A GROUND-WATER MANAGEMENT MODEL FOR THE ENID ISOLATED TERRACE AQUIFER IN GARFIELD COUNTY, OKLAHOMA

By

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PREFACE

The purpose of this study is to simulate ground-water flow through and storage in the Enid Isolated Terrace Aquifer. The primary objective is to determine the maximum annual yield and pumping allocation for the Enid terrace. A computer model is used to determine the maximum annual yield based on pumpage prior to July 1, 1973, and subsequent allocated pumpage until July 1, 1993.

The author wishes to thank Dr. Douglas C. Kent, his thesis adviser, for his help and suggestions during the course of this study. Appreciation is also extended to the Oklahoma Water Resources Board (OWRB) for providing financial support through an OWRB contract to Dr. D. C. Kent. Appreciation is extended to Dr. Fred E. Witz, computer specialist, for providing program assistance. A special note of gratitude is extended to the following staff members of the OWRB for providing much needed information required for the research: Mr. J. A. Wood, Chief of Ground Water Division, and Mr. Mark Belden, geologist, on the ground-water staff. Special appreciation is extended to Dr. Wayne H. Pettyjohn for his critique of this thesis and to Dr. Gary F. Stewart for his moral support and advice. The author also wishes to thank Dr. H. F. Garner, Mrs. Margy Conner, Mr. Harry Conner and Mr. Tim Lyons for their enthusiastic support and friendship. Finally special gratitude is extended to my family, relatives and friends for their love and support. This thesis is dedicated to all of you.

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CHAPTER I

ABSTRACT

The Enid Isolated Terrace Deposit is a minor aquifer, supplying water for irrigation, domestic, municipal and industrial use for the City of Enid and residents of western Garfield County. The terrace deposit covers an area of approximately 82 square miles and the areal boundary of the aquifer is defined by the contact between terrace deposits and the bedrock which consists of the Hennessey Group in the eastern portion and the Cedar Hills Formation of the El Reno Group in the western portion. The aquifer is unconfined and bounded vertically by the water-table above, and the bedrock below.

The intent of the study was to determine hydrogeologic relationships within the unconfined system and to determine a legal annual allocation for the Enid Isolated Terrace as stated under Oklahoma law. A comprehensive hydrogeological-model study was made in order to arrive at these goals.

Previous reports, well records for the area, and geologic field work all were used extensively in the compilation of the data base. Hydrogeologic properties of the aquifer are described and used for computer simulation. Computer simulation runs, using the Trescott-Pinder model, were first run using a one-year period to calibrate the aquifer assuming a recharge-discharge equilibrium. After calibration was completed, twenty-year computer simulations were made to determine a

mass-balance relationship and an annual allocation of pumping rate for the aquifer. The annual allocation for the Enid Isolated Terrace Aquifer is 0.5 acre-feet per acre.

CHAPTER II

INTRODUCTION

General

The Quaternary terrace deposit and underlying Cedar Hills Sandstone Formation represent an aquifer that is in use as a ground-water source for the City of Enid municipal wells in addition to domestic and irrigation supplies.

Ninety irrigation and municipal wells dot the area and these have been used in the hydrogeologic interpretation of the area. Data collected from these wells include location, well elevations, depth of water, bedrock depth, as well as other pertinent geologic information. Municipal, irrigation and United States Geological Survey observation well locations located within the boundary terrace deposit are shown in Figure 1.

Under Oklahoma Statute Nos. 82 §1020.4 and 82 §1020.5, the Oklahoma Water Resources Board is responsible for completing hydrologic surveys of fresh ground-water basins or subbasins within Oklahoma and for determining a maximum annual safe yield which will provide a twenty-year minimum life for each basin or subbasin.

