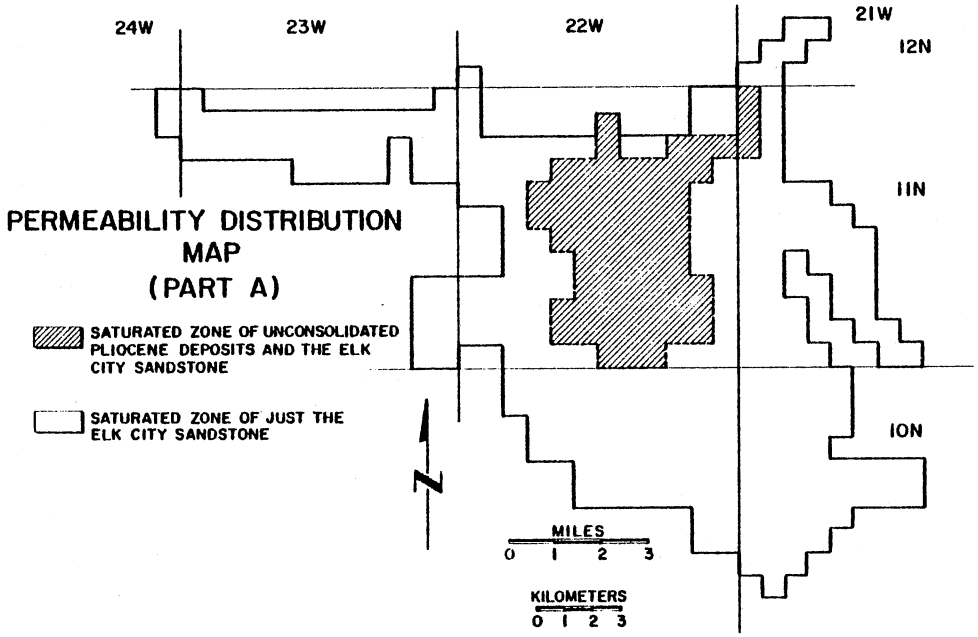


Fig. 11--Location of the Pliocene age deposits.

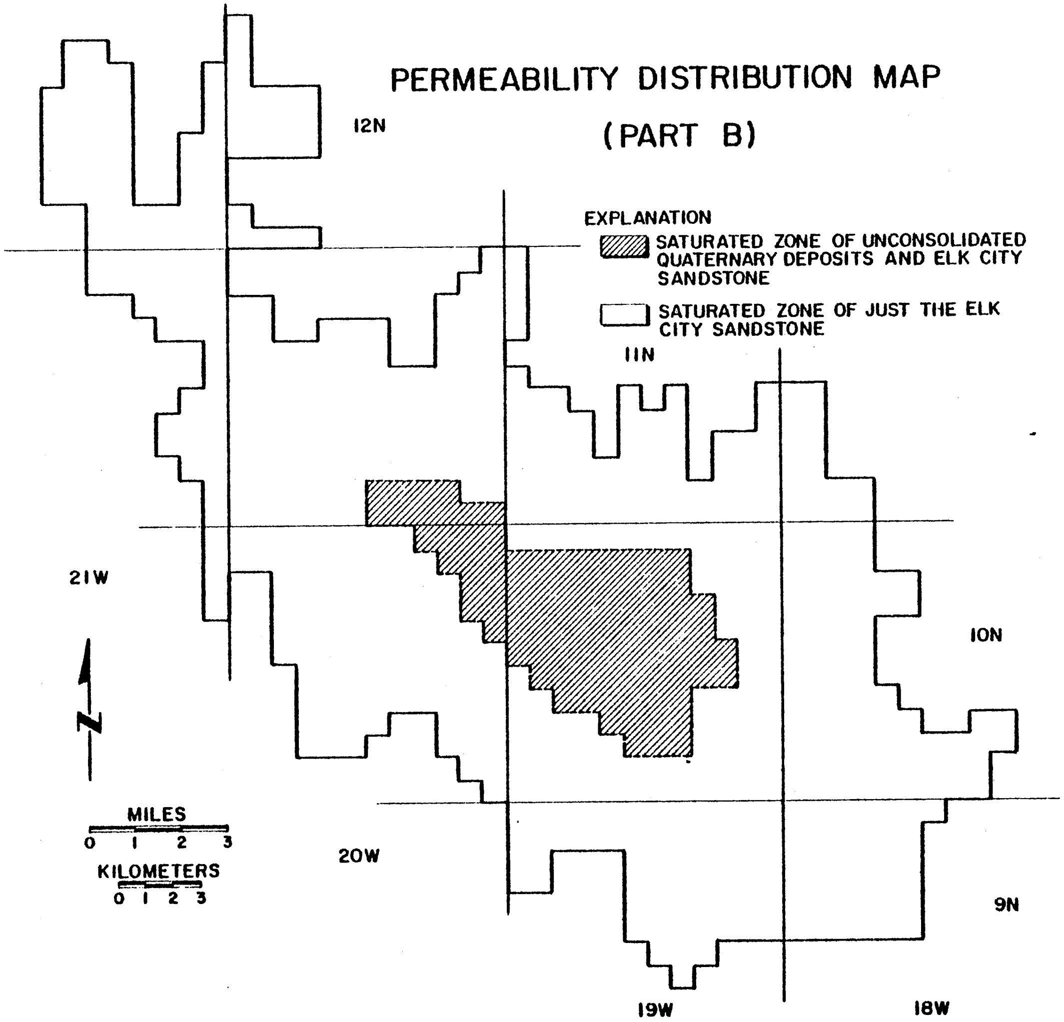


Fig. 12--Location of the buried river channel filled in with Quaternary deposits.

As with most alluvial deposits, the permeability probably varies both vertically and horizontally. With only a few nondescriptive driller's logs, the variable permeability could not be mapped. In the study by Palmquist (1964), a pump test was conducted in the alluvium. A permeability of approximately 500 gpd/ft.^{2} was determined. This value is also used for the saturated Quaternary deposits in the study area.

The last two lithological units, the Pliocene deposits and Quaternary terrace deposits, overlie the Elk City Sandstone. This creates layering of contrasting permeabilities within the aquifer. This change in permeability could result in very small seeps along the contact of the unconsolidated material and the underlying sandstone during the rainy season. A conceptual layered model of the aquifer was used in this study. The methodology and calculation of the conceptual layered approach in the model are discussed in the next chapter.

Water Quality

Planning for development of a water supply requires information on the chemical quality of the water (Palmquist, 1964). The ground-water chemistry depends on the initial rain water quality and the chemical reactions which may occur during downward percolation through the aquifer. The kinds and amounts of dissolved minerals are a function of the rock type and the length of time the water is in contact with those rocks. The ground water may also be subject to contamination from surface pollutants that percolate down into the aquifer.

The mean total dissolved solids (TDS) of the ground water in the Elk City Aquifer is 467 parts per million (ppm). This is based on data from Palmquist (1964) and Al-Shaieb (1980). Moderately high concentrations of calcium (70 ppm) and bicarbonate (321 ppm) were also noted. The Elk City Sandstone is cemented primarily by calcium carbonate ($CaCO_3$) which provides the source for the calcium (Ca^{++}) and bicarbonate (HCO_3^-) ions in the ground water. These concentrations contribute to the relatively high levels of hardness in the ground water.

The mean TDS of 467 ppm of the Elk City Aquifer is considerably lower than what is characterized by ground water in other Permian rocks located in the Anadarko Basin. For example, an average TDS of 1,800 ppm is typical for ground water occurring in the Doxey Shale and Cloud Chief Formation (Al-Shaieb, 1980). The higher values can be attributed to the occurrence of evaporites in the Permian red beds.

A comparison of water quality of the Elk City Sandstone, Rush Spring Sandstone and surface water which occur in the study area is shown in Table III. The quality of the ground water in the Elk City Aquifer and related surface water is very similar. This similarity supports the assumptions that the surface water is recharging the aquifer and that the ground water is leaving the aquifer through the streams in the area as base flow. The higher value of total dissolved solids (TDS) in the Rush Spring Sandstone can be explained by recharge from influent streams which are flowing across the evaporite deposits of the Doxey Shale and Cloud Chief Formation which occur upstream and by the gypsum beds found in the sandstone itself.

Localized pollution may occur from either a nitrate source or brine-water source. Sources of nitrate contamination may be barnyard refuse, sewage, or possibly nitrogen fertilizer applied on agricultural lands (Palmquist, 1964). Sources of brine-water contamination generally occur

TABLE III

COMPARISON OF WATER QUALITY

Occurrence	Average Concentrations (in ppm)					
	TDS	HCO_3	Ca	Na	Cl	SO_4
Elk City Sandstone	467	321	70	30	35	20
Rush Spring Sandstone	1000	-	-	-	21	504
Surface water in the study area	530	340	74	20	40	46

as a result of oil-field operations including salt water injection or of downward percolation of brine water from abandoned mudpits or brine disposal impoundments.

CHAPTER V

COMPUTER MODELING

General

The qualitative aspects of the aquifer have been addressed in the previous chapters. Quantitative values must be assigned to the hydrogeologic parameters of the aquifer in order to model the aquifer within the accuracy of the data used. The quantitative values are either assigned directly by the modeler or generated by the computer model. A value for each hydrogeologic parameter is assigned to each quarter mile section (node) in the aquifer.

The aquifer has been divided into two subareas because of the large areal extent of the aquifer. These subareas will be subsequently referred to as sections A and B (Fig. 3).

The modeling program used in this investigation was originally written by Pinder (1970) and revised by Trescott, Pinder, and Larson (1976). The finite difference model simulates ground-water flow in two dimensions for an artesian aquifer, a water table aquifer or a combination of the two. The water table version was used on the Elk City Aquifer. The program was later modified for a multilayered permeability system. The multilayered approach was used due to the significant differences in permeability caused by the occurrence of different types of sedimentary deposits.

The computer methodology explains the steps used. Steps are shown in Figure 1. The discussion of the mathematical theory is discussed in the publications by Pinder (1970) and Trescott, Pinder, and Larson (1976).

Data Input

Data input refers to all data used in the model. Data are read into the model as either single constants or variables in matrix format. The data which are used as single constants are:

1. Recharge rates from precipitation and irrigation
2. Evapotranspiration rates

Recharge occurs in three forms: precipitation, subsurface inflow and return flow from irrigation.

Initial recharge rate from precipitation was calculated to be 14.1 percent of precipitation (Table II). Precipitation varies east to west. The precipitation recorded at Sayre will be used for the western part (part A) and the precipitation recorded at Clinton will be used for the eastern part (part B). The rainfall data is represented in Table I. The calculated recharge for both areas are:

1. Western part: 22.97 in. x 14.1% = 3.24 in.
2. Eastern part: 27.80 in. x 14.1% = 3.92 in.

These initial values were changed during calibration, which is discussed under calibration. Return flow from irrigation is estimated as 15 percent of the total water pumped and is initially subtracted from the amount of water pumped in the model.

The evapotranspiration rate could not be obtained from hydrogeologic data. Because the aquifer is in a recharge-discharge equilibrium, the evapotranspiration was incorporated in the overall discharge which was finally determined by calibration which is discussed later.

The variable data in matrix form include:

1. Land elevations
2. Water-table elevations
3. Bottom elevations of the aquifer
4. Prior rights pumping
5. Permeability coefficient values
6. Specific yield
7. Constant gradient nodes

An average land elevation was identified for each quarter section and assigned to each node using a 15-minute U.S.G.S. quadrangle topographic maps. Water-table and bottom elevations of the aquifer were assigned to each node using a water-table map (Plate 1) and structure contour map of the base of the Elk City Sandstone (Plate 2), respectively. The computer equivalents of Plate 1 are shown in Figures 13 and 14. The computerized structure contour map of the aquifer bottom are shown in Figures 15 and 16.

Prior rights pumping is the right established by the State of Oklahoma for landowners who have been pumping prior to July 1, 1973 at a rate for which a beneficial use can be shown. Prior rights pumping rates (acre ft./year) were acquired from the Oklahoma Water Board, converted to acre ft./acre/year and assigned to nodes with respect to their quarter-mile location (Figs. 17, 18, 19).

The permeability coefficients of the aquifer consisted of a homogenous value for each of the three major lithological units. The three different permeability units are distributed over the aquifer areally as layers and are shown in Figure 20. Because only two of the three lithological units correspond to one subarea (A or B) at a time (Figs. 9

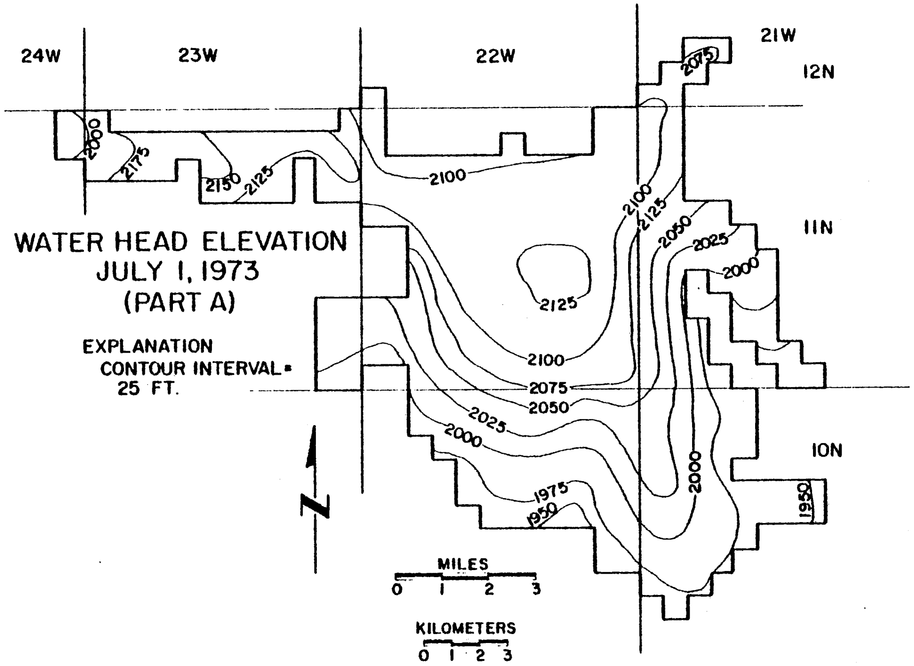


Fig. 13--Contoured (1973) water table map of digitized computer data (Part A).