Oklahoma Statute 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:

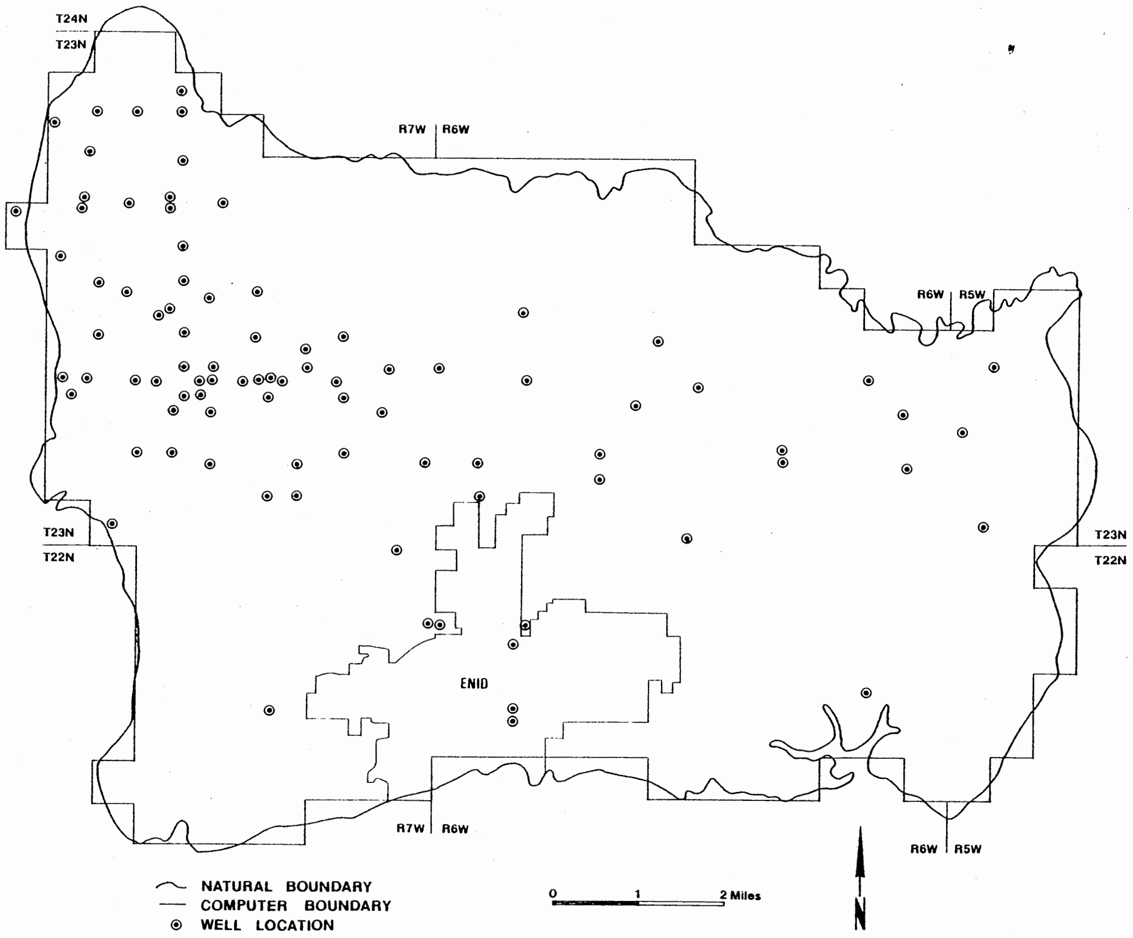

Figure 1. Well Locations

> 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 purposes of this research were to determine the maximum annual yield and a corresponding pumping rate allocation of fresh water that can be pumped from the Enid Isolated Terrace Deposit during a twenty-year period between July 1, 1973 and July 1, 1993. These purposes were addressed using the following steps:

1. A geologic interpretation was made of the area with respect to structure and lithologic characteristics.
2. Geologic factors were compared with available well data as an aid to the interpretation of hydrogeologic parameters within the aquifer.
3. Finally, the recharge-discharge relationships within the aquifer were determined.

With these qualitative factors identified, a quantitative analysis was made by assigning values for well data and other hydrogeologic information to quarter sections. These quantitative values are used in a mathematical model to predict changes in the potentiometric head within the Enid Isolated Terrace Deposit over a twenty-year period. A flow chart showing these steps is shown in Figure 2 (Lyons, 1981).

Previous Work

Gould (1905) conducted a broad study of the water resources for the State of Oklahoma. Brief mention was made of the ground-water resources of Garfield County and pertinent published well records were included. Terrace deposits located along the Cimarron River and their nature were also discussed.

Schwennesen (1914) mapped and described the unconsolidated "Tertiary age" deposits surrounding Enid and made several conclusions concerning their ground-water potential. Published well records and logs were included as well as a preliminary geologic map. Well spacings and general recharge were discussed.