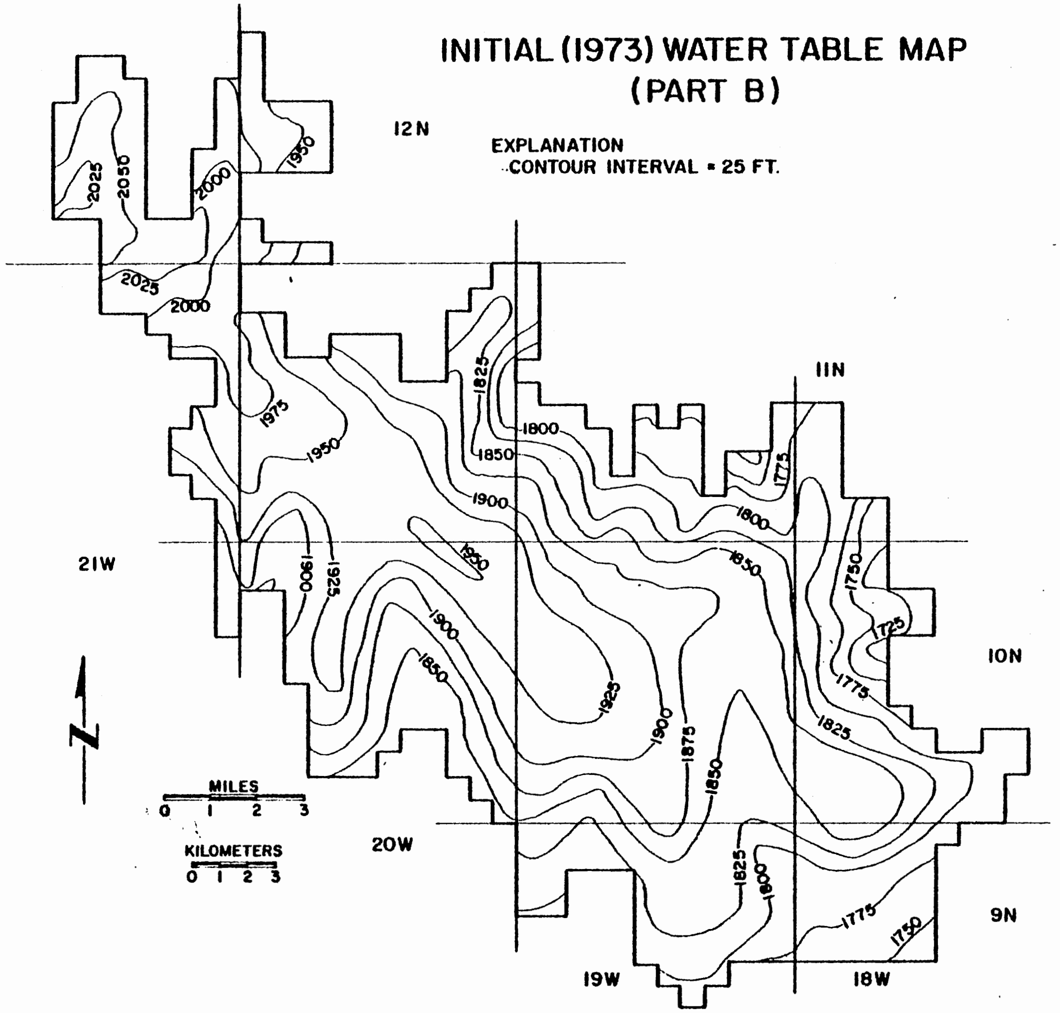


Fig. 14--Contoured (1973) water table map of digitized computer data (Part B).

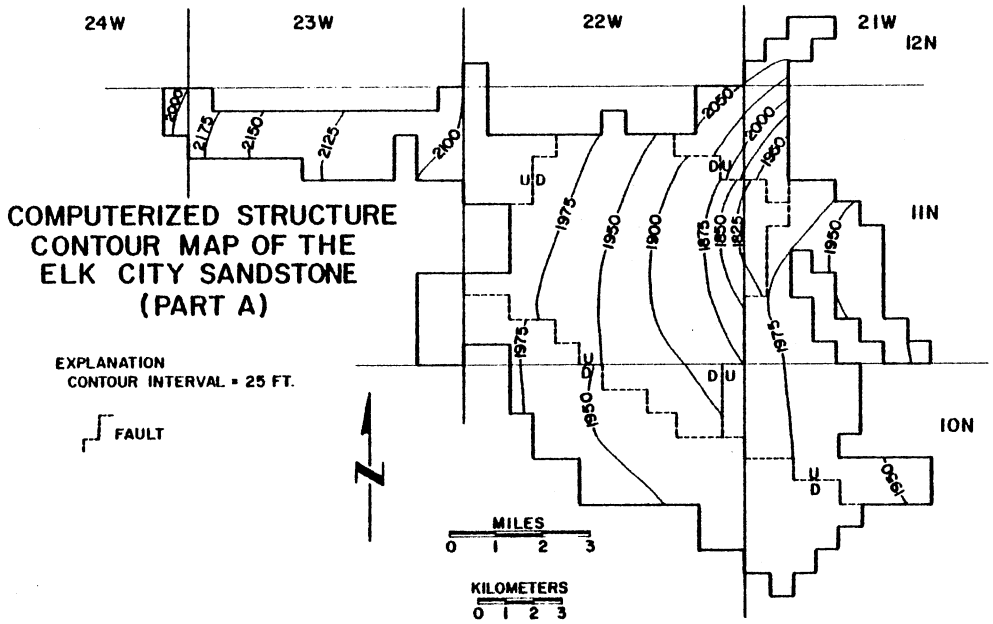


Fig. 15--Computerized structure contour map of the base of the Elk City Sandstone (Part A).

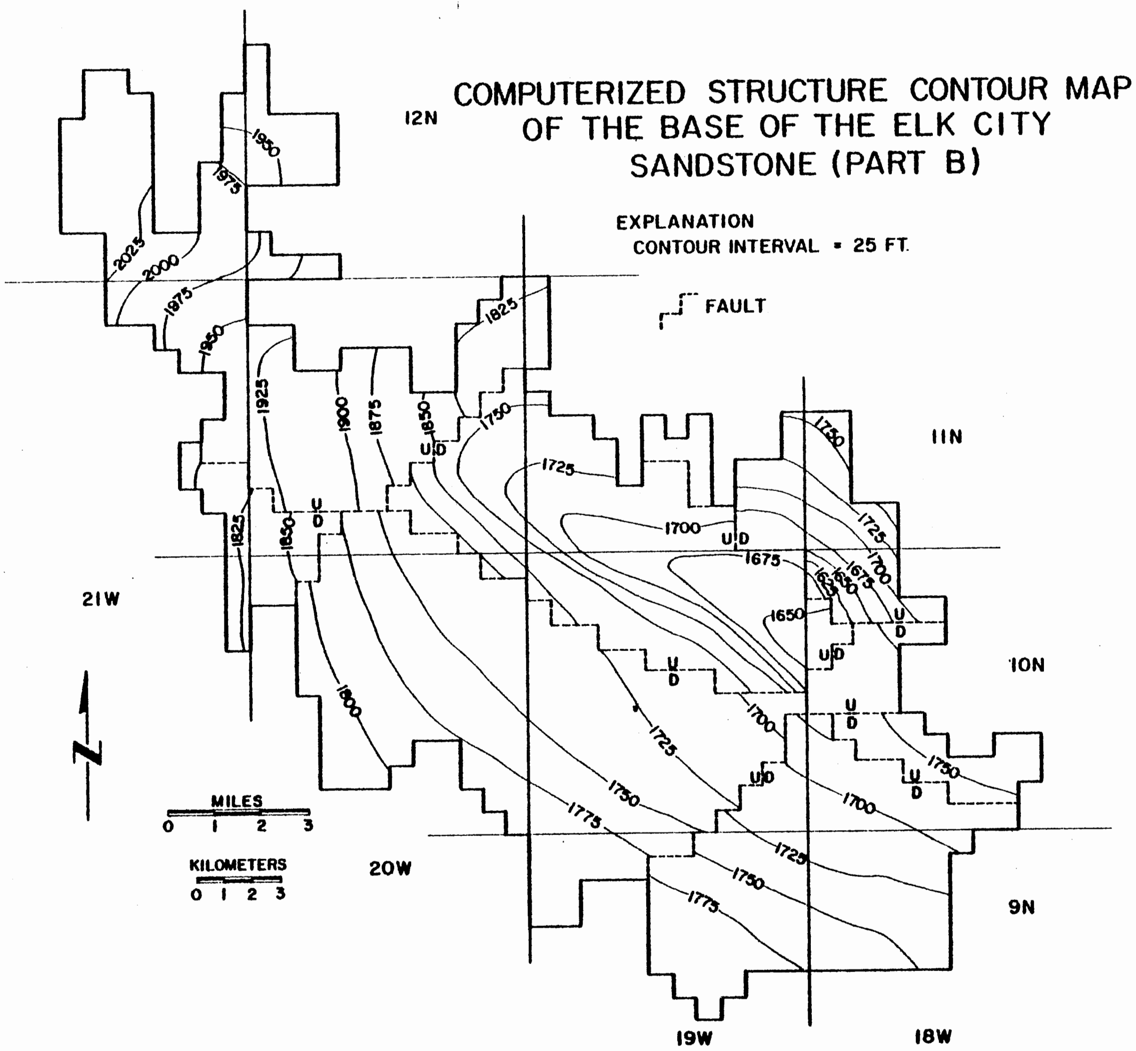


Fig. 16--Computerized structure contour map of the base of the Elk City Sandstone (Part B).

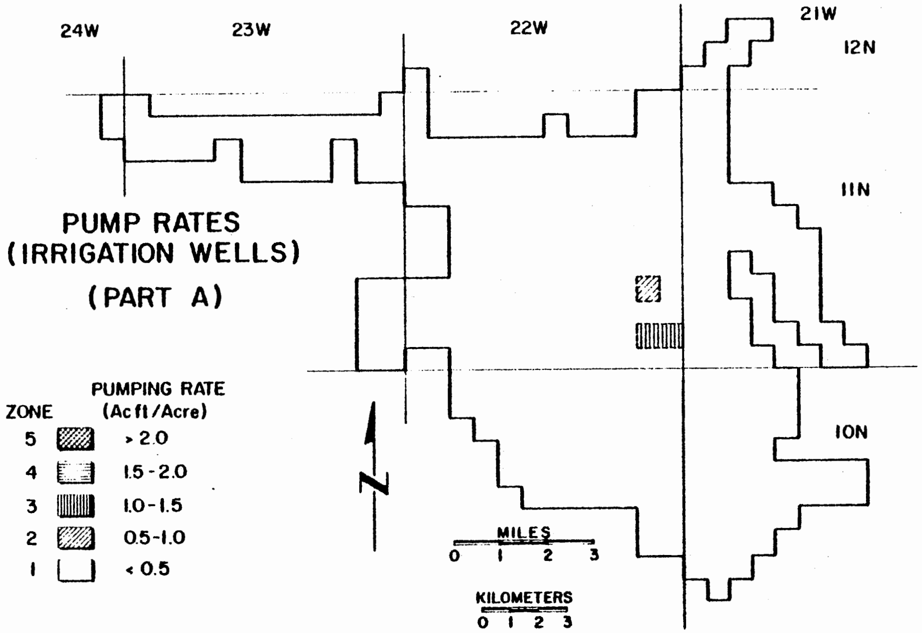


Fig. 17--Prior rights pumping for irrigation (Part A).

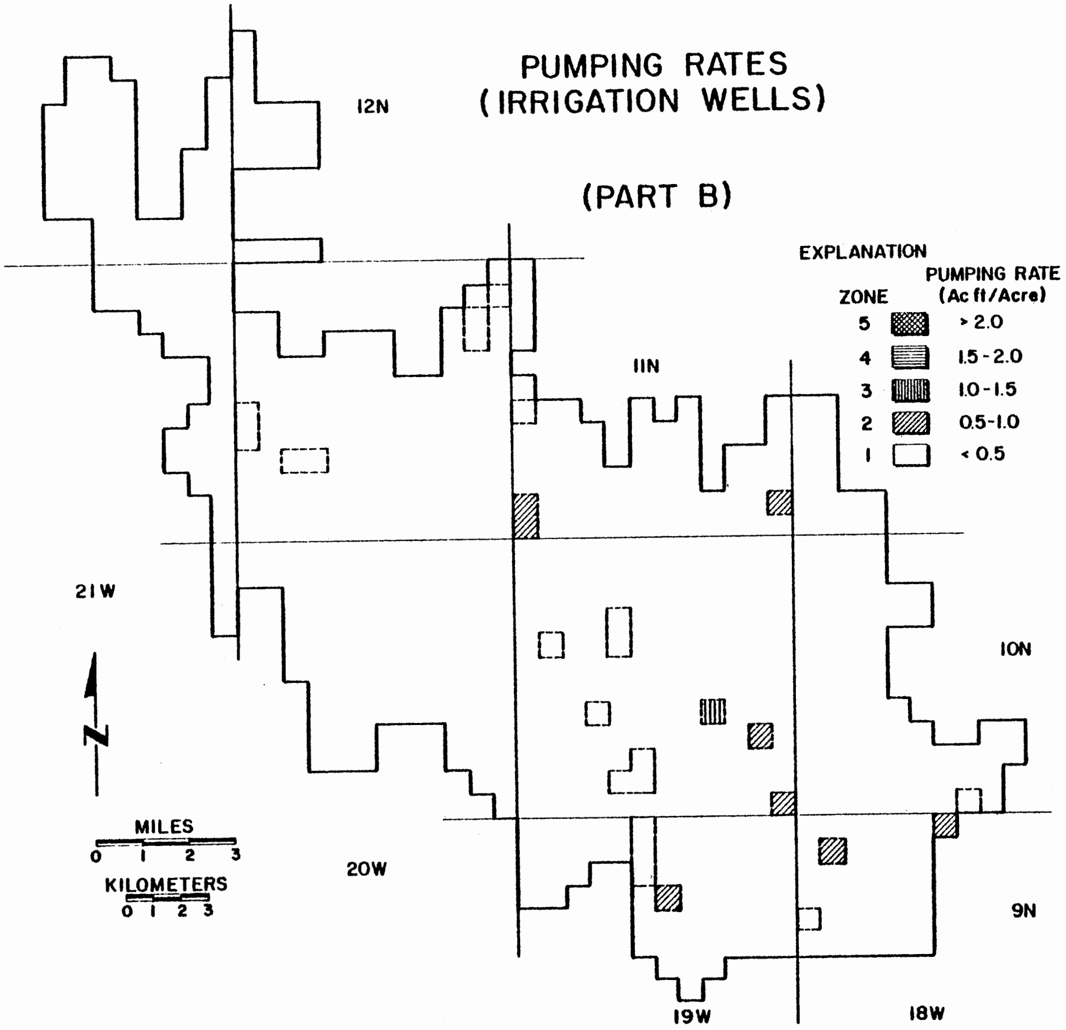


Fig. 18--Prior rights pumping for irrigation (Part B).