Renick (1924) followed Schwennesen's investigation with a more comprehensive study of the Enid terrace deposits. A detailed analysis of the terrace material as to lithology, origin and thickness was undertaken and recommendations for future municipal well sites were made.

Clark (1927) mapped the Enid terrace deposit along with the Permian bedrock units. In this study the Cedar Hills Sandstone Formation was identified as the Duncan Sandstone Formation of the Enid Group.

Reed (1952) proceeded with an extensive geologic, hydrologic study of a 600 square mile area located 5 miles southwest of the Enid isolated terrace. A detailed geologic analysis of the Quaternary

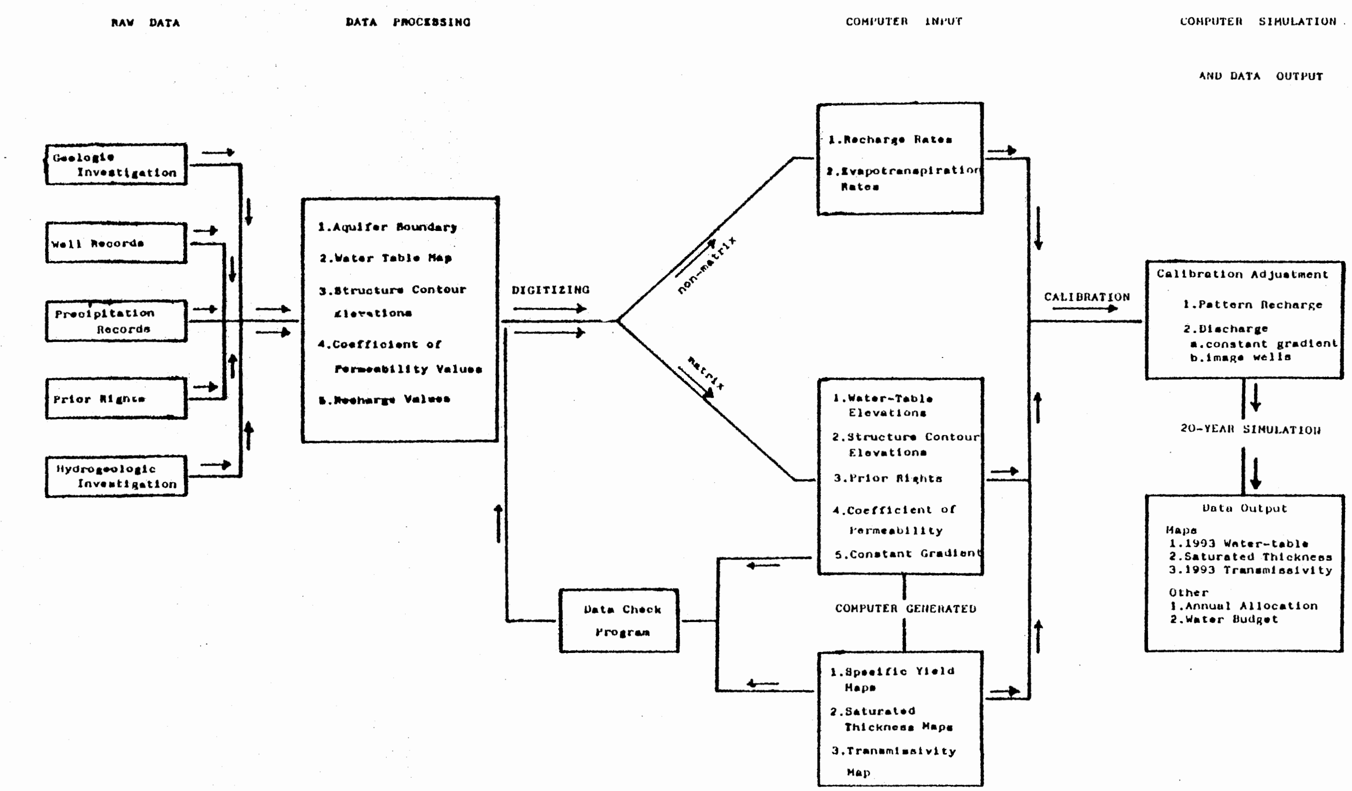

Figure 2. Flow Chart of Computer Modeling

deposits and Permian strata was undertaken and published aquifer test data, well logs, and water quality data were included. The purpose of the study was to determine the occurrence, quantity and quality of the ground-water resources found in the area and analyze the effect of water withdrawals from the deposits. Recommendations were made as to the future development of these deposits, with respect to irrigation, industrial and municipal supplies. Because of the proximity of this investigation to the Enid study area and because of similar lithologies present, this report has been extensively used in the present analysis of the Enid Isolated Terrace Aquifer.

In his study of Blaine and Major Counties, Fay (1962, 1965) describes many of the units found within the Enid study area. The Cedar Hills Sandstone Formation is classified by Fay as being uppermost in the Hennessey Group. Later Fay (1972) classifies the Cedar Hills Sandstone Formation as the lowermost formation of the El Reno Group. Information regarding climate, landuse, and socio-economic information is also described in this report.

Miscellaneous reports used in this thesis include an investigation of the subsurface units of western Garfield County by Caylor (1957) and a soil survey for Garfield County by Swafford (1967) who briefly discusses the geology as well as the climate and landuse in the area.

The United States Environmental Protection Agency (1975) prepared an extensive study of salt water contamination by using geophysical methods in and around the Enid area. Objectives of the study were to demonstrate the applicability of surface resistivity techniques to delineate salt water contamination in a shallow alluvial 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 United States Geological Survey (USGS) to determine maximum annual yield and annual allocations for those aquifers. Many of the hydrogeologic and modeling techniques used by Kent (1980) and Lyons (1981) 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 and described by Trescott and Larson (Trescott, Pinder and Larson, 1976). Witz (1978) developed new input-output options for the IBM 370-158 computer. The 1974 version of this model developed by the United States Geological Survey plus the latter modifications were used in the study.

CHAPTER III

DESCRIPTION OF THE STUDY

Location

The study area is located in the western half of Garfield County, in North Central Oklahoma. The location of the Enid Isolated Terrace Aquifer is shown in Figure 3. The aquifer extends over 52,000 acres in Garfield County and has an areal extent of 82 square miles.

Boundaries of the Enid Isolated Terrace Aquifer are controlled geologically. In the eastern half of the area, the boundary is defined by the Hennessey group - Quaternary terrace contact. The Cedar Hills Sandstone Formation - Quaternary terrace contact delineates the boundary in the western half of the area.

General Geology

The Enid Isolated Terrace Deposit is located on the northern shelf of the Anadarko Basin and within the Central Redbed plains geomorphic province of Oklahoma (Johnson, 1971). The topography within this geomorphic province can be described as red Permian shales and sandstones that form gently rolling hills and broad, almost flat plains. These Permian shales are overlain by Quaternary terrace deposits, which form the topographic highs in the northern corner.