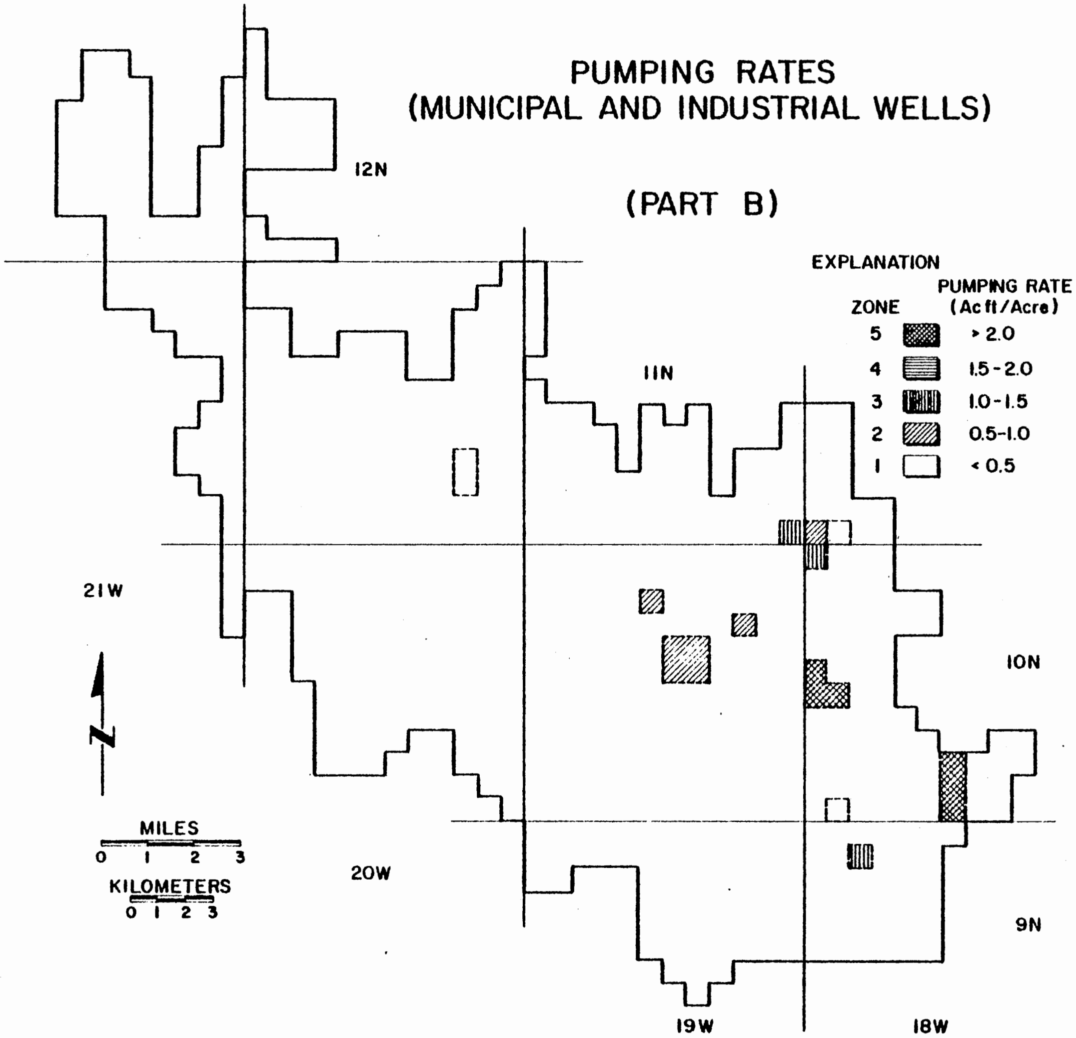


Fig. 19--Prior rights pumping for municipal and industrial use (Part B).

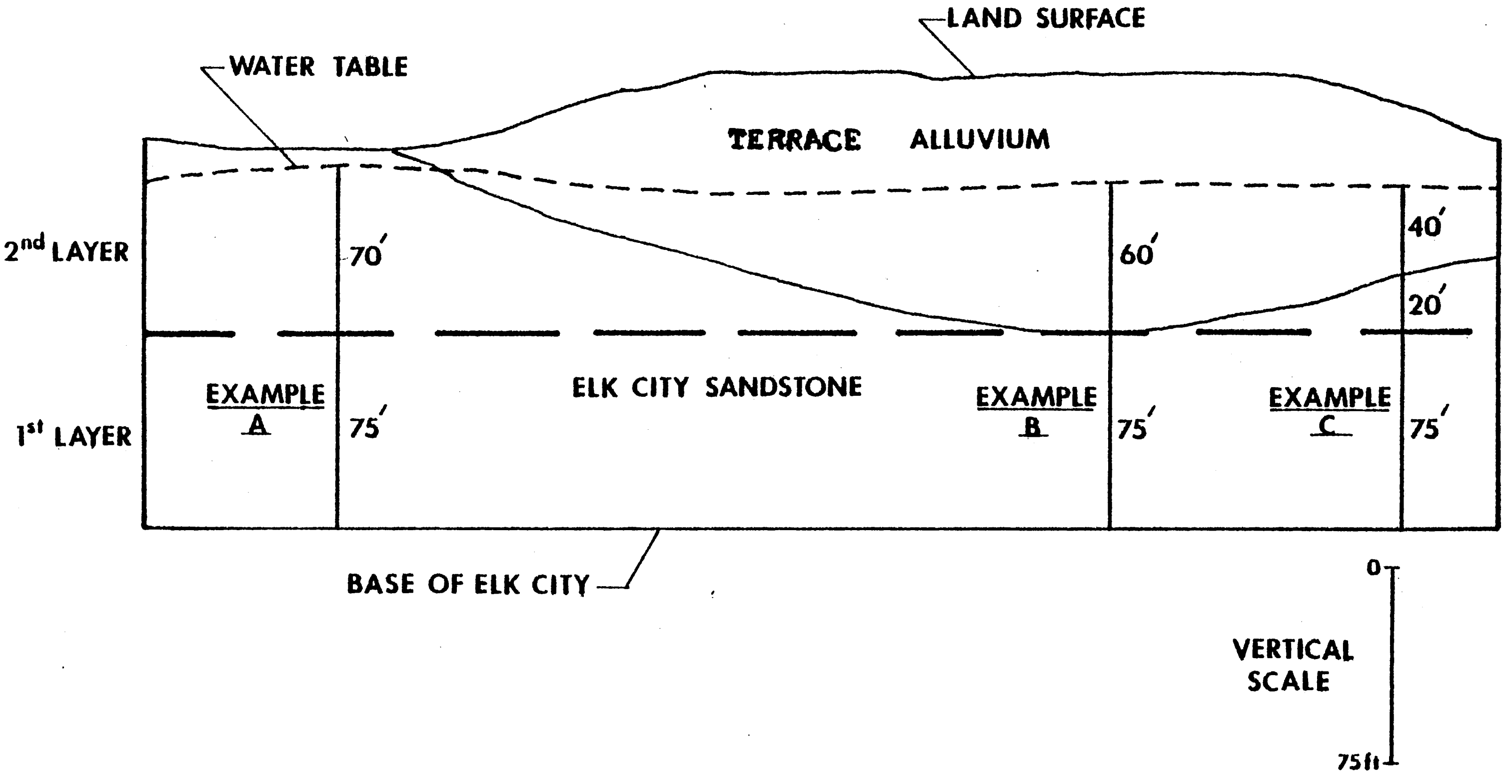


Fig. 20--Representation of layered condition in the study area.

and 10), a two-layer model is needed.

The layered model reference datum is the base of the aquifer. The lower 75 ft. are composed entirely of the Elk City Sandstone throughout the aquifer. A constant permeability of 50 gpd/ft.^{2} is assigned to the first layer. The second layer is characterized by the remaining saturated material and a weighted average permeability is used for each node. Three examples are used to show the calculations of weighted average permeability for the second layer:

Example A in Figure 20

$$70 \text{ ft.} \times 50 \text{ gpd/ft.}^2 \div 70 \text{ ft.} = 50 \text{ gpd/ft.}^2 \qquad (1)$$

Example B in Figure 20

$$60 \text{ ft.} \times 500 \text{ gpd/ft.}^2 \div 60 \text{ ft.} = 500 \text{ gpd/ft.}^2 \qquad (2)$$

Example C in Figure 20

$$\begin{aligned} 40 \text{ ft.} \times 500 \text{ gpd/ft.}^2 \div 60 \text{ ft.} &= 333.33 \text{ gpd/ft.}^2 \qquad (3) \\ &\quad + \\ 20 \text{ ft.} \times 50 \text{ gpd/ft.}^2 \div 60 \text{ ft.} &= \underline{16.67} \text{ gpd/ft.}^2 \\ &\quad 350 \text{ gpd/ft.}^2 \end{aligned}$$

Values of specific yield (Sy) were automatically assigned to each node by computer correlation of the average permeability determined for each layer of each node and the corresponding Sy value from the curve shown in Figure 21.

Constant gradient nodes were used as boundary discharge and subsurface recharge elements and were assigned around the edge of the aquifer. The calculation of the outflow or inflow from the constant gradient is made by the equation:

$$Q = (D) \times (K) \times (I) \qquad (1)$$

where:

Q = the amount of inflow or outflow

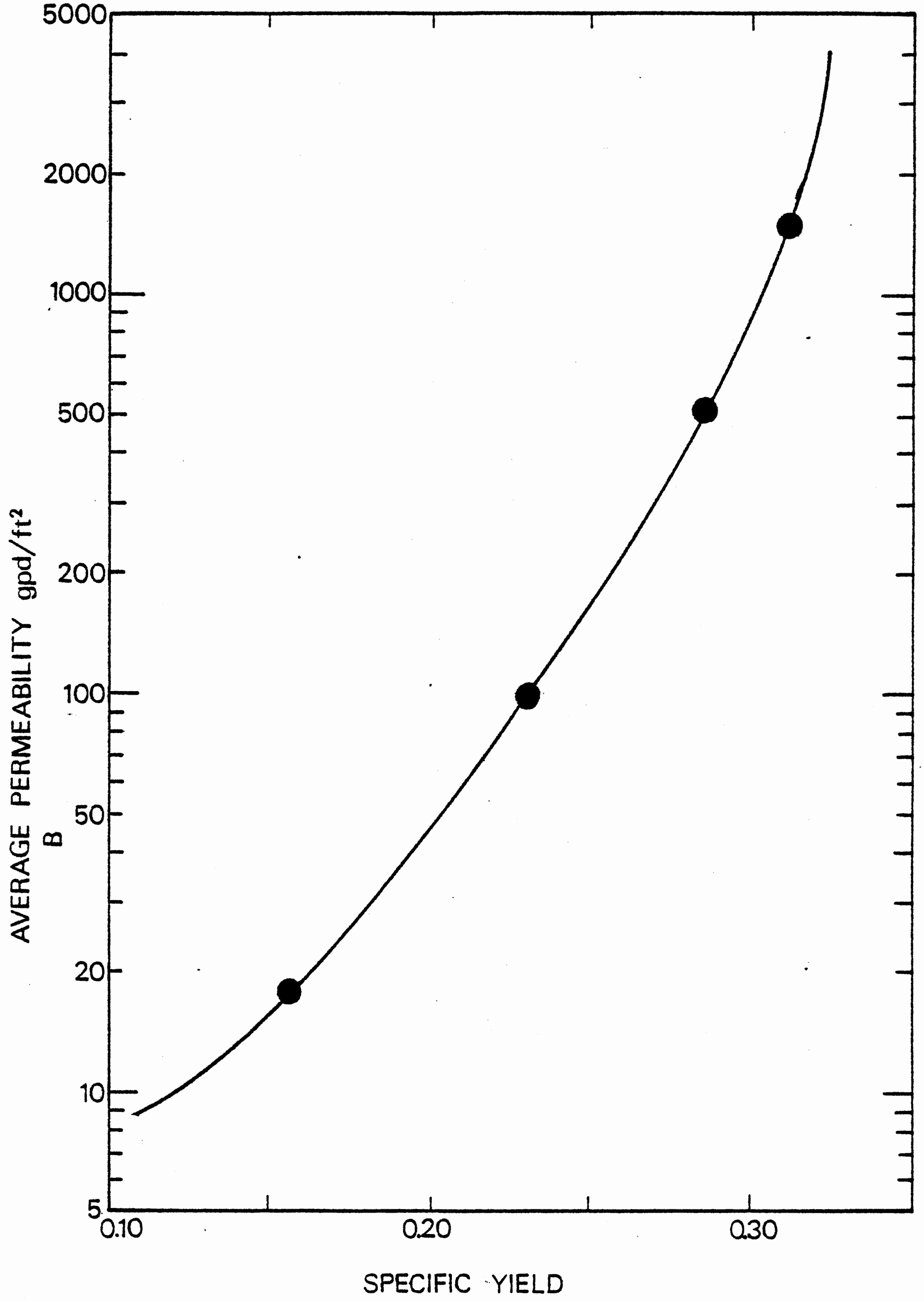


Fig. 21--Relationship between permeability and specific yield (after Kent, 1978).

D = saturated thickness of the adjacent node

K = the permeability of the constant gradient node

I = change in head from constant gradient node to adjacent node

Equation (1) is a form of the Darcy equation; $Q = K(W \times D)(\Delta H \div L)$. The cross sectional width (W) of the node and the distance between centers of nodes (L) are cancelled out when using a square node size.

Data Input Symbols

The symbols used for data input are as follows: QET--evapotranspiration rate; ETDIST--depth (foot) at which evapotranspiration ceases below land surface; ERR--error criteria for convergence of the mathematical solution (0.1 foot); ITMAX--maximum number of iterations per time step (50); NPER--number of the pumping periods (36); NUMT--number of time steps in pump period (assume time step of ten days); TMAX--number of days of the pumping periods(10); DELX--grid spacing in X-direction; and DELY--grid spacing in Y-direction; DIML--number of rows used in the model; and DIMW--number of columns. Other input cards were followed by variables entered as matricies: LAND--elevation of land surface; BOTTOM--elevation at the top of the Doxey Shale; PERM--coefficient of permeability; SY--specific yield; STRT--water-table elevations; QRE--recharge; and WELL--pump rates when pumping is on.

Check Program

All of the matrices are loaded into the computer using an IBM terminal. A check program is used to correct digitizing and contour errors. Saturated thickness is computed by subtracting the bottom elevations from the water table elevations and corresponding maps for quarter-section node (Figs. 22 and 23). Transmissivity is calculated in the model by multiplying the value of permeability of each layer by the saturated thickness of each layer, and then adding the two transmissivities of the two layers (Figs. 24 and 25). If an error exists, such as a negative saturated thickness, a code number will be printed for the following errors:

1. Missing data
2. Land elevation below water-table elevation
3. Land elevation below bottom elevation
4. Water table below bottom elevation
5. Data exceeding a certain value declared by the programmer.

The check program is an easy and efficient way to correct errors that might arise in the data input.

Calibration

In calibrating the two areas (A and B), the main objective was established as recharge-discharge equilibrium. Equilibrium is established when the mass balance shows the inflow and the outflow as being equal and is indicated by negligible fluctuations in the water table elevations. Due to the limited data base, small fluctuations in the water-table elevations were considered negligible due to error inherent in the data base. The study area was calibrated using one-year runs, because the water budget was established on an annual basis.

To calibrate the model, natural recharge and discharge values were adjusted to create an equilibrium in the aquifer. Recharge was initially calibrated by a systematic pattern recharge method. The discharge was then adjusted to establish the recharge-discharge equilibrium.

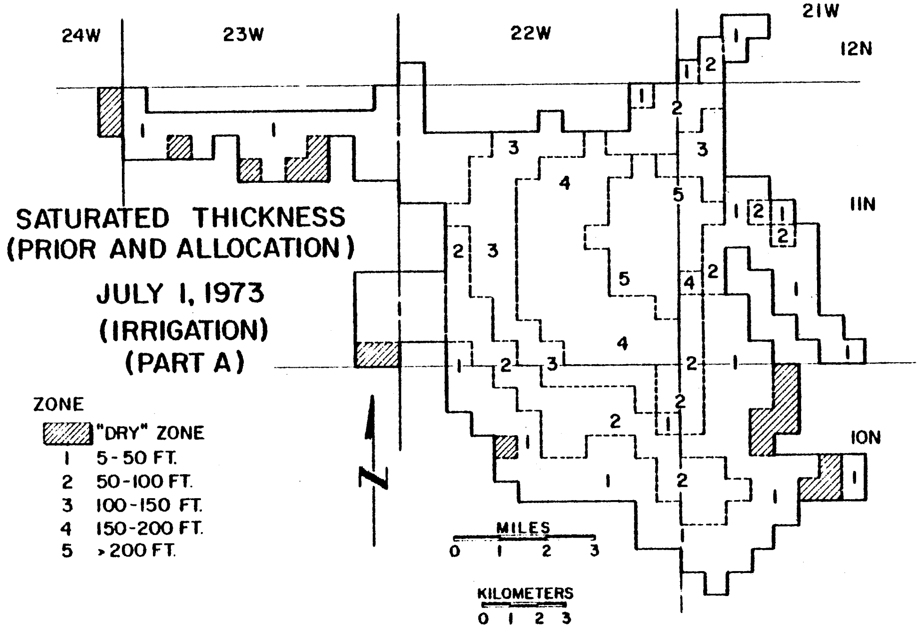


Fig. 22--1973 saturated thickness (Part A).

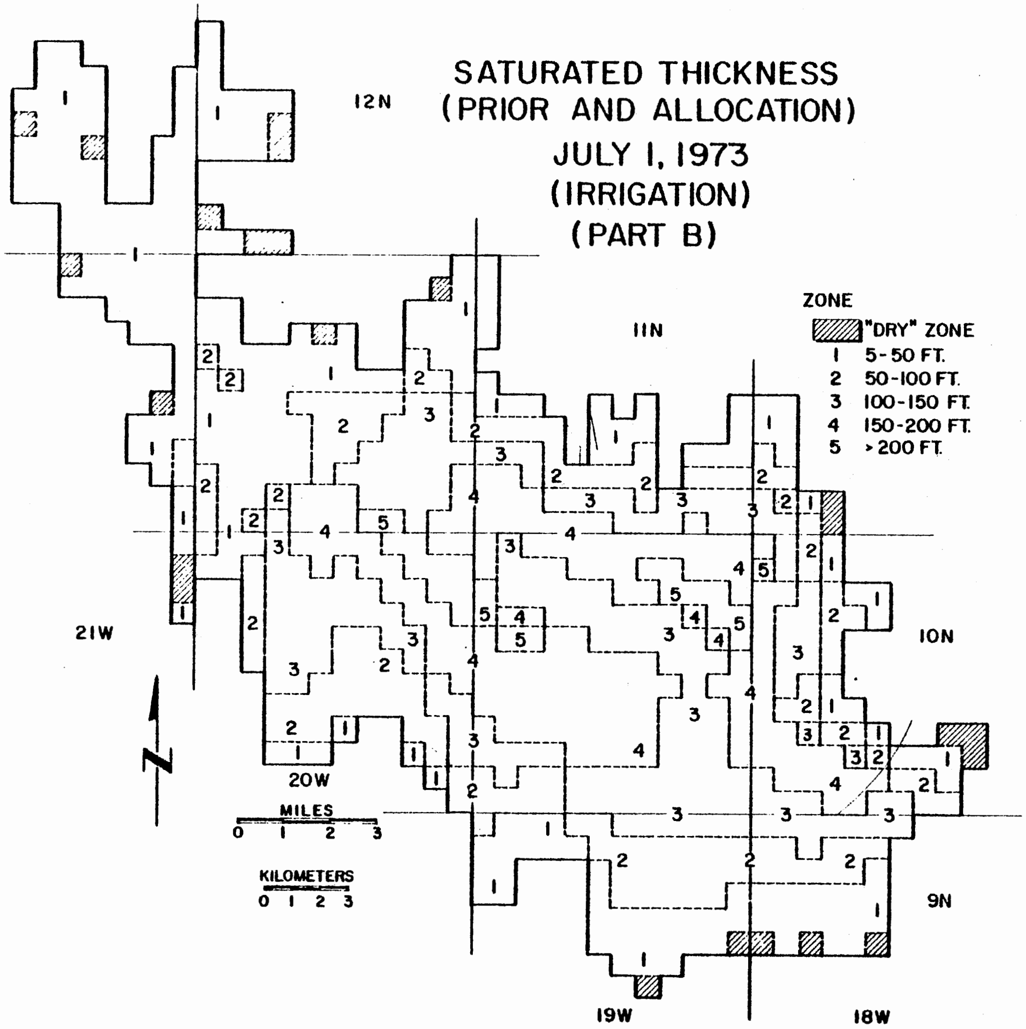


Fig. 23--1973 saturated thickness (Part B).

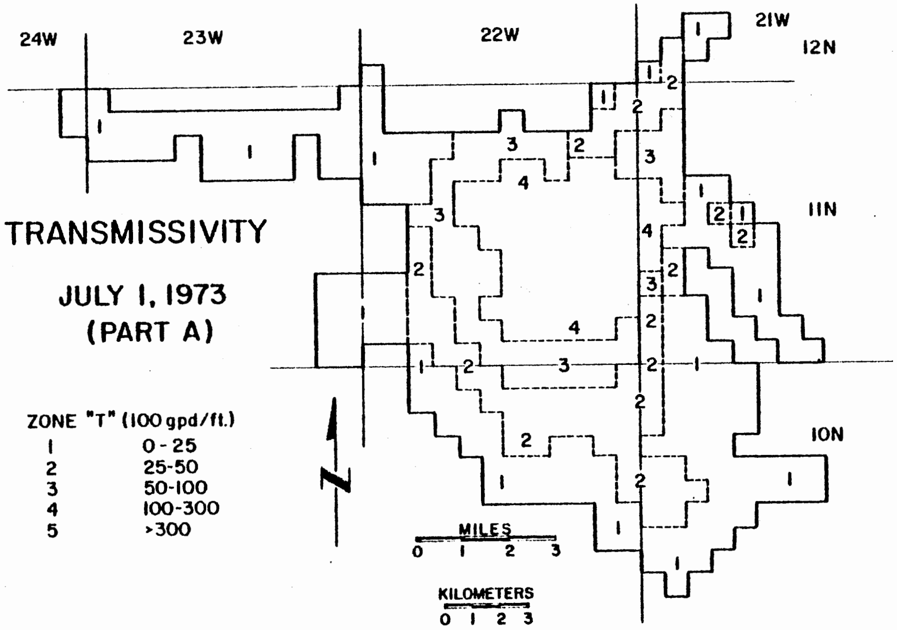


Fig. 24--1973 transmissivity (Part A).

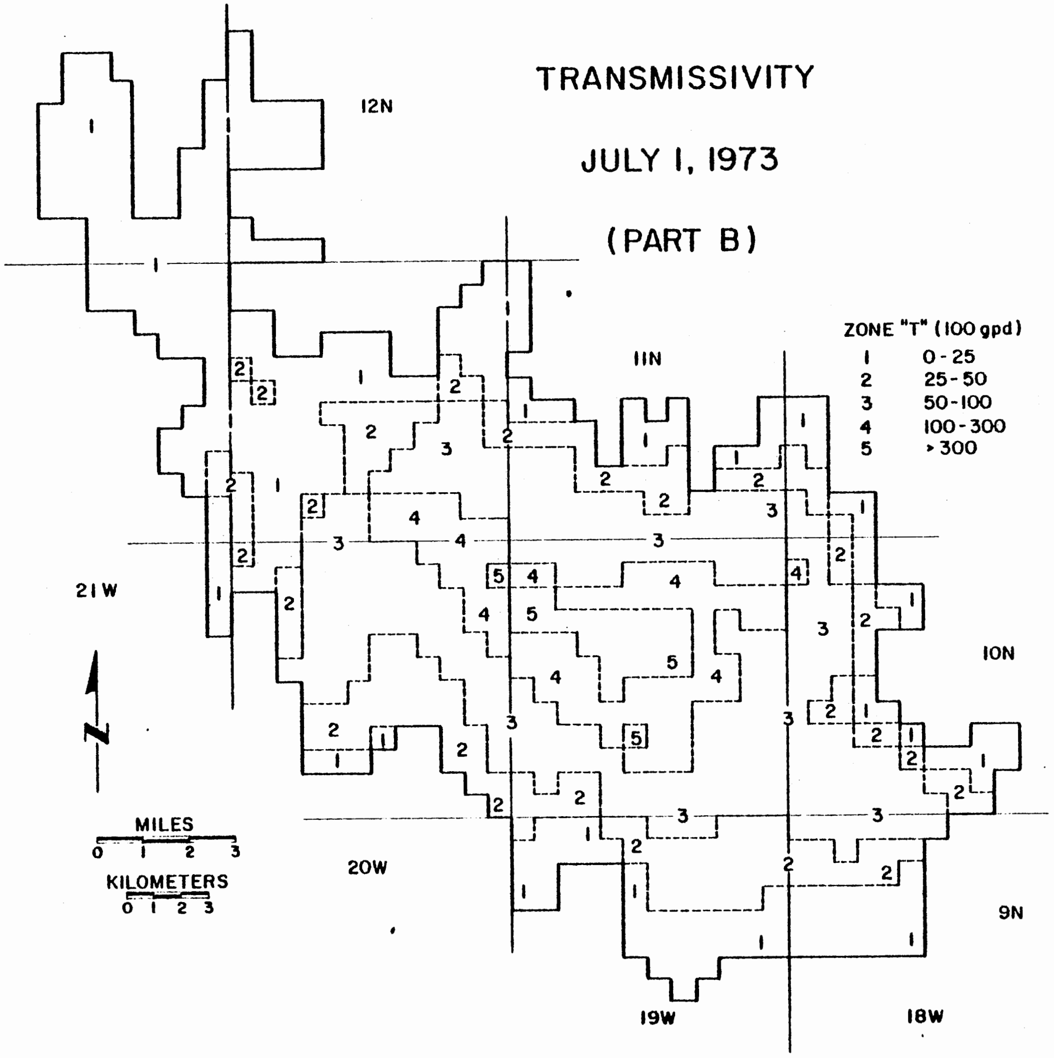


Fig. 25--1973 transmissivity (Part B).

An initial recharge rate was calculated from well hydrographs and precipitation frequency magnitude records (Table II). The natural recharge rate varies due to many factors as described earlier. Refinement of the recharge rate was incorporated in the initial calibration in the form of pattern recharge. Pattern recharge consists of dividing the aquifer into subareas that have relatively the same recharge characteristics. The two main recharge characteristics that were used to develop pattern recharge were soil type and topography. By identifying soil types and drainage within each subarea, quantitative values based on relative percolation rates can be assigned to those subareas.

Two distinct recharge areas are found in part A (Fig. 26). The recharge areas correspond to the lithologic and soil differences in the area (Fig. 9). The Pliocene deposits represent one area and the soil derived from the Elk City Sandstone represent the other area. Due to the flat topography and permeable soils of the Pliocene deposits, a recharge rate which is higher than the initial recharge estimate was assumed. Four inches per year was used for recharge of the subarea where the Pliocene deposits exist. The remaining area (Fig. 26) consisted of better drainage and thinner, less permeable soils. A recharge rate of two inches per year was established. The weighted average of the two recharge rates was the same as the originally assigned values.

Part B is also represented by two recharge areas (Fig. 27). The flat upland Quaternary terrace deposits represent one recharge area. The recharge rate of this area is equivalent to the originally estimated recharge of 14.1 percent of rainfall or 3.92 inches. The other calibrated subarea in part B has the same recharge characteristics as the less permeable area of part A (2 in.). The weighted average of the two

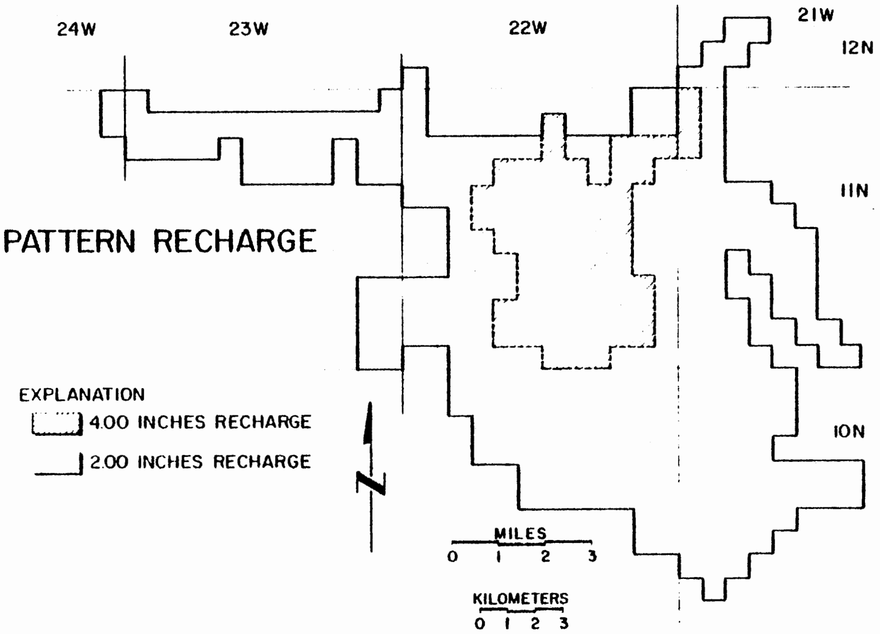


Fig. 26--Pattern recharge (Part A).

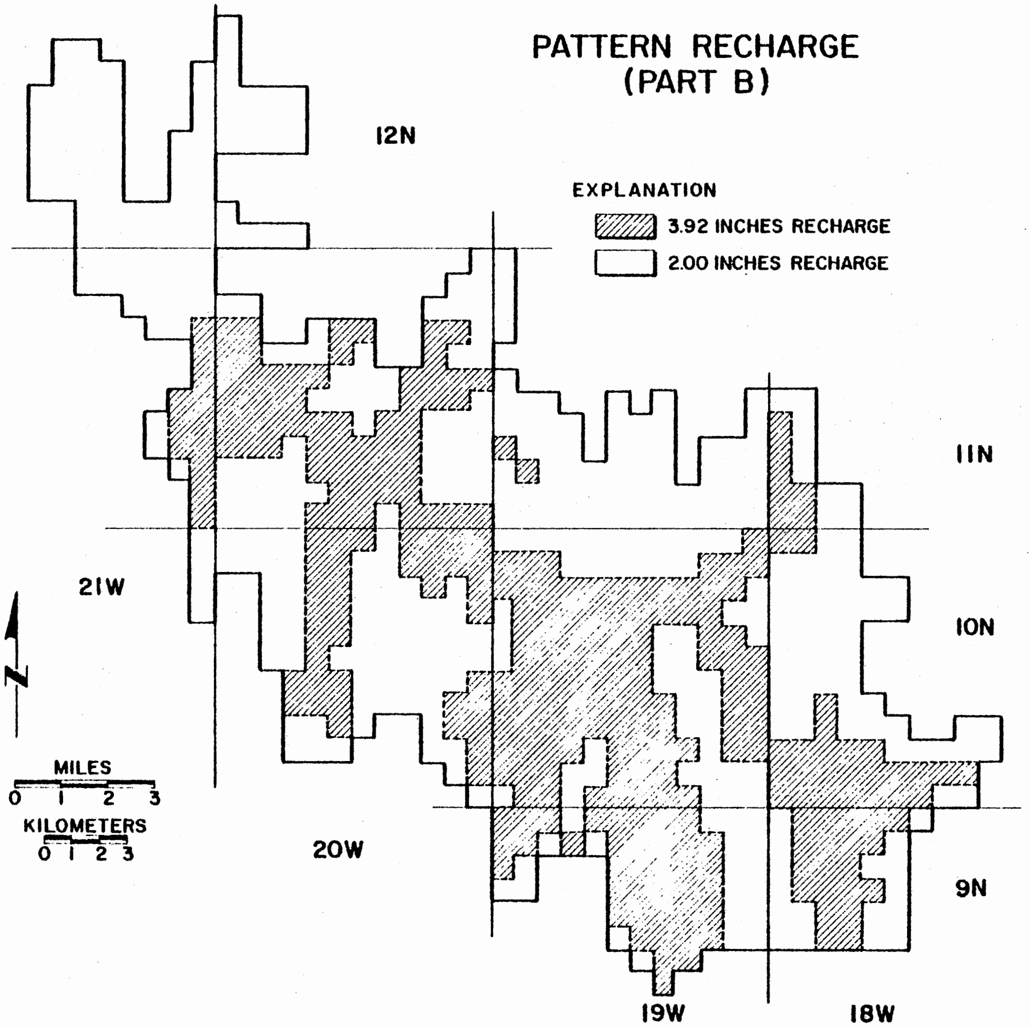


Fig. 27--Pattern recharge (Part B).

recharge rates is slightly lower than the originally assigned value.