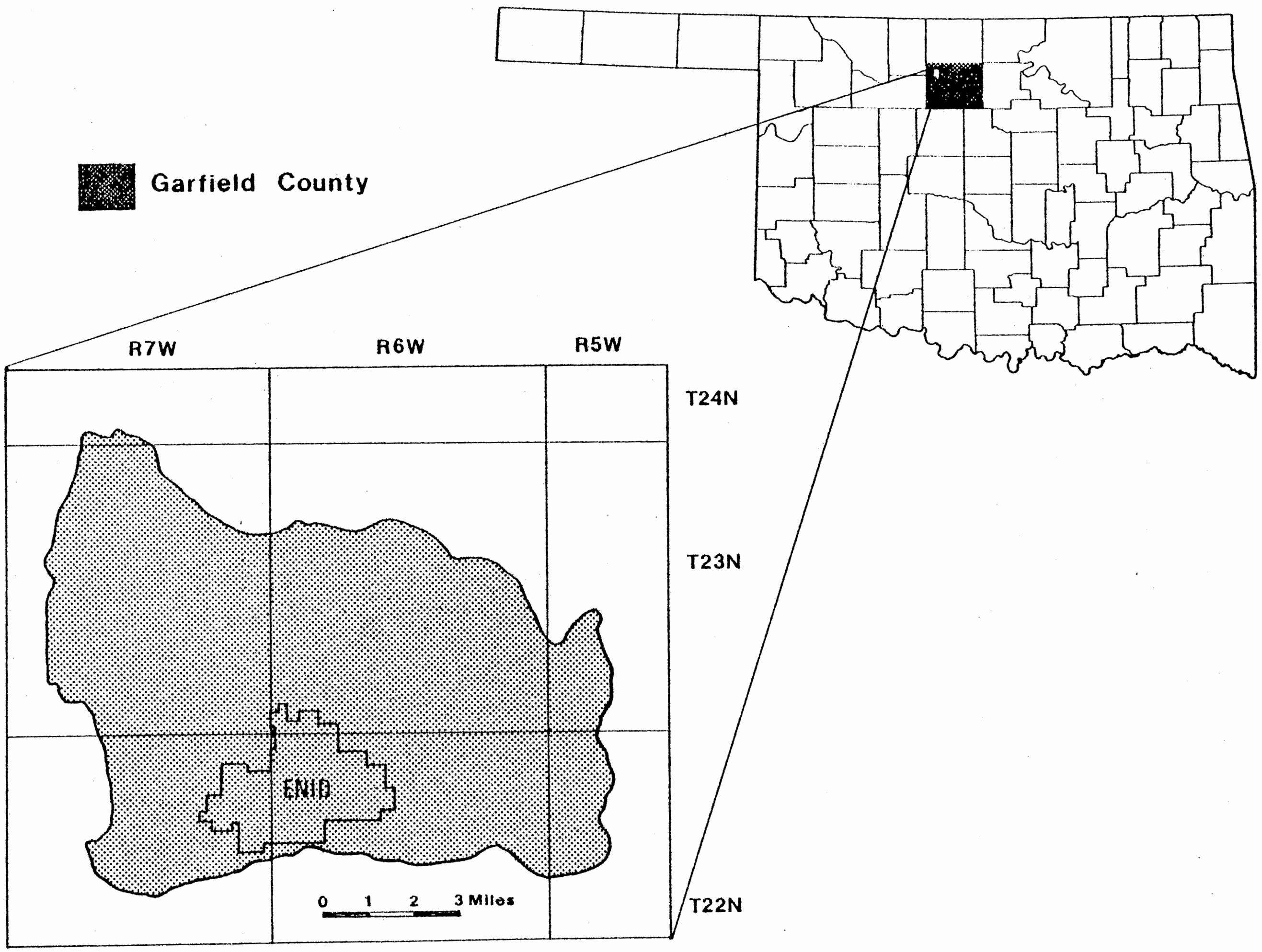

Figure 3. Location of Study Area by Township and Range

Reed (1952) notes that the terrace deposits form a topographic feature that is not readily discernible more than two miles from the Cimarron River. Their full topographic expression has been obscured by subsequent erosion and dune formation. The geologic exposures in the area range in age from lower Permian to Quaternary, with the Quaternary sediments lying unconformably on Permian bedrock.

The Permian units are classified as the Hennessey Group and the El Reno Group of the Cimarron Series. The Hennessey Group consists of the Kingman Formation, Salt Plains Formation and the Bison Formation (Figure 4).

The Kingman Formation, which is the oldest of the Permian units, underlies the terrace deposit and delineates the eastern most boundary of the study area. It is orange-brown to greenish-gray, fine-grained sandstone and siltstone, with some red-brown shale. Morton (1980) recognizes shales which are up to 70 feet thick.

The Salt Plains Formation is younger than the Kingman Formation and delineates the north-central and south-central boundaries of the Enid terrace aquifer. It is characterized by a red-brown siltstone with several thin layers, of greenish-gray and orange-brown calcitic siltstone. Bingham (1980) recorded as much as 160 feet of the following based on well-log information.

The Bison Formation which is uppermost and youngest in the Hennessey Group, is mainly a red-brown shale, with interbeds of greenish-gray and orange-brown calcitic siltstone present. The maximum thickness of the formation is 120 feet (Figure 5).

The Cedar Hills Sandstone Formation of the El Reno group rests conformably on the Bison Formation and underlies the terrace material