After the initial calibration using pattern recharge was accomplished, the discharge was calibrated to set the aquifer to the recharge-discharge equilibrium. The initial one-year simulation resulted in an appreciable rise in the water table near the constant gradient nodes located at the edge of the aquifer. Apparently the water could not be sufficiently drained by the constant gradient nodes. It was noted that ground-water drainage coincided with perennial streams existing in the area. Water was not sufficiently discharged into the streams and removed from the ground-water system. In order to increase this discharge into perennial streams, a series of image wells were placed on the nodes where the perennial streams were located.

Other excessive rises in the water table occurred where the contact exists between the Elk City Sandstone and the more permeable overlying sediments. Image wells were used to simulate small springs or seeps which are expected to occur at the contact of the unconsolidated material and Elk City Sandstone. The location of the image wells is found around the boundary of saturated unconsolidated material (Figs. 11 and 12). After making final adjustments of the image wells, an equilibrium condition was achieved and model calibration completed.

Simulation Period

The model was used to simulate pumping and corresponding water-level changes over a one-year and a 20-year period. The one-year simulation run was used to calibrate the model. Twenty-year simulation runs were initiated on July 1, 1973 and terminated on July 1, 1993. The longer simulation period based on Oklahoma Water Law statue 82, sections 1020.4 and 1020.5 requires that new annual pumping allocations be assigned based on a minimum aquifer life of 20 years.

Values placed into the model for simulation purposes include:

1. Pumping period (NPER)
2. Time step (NUMT)
3. Iteration limit for one time step (ITMAX)

Two pumping periods were considered in order to facilitate irrigation and municipal supply withdrawals. The pumping period for irrigation wells is four summer months, followed by eight months of recharge only. The pumping period for wells used for municipal and industrial use occurs throughout the year at constant pumping and recharge rates.

The simulation period was subdivided into 36 pumping periods and a time step of 10 days was used. A time step is the period of time in which the model readjusts water-table elevations due to recharge and/or discharge in the system. Each time step requires several iterations to calculate changes in water level. These calculations are recalculated until they converge on an arbitrary error factor. The error factor is set at one-tenth of a foot. The maximum number of iterations in one time step is 50.

The 20-year simulation included three simulation runs: (1) prior appropriative rate only (Figs. 17, 18, 19); (2) prior appropriative rates combined with allocation for irrigation assigned to all other nodes; and finally one run using prior appropriative rates combined with allocation for industrial and municipal use to all other nodes. The model was designed to automatically turn the pumping on or off at the beginning and end of each pumping period when assuming irrigation (June 1 to September 30).

Wells in the study area average 160 ft. in depth and may or may not be cased in the sandstone below the unconsolidated surficial deposits. Only the larger wells used for irrigation or public supplies have been cased and have been perforated or have commercial well screens. Also, most of these wells have a gravel pack (Palmquist, 1964). Gravel packed, cased, screened wells are recommended for future well development. Construction design for an average well capable of producing 200 gpm is shown in Figure 28. Well design will vary from place to place depending on the saturated thickness and permeability at each location.

The minimum saturated thickness for simulated pump withdrawal of water from a well, which is designed in accordance with the one shown in Figure 28, is determined by considering the well yield and the corresponding screen length required to accomodate the well yield. The well yield is determined using the following equations, 2 and 3, according to Walton (1970, p. 315):

$$Q_y = \frac{Q}{s} \int_0^t s \, dt \qquad (2)$$

where: Q_y = well yield

s = drawdown

Q/s = specific capacity

and:

$$\frac{Q}{s} = \frac{T}{264 \log \left[\frac{Tt}{2{,}693 r_w^2 S_y} \right] - 66.1} \qquad (3)$$

where: $\frac{Q}{s}$ = specific capacity, in gpm/ft

Q = discharge, in gpm

s = drawdown, in ft

T = coefficient and transmissivity, in gpd/ft

S_y = specific yield, fraction

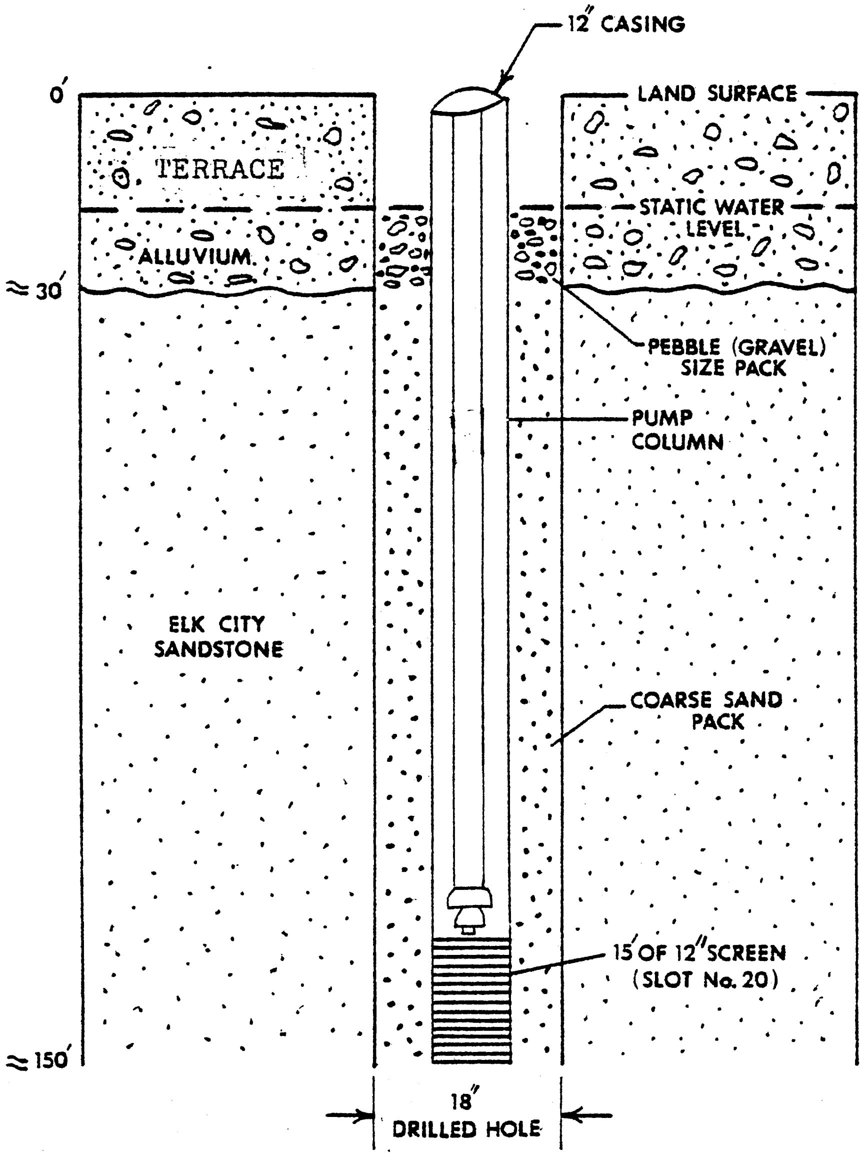


Fig. 28--Average well construction for 200 gpm pumping rate.

r_w = nominal radius of well, in ft

t = time after pumping started, in minutes

The well yield for areas A and B are shown in Figures 29 and 30. Nodes with well yields of 200 gpm or greater were assigned a well screen length of 15 ft. (Fig. 28). The remaining area with well yields less than 200 gpm were assigned a well screen length of five feet. The average well yields in areas A and B, where the well yield exceeds 200 gpm, are 1107 gpm and 1272 gpm, respectively; whereas, well yields average 57 gpm in area A and 123 gpm in area B, where the well yield is less than 200 gpm. If the water levels in a well drops to an elevation below the top of the well screen, the simulated pump withdrawal automatically ceases and the node is considered "dry".

Maximum annual yield is determined by adjusting the amount of allocated pumpage that would cause 50 percent of the nodes to go dry by the end of the simulation period. The maximum yield and allocated pumpage are optimized by repeated 20-year simulation to obtain the required 50 percent dry area. Under these conditions, various parts of the area go dry at different times. This is due to the variability of the saturated thickness (variable transmissivity). The 50 percent dry criteria was used to accomodate this variability. The wells are turned off in the model when the 5- and 15-foot saturated thickness is reached and will turn on periodically to remove accumulation due to recharge. The maximum annual yield is the resulting amount of water recovered over the 20-year period during which wells are being turned off and on as the aquifer is depleted and recharged. Because of these factors, the maximum annual yield does not simply equal the product of allocation rate times the area.

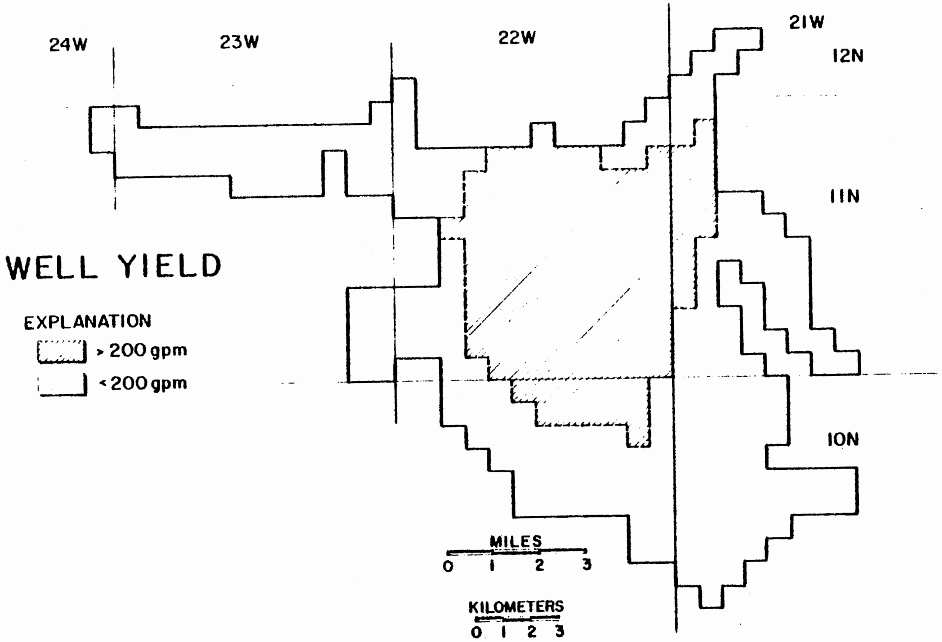


Fig. 29--Well yield (Part A).

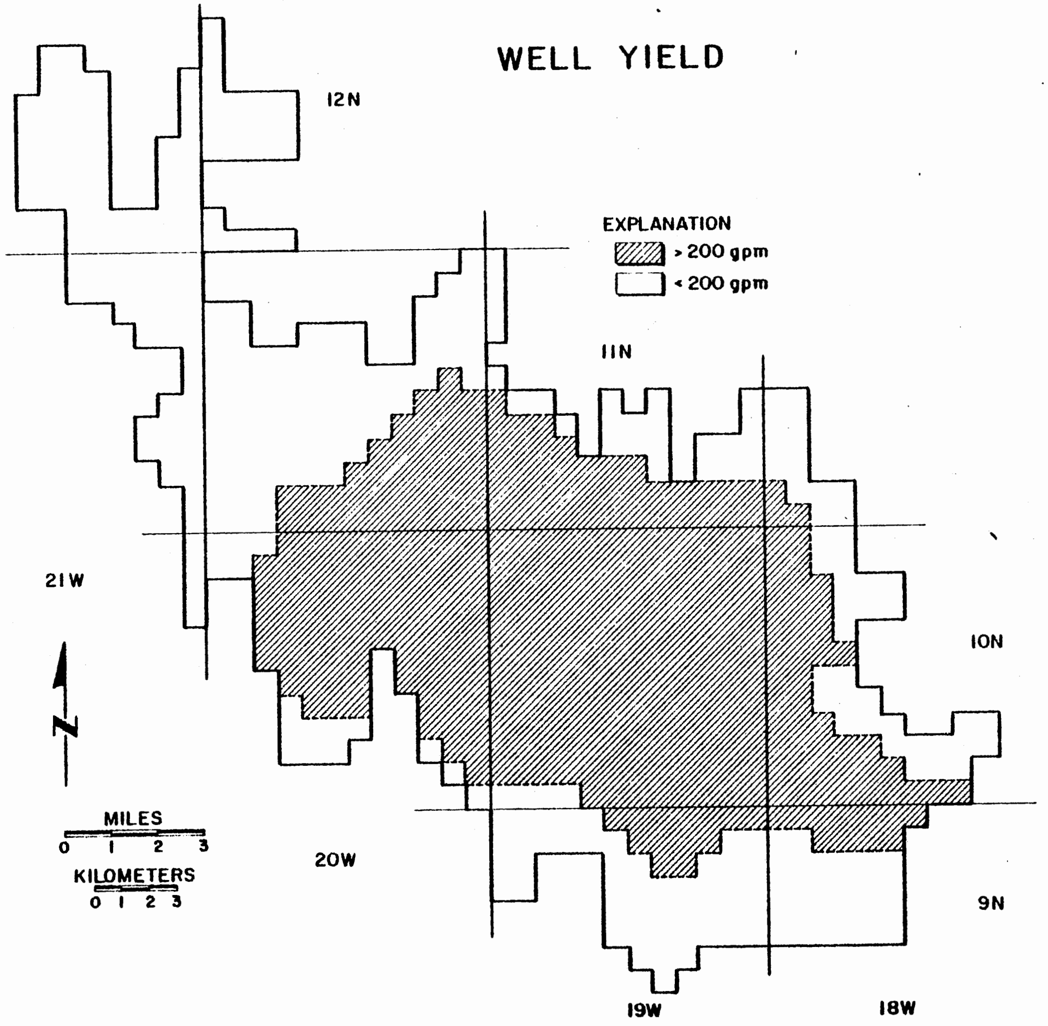


Fig. 30--Well yield (Part B).

CHAPTER VI

RESULTS

General

The final 20-year computer simulation was conducted for the 1973 to 1993 period for each area (A and B) using pumping rates of prior appropriative right owners (owners with water rights established before July 1, 1973). This simulation is repeated with allocation pumping in conjunction with prior appropriative pumping (Kent, 1980). If the allocation pumping is greater than the prior appropriate pumping for a node, the allocation pumping is used.

The prior right wells are mostly irrigation wells, but some industrial and municipal wells exist. The legal annual allocation is determined for irrigation pumping. This would seem the most accurate under the rural conditions that exist in the area during the time of this investigation, but these conditions may change over the next 20 years. Industrial and municipal growth could become a key factor in determining the legal annual allocations. For this reason, three model simulations are used for the Elk City Aquifer. These three versions include:

1. 20-year simulation using only prior rights pumping
2. 20-year simulation using prior right pumping and allocation pumping during four month irrigation season assuming 15% return flow.
3. 20-year simulation using prior rights pumping and allocation

pumping during a 12-month period for municipal water supply assuming 15% return flow.

The first two versions are required by Oklahoma Law to determine the legal annual allocation of the Elk City Aquifer. To determine the legal annual allocation, prior rights results are deducted from total area allocation in order to protect prior rights owners. The last two runs can be used to compare municipal and irrigation use.

Prior Rights Simulation

After calibrating the model using one-year simulation runs to achieve equilibrium, a 20-year simulation is conducted using prior rights pumping (Figs. 17, 18, 19) for parts A and B. The mass balance of both A and B are shown on Tables IV and V, respectively. It is apparent from net change between recharge and discharge that a perfect equilibrium is not established over the 20-year period. The reason for the change is probably due to the fluctuating outflow associated with the constant gradient nodes. The constant gradient nodes regulate ground-water outflow. Calculations for these nodes are found in Chapter V. The boundary flux values are determined by assuming that the gradient and permeability are held constant, and that the saturated thickness will vary depending on the amount of water coming into or going out of the adjacent nodes. This variability in the saturated thickness of the adjacent nodes will effect ground-water outflow from the constant gradient nodes. The net flow of recharge and discharge predicted to occur after 20 years is less than two percent in both parts A and B and is considered well within model simulation error for a 20-year period.

The other criterion for establishing an equilibrium is to achieve a

TABLE IV

MASS BALANCE OF PRIOR APPROPRIATIVE PUMPING FROM JULY 1, 1973 TO JULY 1, 1993 (PART A)

	AVERAGE ANNUAL (ACRE FEET)		TWENTY YEAR TOTAL (ACRE FEET)	
	Inflow	Outflow	Inflow	Outflow
Recharge	10,159		203,187	
Pumpage		520		10,400
River Leakage		4,912		98,240
Subsurface Flow	10	4,674	204	93,482
Totals	10,169	10,106	203,391	202,122
Net Storage Change	+63		+1,269	
%Net Storage Change			<2%	

TABLE V

MASS BALANCE OF PRIOR APPROPRIATIVE PUMPING FROM JULY 1, 1973 TO JULY 1, 1993 (PART B)

	AVERAGE ANNUAL (ACRE FEET)		TWENTY YEAR TOTAL (ACRE FEET)	
	Inflow	Outflow	Inflow	Outflow
Recharge	26,299		525,986	
Pumpage		6,767		125,340
River Leakage		14,234		286,484
Subsurface Flow		5,581		111,623
Totals	26,299	26,672	525,986	533,447
Net Storage Change	-373		-1,454	
% Net Storage Change			<2%	

negligible change in the water-head elevations. The 1993 water-head elevation maps for A and B are shown in Figures 31 and 32. When comparing the 1993 maps to the corresponding 1973 versions (Figs. 15 and 16), fluctuations in head are noted and vary between 0 and 40 ft, however, the average change in head is only 1 ft. and is considered to be negligible. None of the nodes go dry in this simulated run, which is to be expected if the aquifer is in equilibrium.

Prior Rights and Allocated Pumping for Irrigation

The simulated runs using prior rights pumping and irrigation allocation pumping were performed in order to establish a legal, annual allocation for the Elk City Aquifer. Maximum annual yield is determined by adjusting the amount of allocated pumpage that would cause 50 percent of the nodes to go dry by the end of the simulation period. The maximum annual yield and allocated pumpage is optimized by repeated 20-year simulation to obtain the required 50 percent dry area. A saturated thickness of 5 ft. or 15 ft. was considered dry due to size limitations of the well screen.

The annual allocation of 0.91 acre-feet per acre is determined for the entire area. The allocation is acquired by averaging the computed allocations for each area (A and B) using a weighting factor based on the percent of total aquifer occupied by each subbasin (A and B). The final allocation for each subarea is as follows: Subarea A, 0.70 acre-feet per acre; Subarea B, 1.00 acre-feet per acre. The weighted average is computed as follows:

0.70 acre-feet per acre (0.3) + 1.00 acre-feet per acre (0.7)

= 0.91 acre-feet per acre

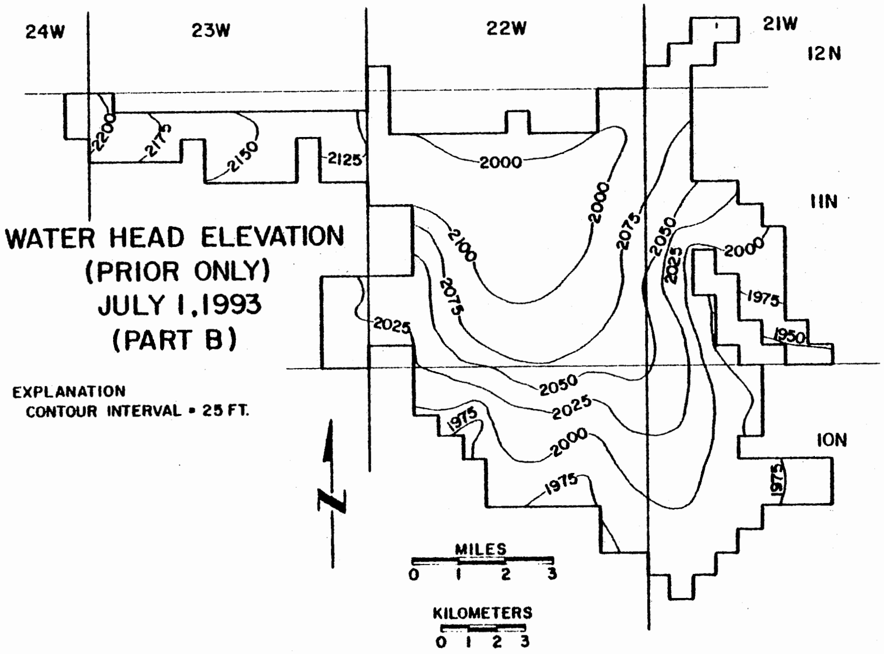


Fig. 31--1993 prior rights water table map (Part A).

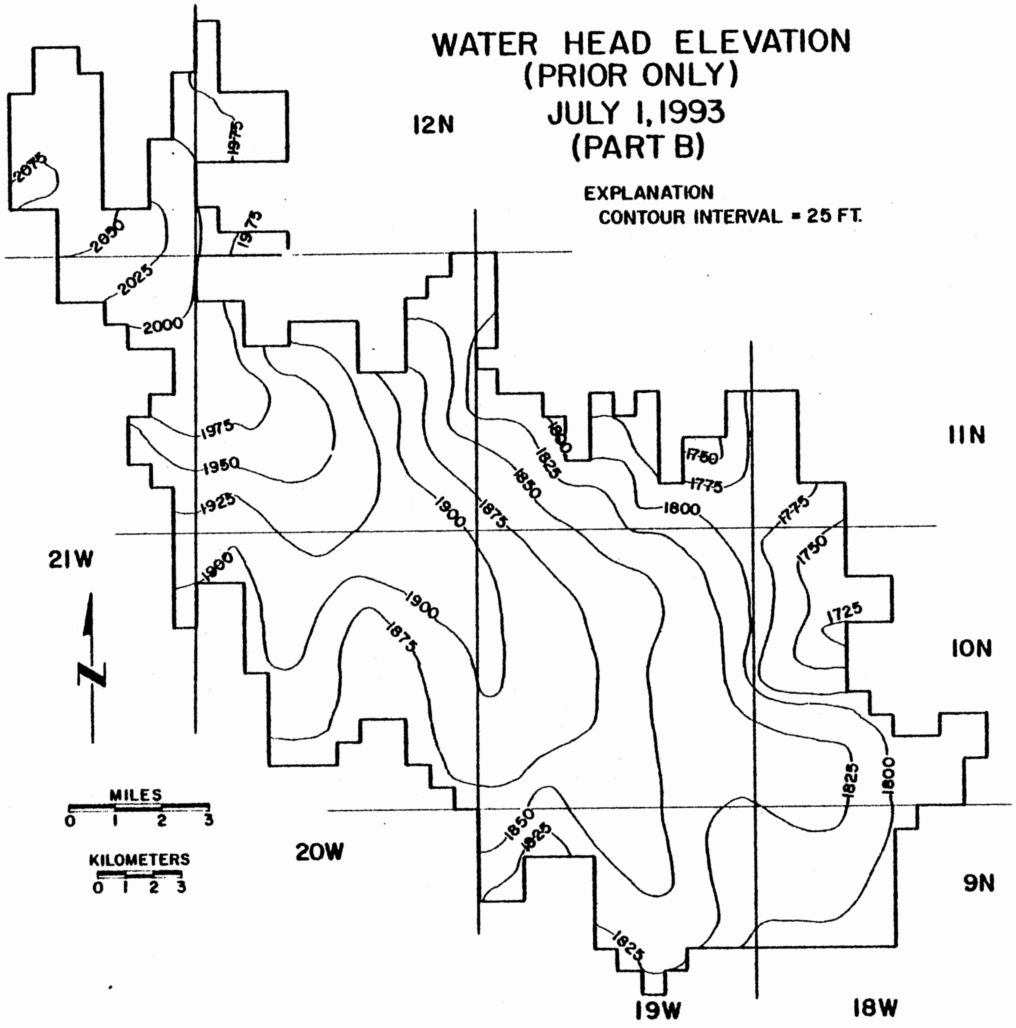


Fig. 32--1993 prior rights water table map (Part B).

Simulated changes in saturated thickness and of areas that become dry within each subarea (A and B) are shown in Figures 33 to 40. A 20-year ground-water budget is computed for the final computer allocation runs of each subarea and of the entire aquifer area (Figs. 41, 42, 43).

Each node (160 acres) is pumped continuously for a four-month period during the summer months (June 1 to September 30) of each year throughout the 20-year simulation period. An instantaneous pumping rate is used at three times the allocation rate because the allocation rate represents continuous pumping prorated over a one-year period. It is assumed in the model that all nodes are pumped at the average maximum legal limit (0.91 acre-feet per acre). These rates correspond to instantaneous pumping rates of approximately 100 gallons per minute and 300 gallons per minute continuous pumping for one year and a four-month period, respectively. Under these conditions, various parts of the area go dry at different times. This is due to the variability in saturated thickness in the aquifer. The 50 percent dry criteria is used to accomodate this variability. The wells are turned off in the model when the 5-ft. or 15-ft. saturated thickness is reached and will turn on periodically to remove accumulation due to recharge.

The maximum annual yield is 2,177,295 acre-feet or 0.69 acre-feet per acre for the combined subareas A and B.(fig.443). The maximum annual yield is in reality the optimum average annual yield of non-prior-appropriative pumping (Figs. 41, 42, 43). This represents the average amount of water recovered over the 20-year period during which wells are being turned off and on at the 300 gallons per minute rate as the aquifer is depleted and recharged. Therefore, the maximum annual yield rate of 0.69 acre-feet per acre is less than the annual allocation rate

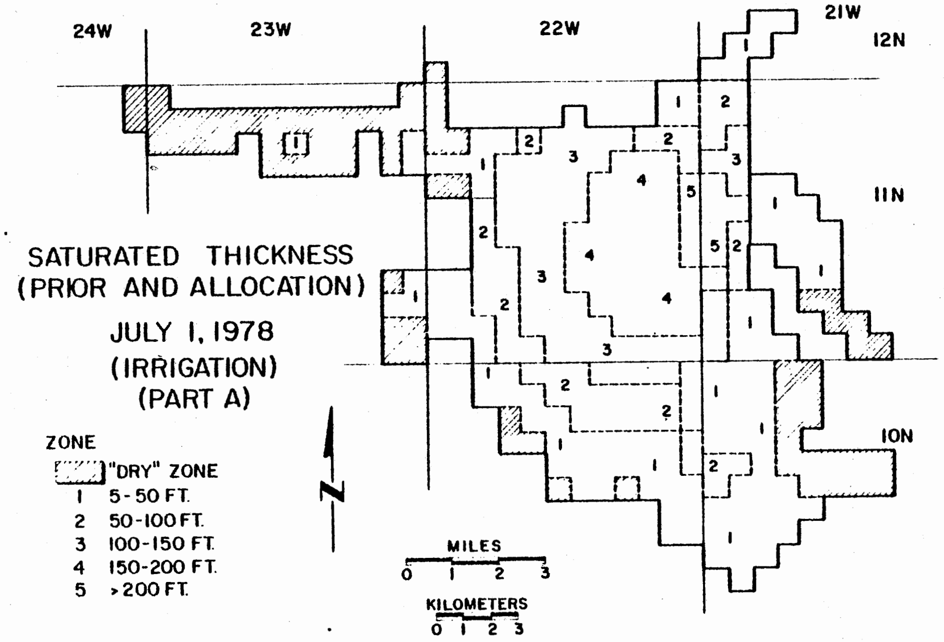


Fig. 33--1978 saturated thickness map (irrigation allocation) (Part A).

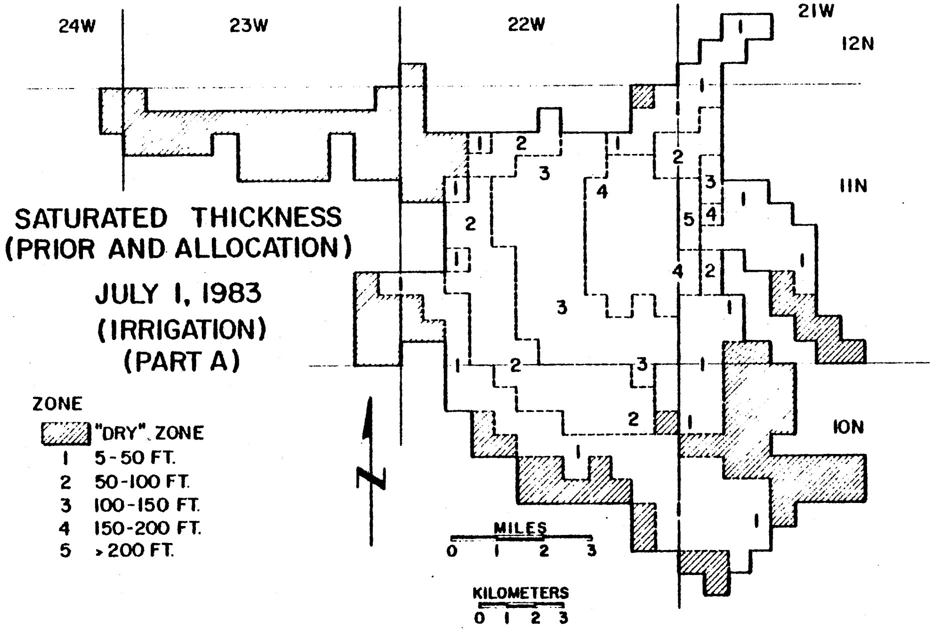


Fig. 34--1983 saturated thickness map (irrigation allocation) (Part A).

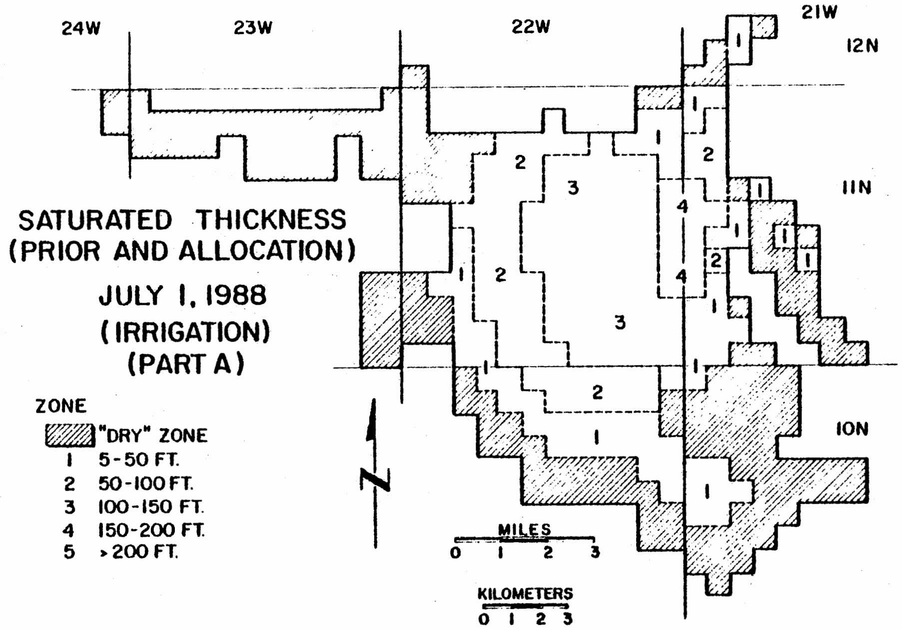


Fig. 35--1988 saturated thickness map (irrigation allocation) (Part A).