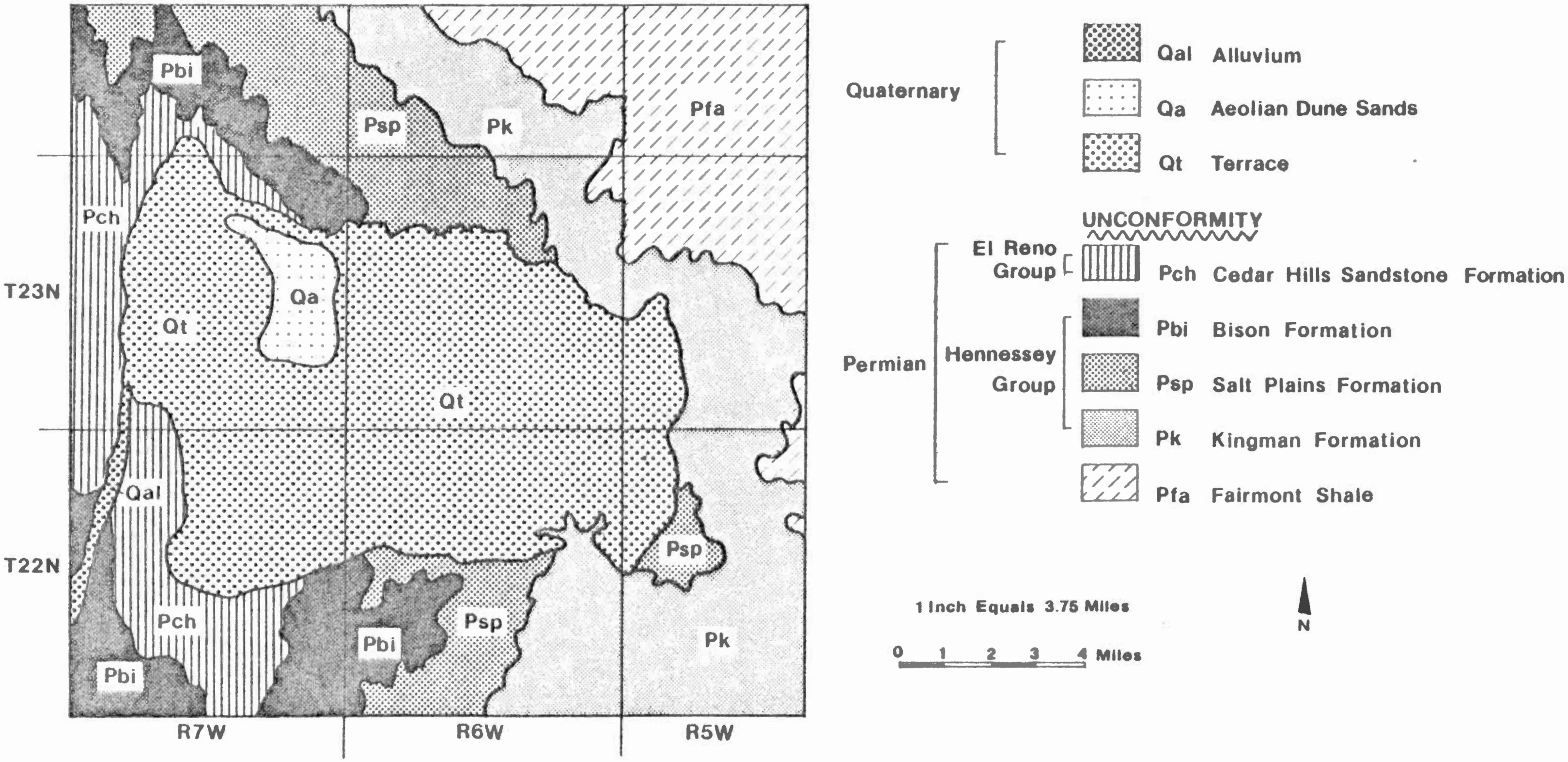

Figure 4. Geologic Map

Figure 5. Bison Formation in NW 1/4 Sec. 17 T.22N R.6W

in the western half of the study area (Figure 6). The northwestern, southwestern and western boundaries of the aquifer are delineated by the Cedar Hills - Quaternary terrace contact.

The Cedar Hills Sandstone Formation is a friable, well sorted, orange-brown to greenish-gray, fine-grained calcitic sandstone. Grain size variations occur throughout the area. Siltstones and some soft red-brown shale units have also been recognized as well as a thin siltstone bed that contains especially good depositional features. These features are shown in Figure 7. Although the maximun thickness is 180 feet, Swafford (1967) states that the sandstone is only 50 feet thick in Garfield County.

The Quaternary sediments vary considerably over the study area. These sediments are primarily composed of discontinuous layers of clay, sandy clay, sand and gravel. The sand and gravels generally are not well sorted, although in the southeastern part of the area the lower Quaternary material is extremely well sorted where it overlies the Permian formations. Color of the terrace materials vary laterally and vertically within the deposits.