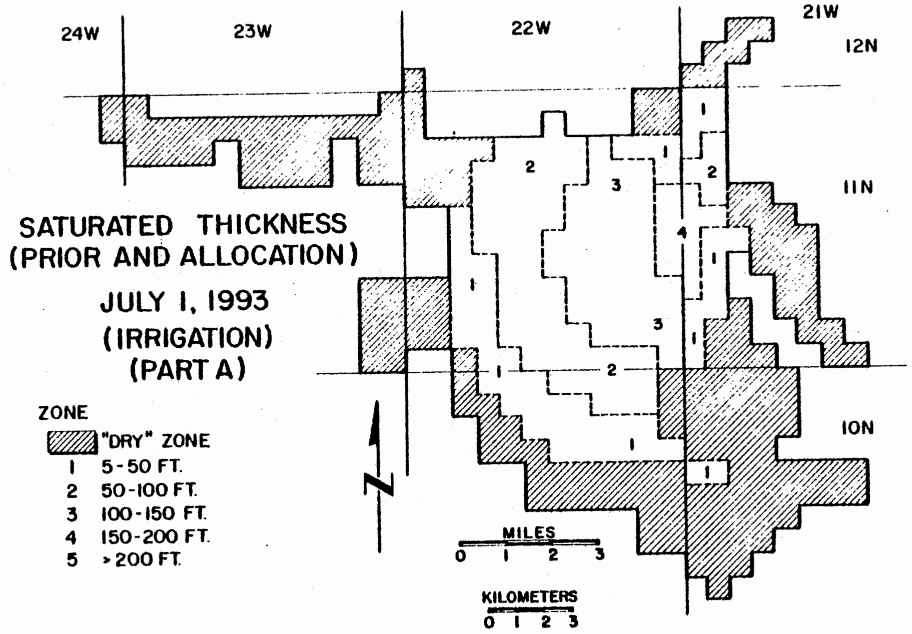


Fig. 36--1993 saturated thickness map (irrigation allocation) (Part A).

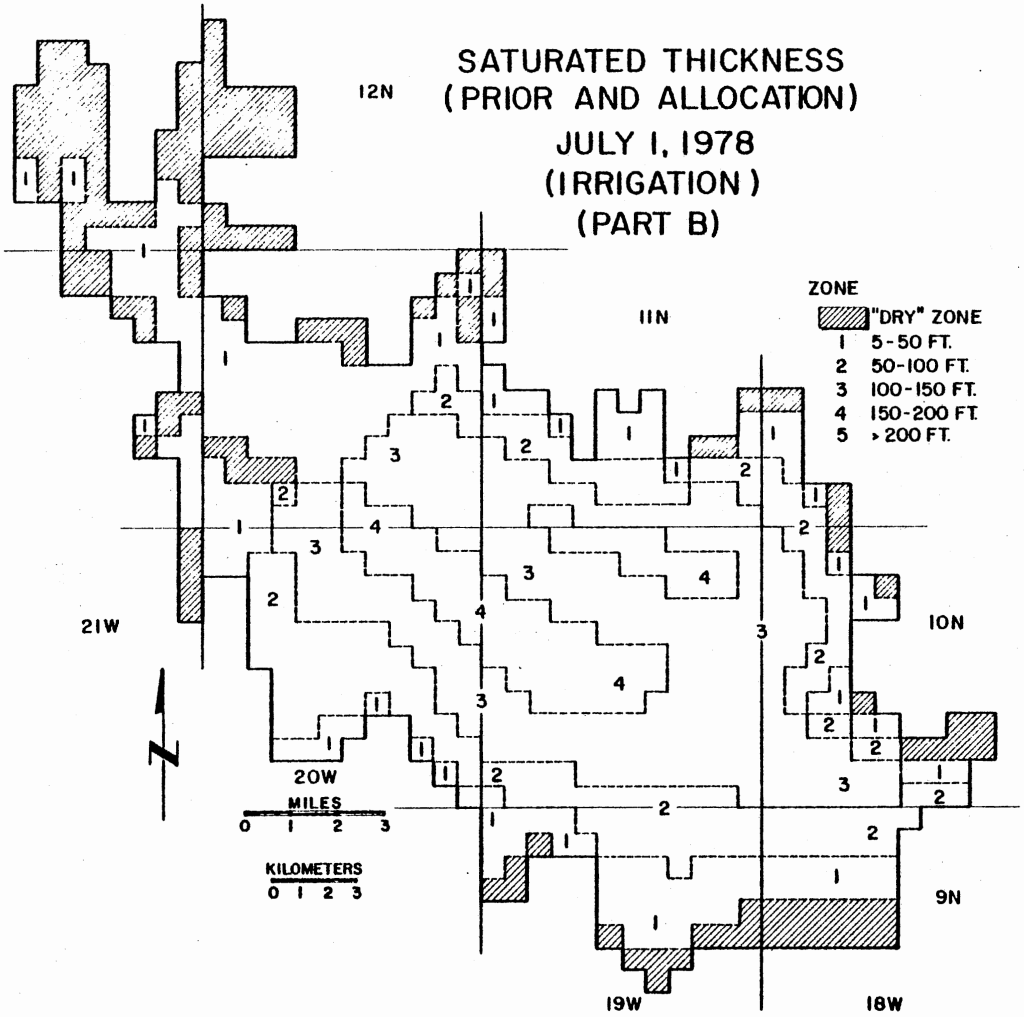


Fig. 37--1978 saturated thickness map (irrigation allocation) (Part B).

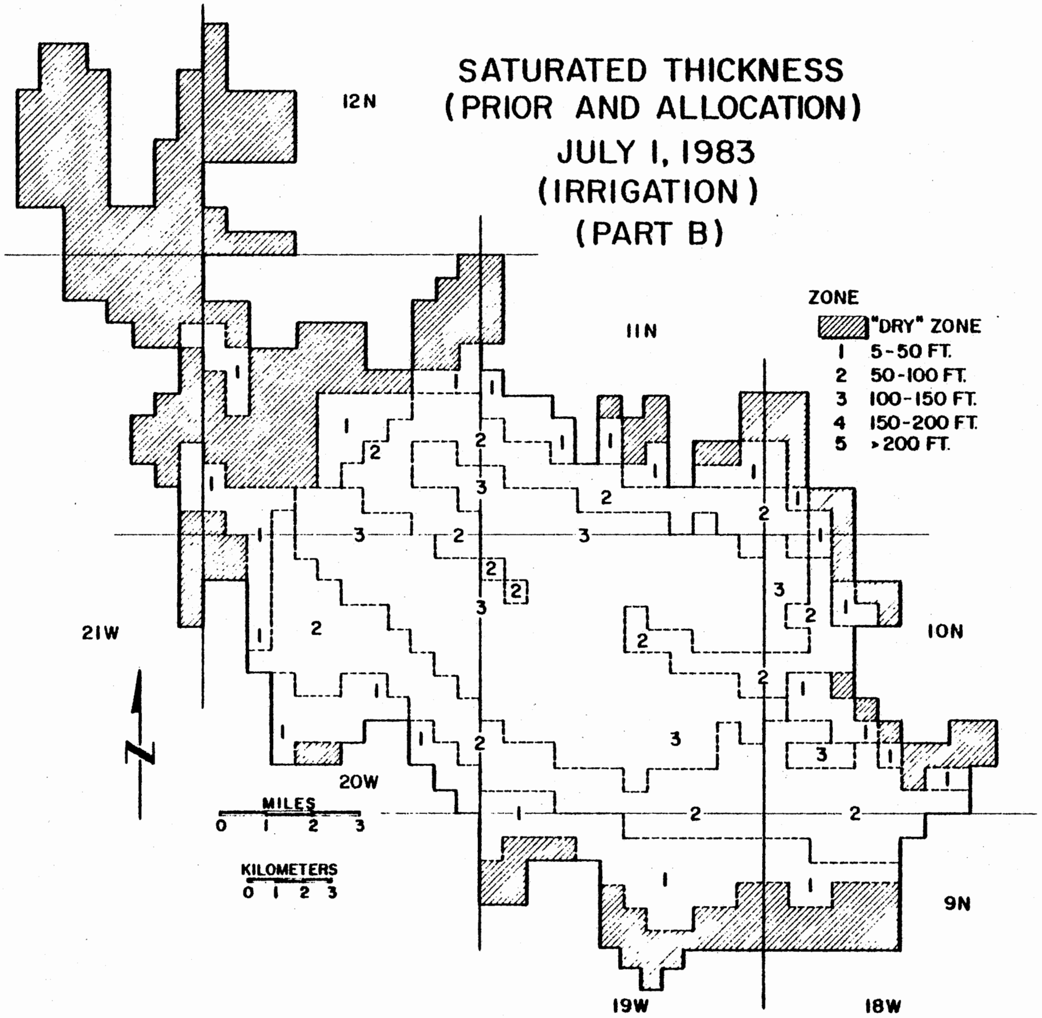


Fig. 38--1983 saturated thickness map (irrigation allocation) (Part B).

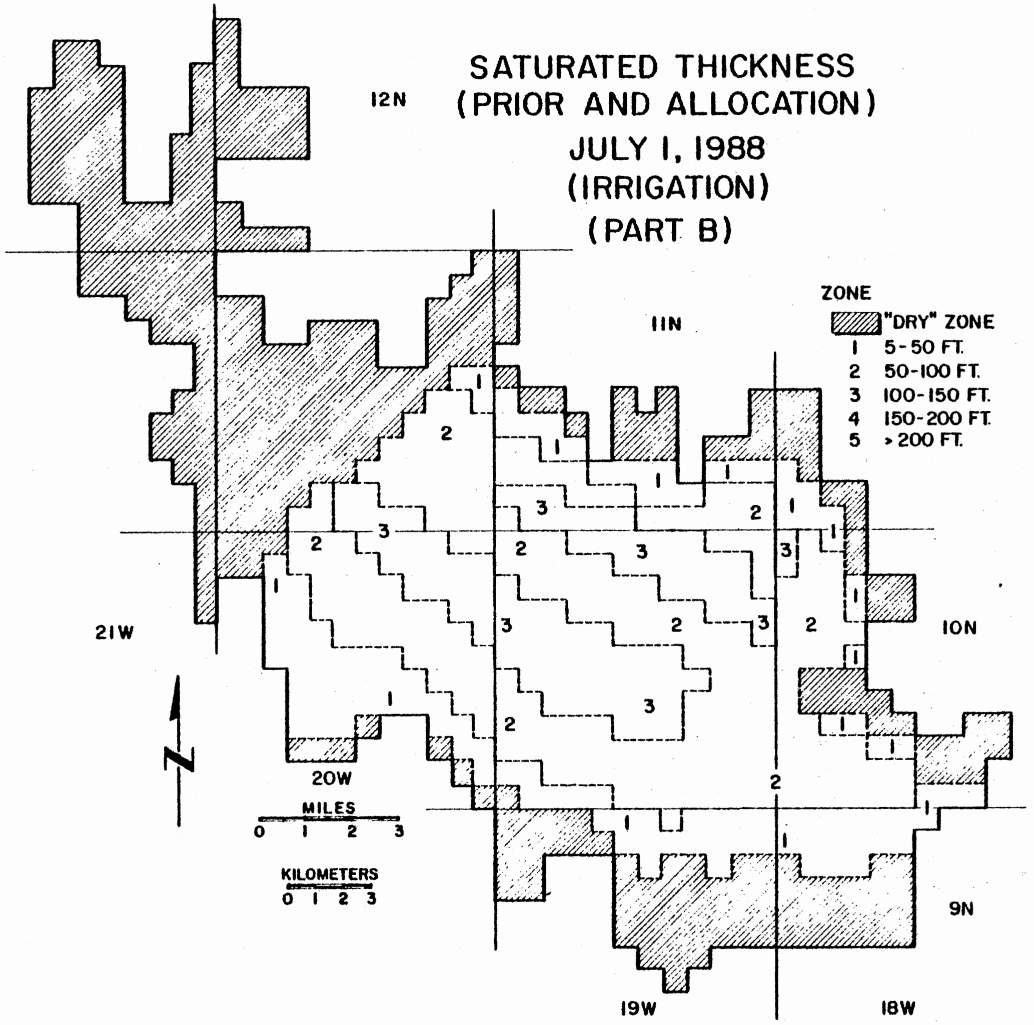


Fig. 39--1988 saturated thickness map (irrigation allocation) (Part B).

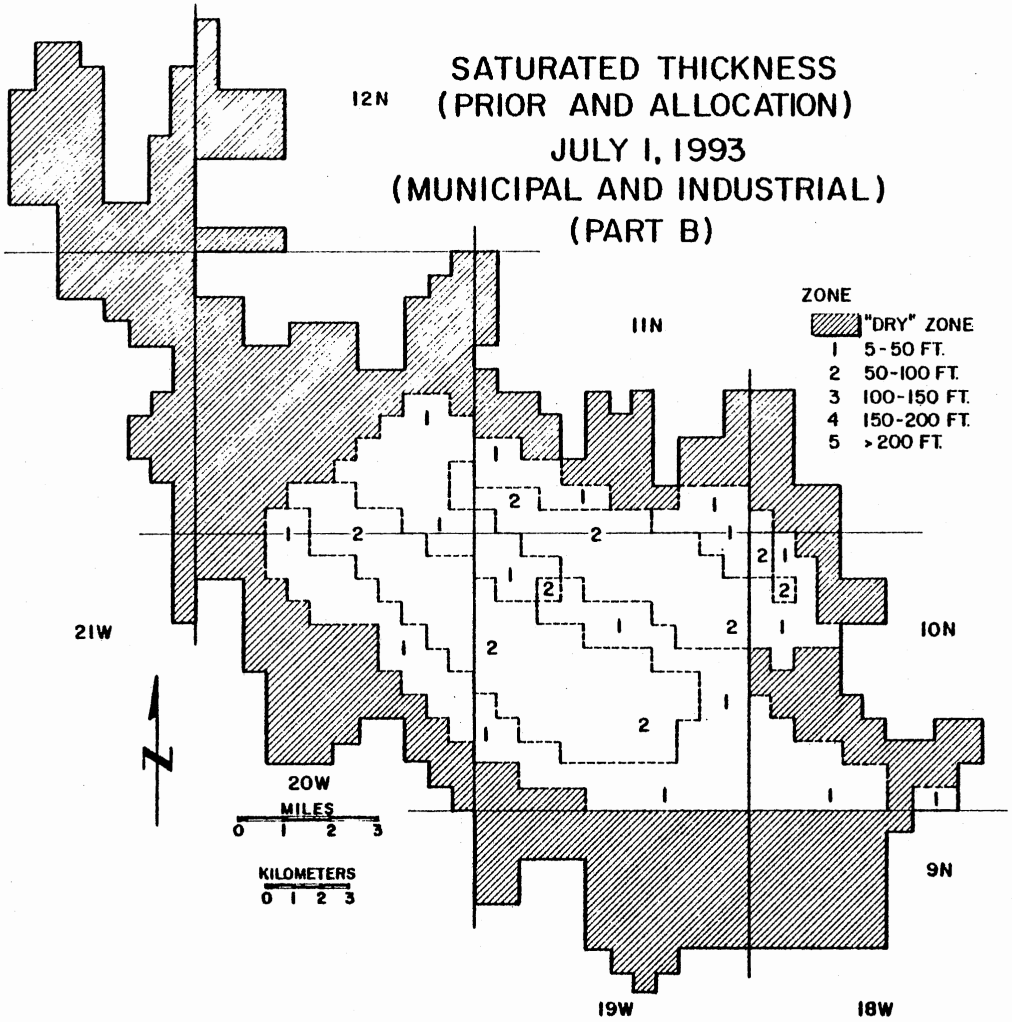


Fig. 40--1993 saturated thickness map (irrigation allocation) (Part B).

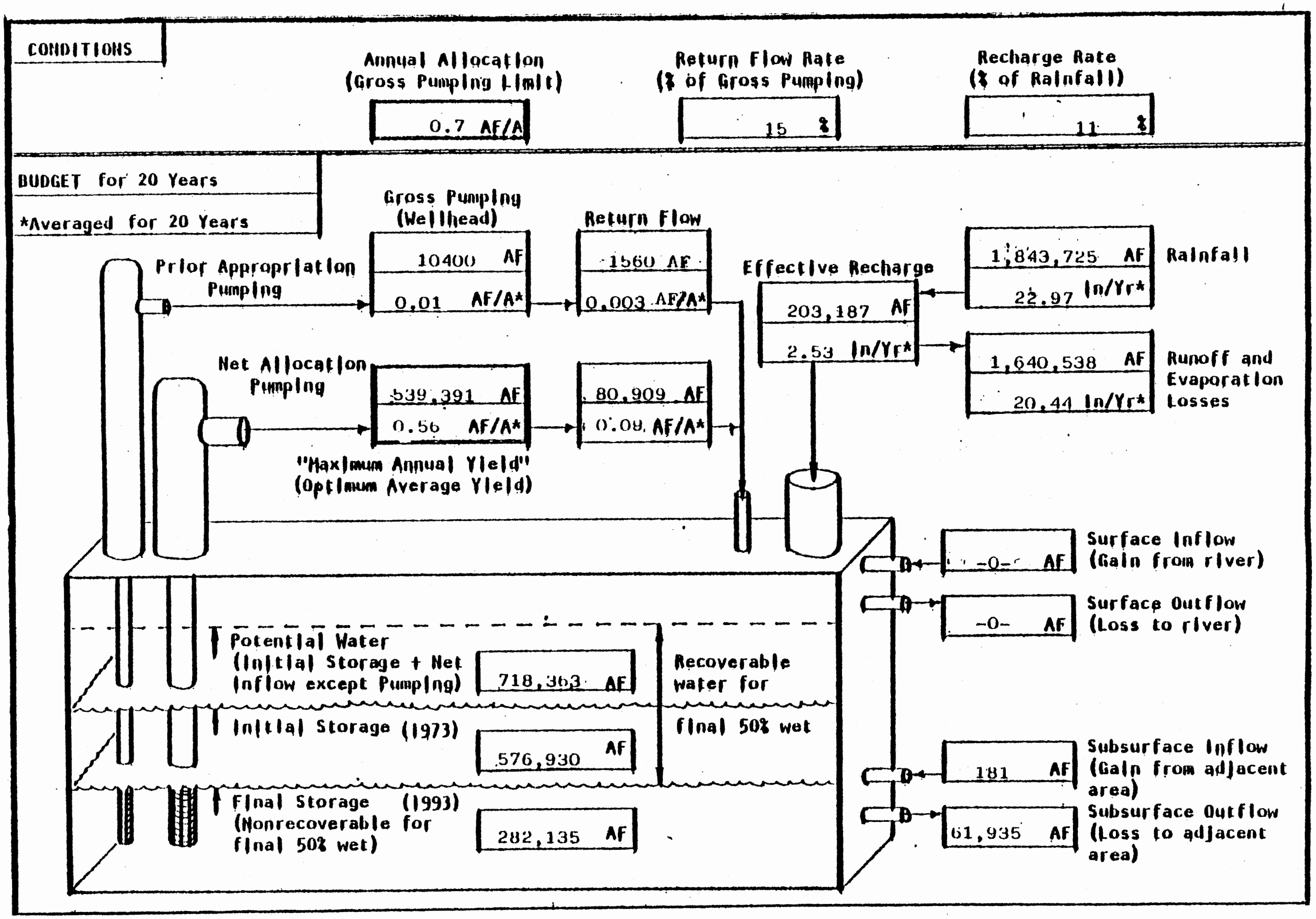


Fig. 41--Water budget (part A) (after Kent, 1980).

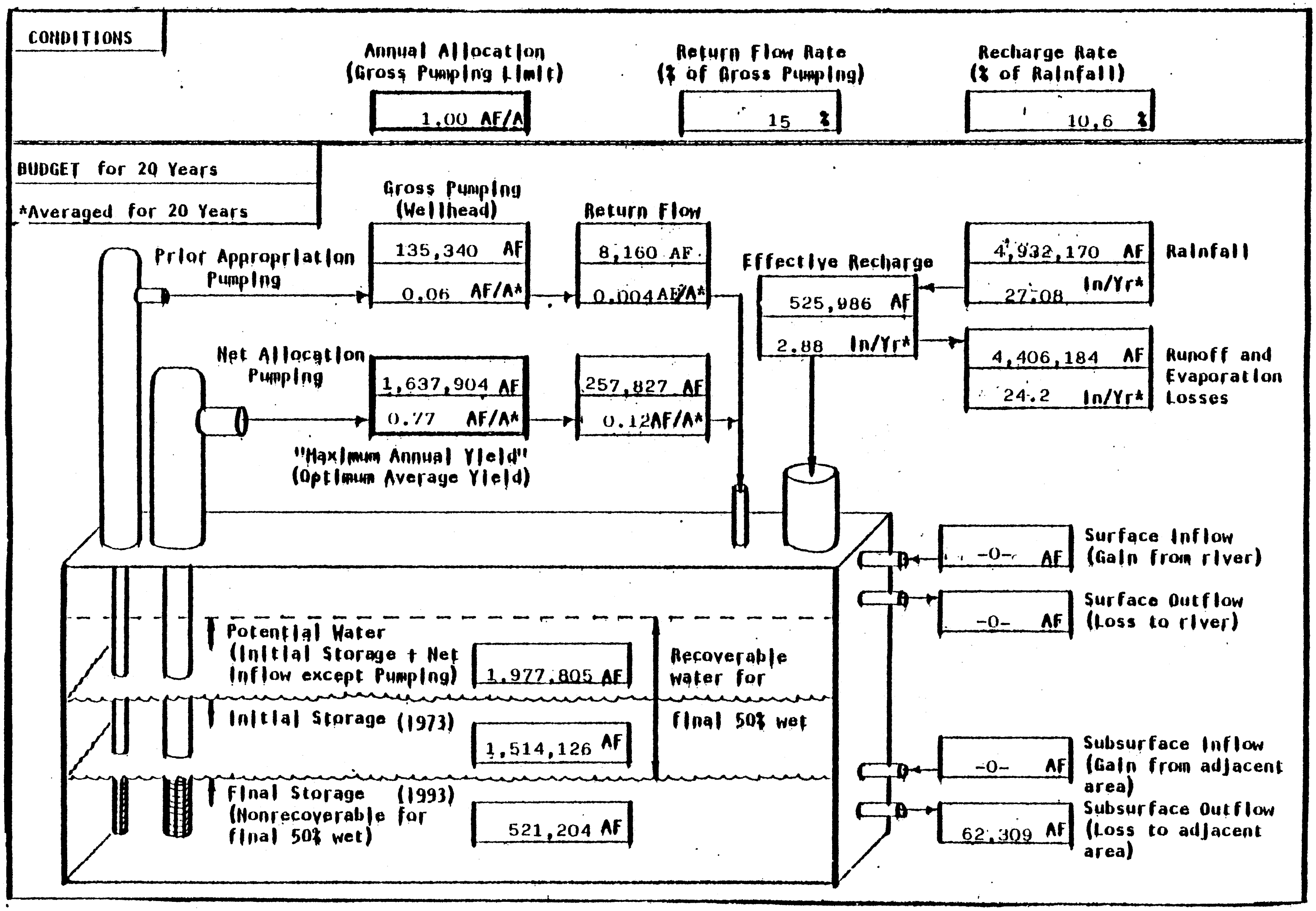


Fig. 42--Water budget (part B) (after Kent, 1980).

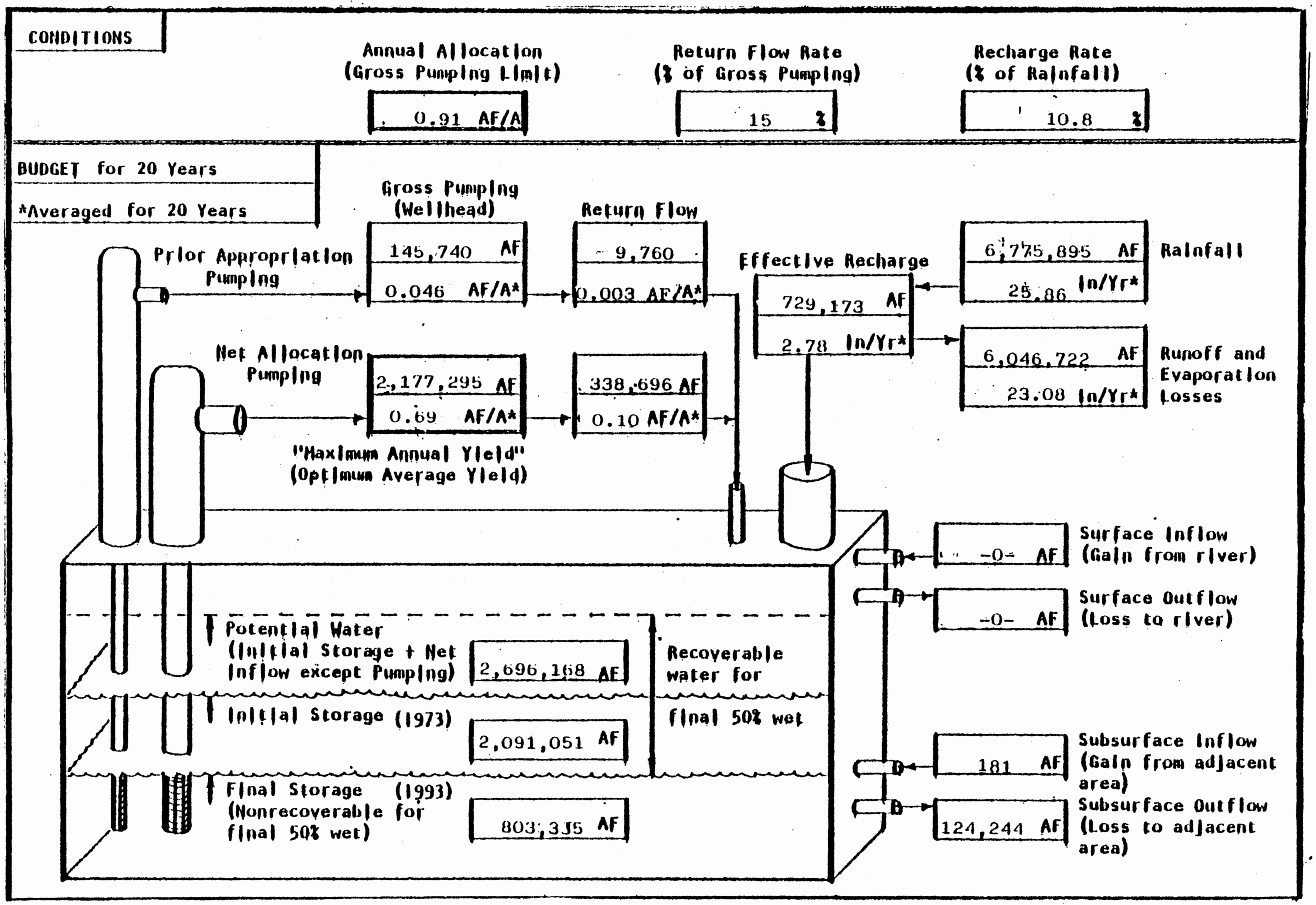


Fig. 43--Water budget (parts A and B) (after Kent, 1980).

of 0.91 acre-feet per acre which is based onthe gross pumping limit.

Municipal Supply

This final run is identical to the simulation run where irrigation is assumed but instead of pumping during a four-month period at three times the annual allocation rate, a continous pumping at the normal pumping rate is assumed. The 1993 mass balances and computer maps of the two simulation runs (four-month and twelve-month pumping) are compared to show if differences exist. The mass balances are identical and only a change of 1 to 3 ft. in a few water-head elevation nodes are noted. From this comparison, it is concluded that the aquifer is not under additional stress annually when pumping is restricted to four summer months at three times the annual pumping rate. Therefore, an annual allocation rate derived derived from this case will be the same as for the irrigation case (0.91 acre-feet per acre).

CHAPTER VII

CONCLUSIONS

The geologic and hydrogeologic parameters of the Elk City Aquifer have been addressed. The conclusions in this investigation are based on two different aspects of a hydrogeological study. One aspect comes from looking at the raw data and making assumptions of the conditions that exist in the study area. The second is the quantification of these data which can be used for prediction using a computer model.

The conclusions are only as accurate as the raw data and the accuracy of the assumptions made. The main assumptions used for the Elk City Aquifer in this study are as follows:

1. The Elk City Aquifer is bounded vertically by the water table above and the impermeable Doxey Shale below. The base of the aquifer represents a faulted, gently plunging syncline.
2. The Elk City Sandstone does have some variation in grain size and cementation. These factors, plus the jointed character of the sandstone, give the aquifer a heterogeneous permeability, both vertically and horizontally; however, a homogeneous permeability value is assigned to the sandstone because of the lack of precise data.
3. An aquifer equilibrium does exist within the Elk City Aquifer and will continue to exist unless more pumping from irrigation, municipal and/or industrial wells are used in the aquifer.

The main conclusions which can be drawn from the computer runs are:

1. The irrigation allocation was used to determine the maximum annual allocation, due to the fact that rural conditions dominate the lifestyle in the area.
2. The comparisons of computer simulations using irrigation pumping to constant pumping shows no change in the aquifer.
3. The saturated thickness of the aquifer represents a bimodal distribution which is related to the structure in the area. This characteristic will result in high and low well yield areas. Due to this fact, the possibility of the two areas (A and B) becoming hydrologically disconnected during pumping at the allocated rate of 0.91 acre ft. per acre is relatively high. This observation is supported by noting that the 1993 water table gradient will change from being topographically controlled to being controlled by the base of the aquifer.

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VITA

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Master of Science

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PLATE 1 : STRUCTURE CONTOUR MAP

"BASE" ELK CITY SANDSTONE

CONTOUR INTERVAL 25'
NATURAL BOUNDARY ∫
COMPUTER BOUNDARY ⌐
FAULTS — — —

PLATE 2 : WATER HEAD ELEVATION

ELK CITY AQUIFER