Schwennesen (1914) recognized vertical color variation, and lithologic variation in the terrace deposits. He separated the terrace material into three layers. The uppermost layer is a dark brown soil varying from sand to heavy clay. The second layer consists of a reddish or bluish sandy clay which grades upward into layer one. Layer three is composed of well rounded quartz fragments, varying from fine sand to fine gravel, coarsest near the bottom. A photograph showing this vertical variation is shown in Figure 8.

Figure 6. Contact Between Bison Formation and Cedar Hills Sandstone Formation in NW 1/4, SW 1/4 Sec. 28 T.32N R.7W

Figure 7. Ripple Marks Found in the Cedar Hills Sandstone Formation in SW 1/4 Sec. 32 T.23N R.7W

Figure 8. Vertical Variations Within the Quaternary Material in SE 1/4 NE 1/4 Sec. 14 T.22N R.6W

Terrace materials which are directly in contact with the Permian bedrock will reflect the characteristic red-oxide color and will contain rounded, reworked clasts of the lower Permian units, varying in size from pebbles to cobbles (Figure 9). The lower Quaternary material may also take on the characteristic calcitic nature of the underlying formation and may be difficult to differentiate from various Permian units in the area. Small scale cross bedding is also present in the lower Quaternary material near the contact with the bedrock units.

The distinction between the terrace deposits and the Permian Cedar Hills Sandstone Formation has been made extremely difficult due to poor well records and similar characteristics in lithology. However, discrete color changes as well as grain size may be used as a criteria for differentiation where gravel deposits of the lower Quaternary material occur at the unconformable boundary. Reed (1952) noted that cross bedding and poor sorting are characteristic of the sand and gravel with the gravel composed of quartz with minor amounts of feldspar, ferruginous shale, and small pebbles of black quartzitic sandstone. Renick (1924) recognized the fact that these gravel deposits, at the base of the terrace deposit, are limited in distribution, but do possess favorable aquifer properties, i.e. moderate permeabilities and specific yields.

The thicknesses of the terrace deposits change radically from locality to locality within the area due to the eroded Permian bedrock surface and later erosional surface of the Quaternary deposits. The average thickness for the Quaternary age material is sixty feet.

Figure 9. Terrace Material With Reworked Clasts of Permian Age Material in NW 1/4 Sec. 15 T.22N R.6W

Geomorphology

The terrace material can be separated into three distinct localized geomorphic areas based on the topographic expression found in the area. The northeastern and southwestern regions can be characterized as a relatively flat area which has not been altered by extreme erosion or aeolian processes. Sands in this area thin toward the edge of the terrace deposits. Heavily incised, dendritic drainage systems prevail over the southeastern and north-central portions of the area. Permian units can be found in the stream beds and thicknesses of the terrace material are extremely variable depending on location. Headward erosion along Skeleton Creek and its tributaries is the predominant causitive agent for this topography.

The northwestern and west-central portions of the area are almost unaffected by headward erosion of streams. Renick (1924) characterizes this area as being relatively undissected by drainage with many undrained depressions. Aeolian deposits are distributed throughout this area. The sandy nature of the soils are favorable for rainfall infiltration and ground-water recharge. In his recommendations to the City of Enid, Renick (1924) stated that conditions were favorable for the accumulation of ground-water in Sec. 15, 22, 23, 24 and S 1/2 of Sec. 13 & 14 and N 1/2 of Sec. 25, 26, 27, T23N, R7W. Based on these recommendations, an extensive network of municipal and irrigation wells have been located within the boundaries of this geomorphic area.

The Permian units and Quaternary material have been mapped several times. The geologic map used initially for this investigation was based on a compilation of maps by Gould (1905), Schwennesen

(1914), Clark (1927), Reed (1952) and Miser (1954). Modifications to these maps were based on personal field work and on personal interviews with Fay (1981) and Morton (1981).

Climate

Climate of the red-bed plains region of north-central Oklahoma is continental, temperate, and subhumid. The mean annual temperature at Enid is 60.8°F (Swafford, 1967). The average annual precipitation of 1950-1979 is 31.11 inches, with May, June, and September having the greatest concentration of precipitation. Monthly and annual precipitation for the City of Enid are presented as graphs in Figures 10 and 11.

Ground-Water

The Enid Isolated Terrace Aquifer is an unconfined system; the upper boundary of the aquifer is formed by the water-table and the lower boundary by the semipermeable Hennessey Group. This condition is displayed on Plates 1 and 2. The water-table generally follows the topography of the area and subsurface flow is predominantly from the northwest to the southeast. The water-table gradient is fairly low except in the proximity of the aquifer boundary where seeps and springs are associated with steeper gradients.

The terrace deposits and Cedar Hill Sandstone have been treated as an undifferentiated aquifer where they overlie one another. Although geologic time and environments of deposition most assuredly have differed in the laying down of these sediments, hydraulically

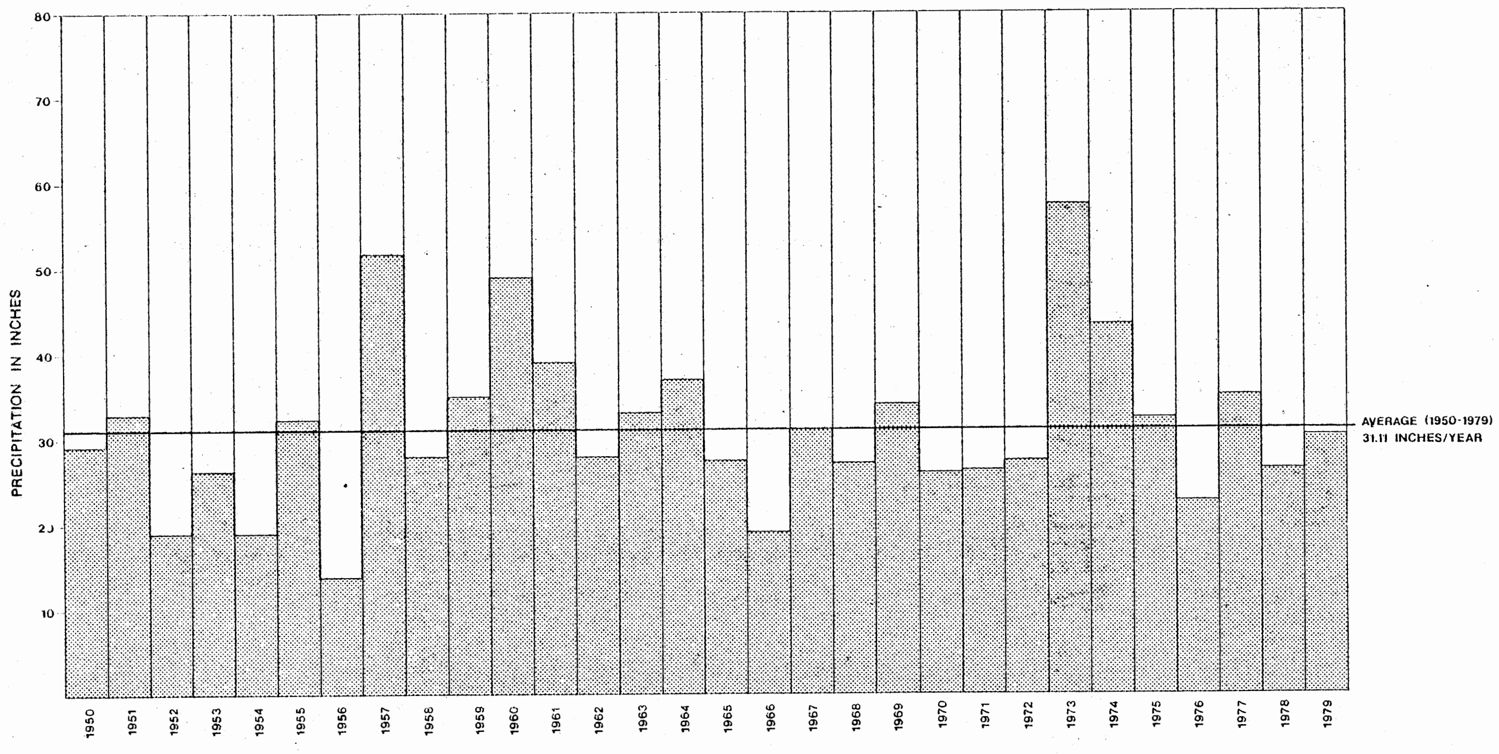

Figure 10. Annual Precipitation at Enid, Oklahoma 1950-1979

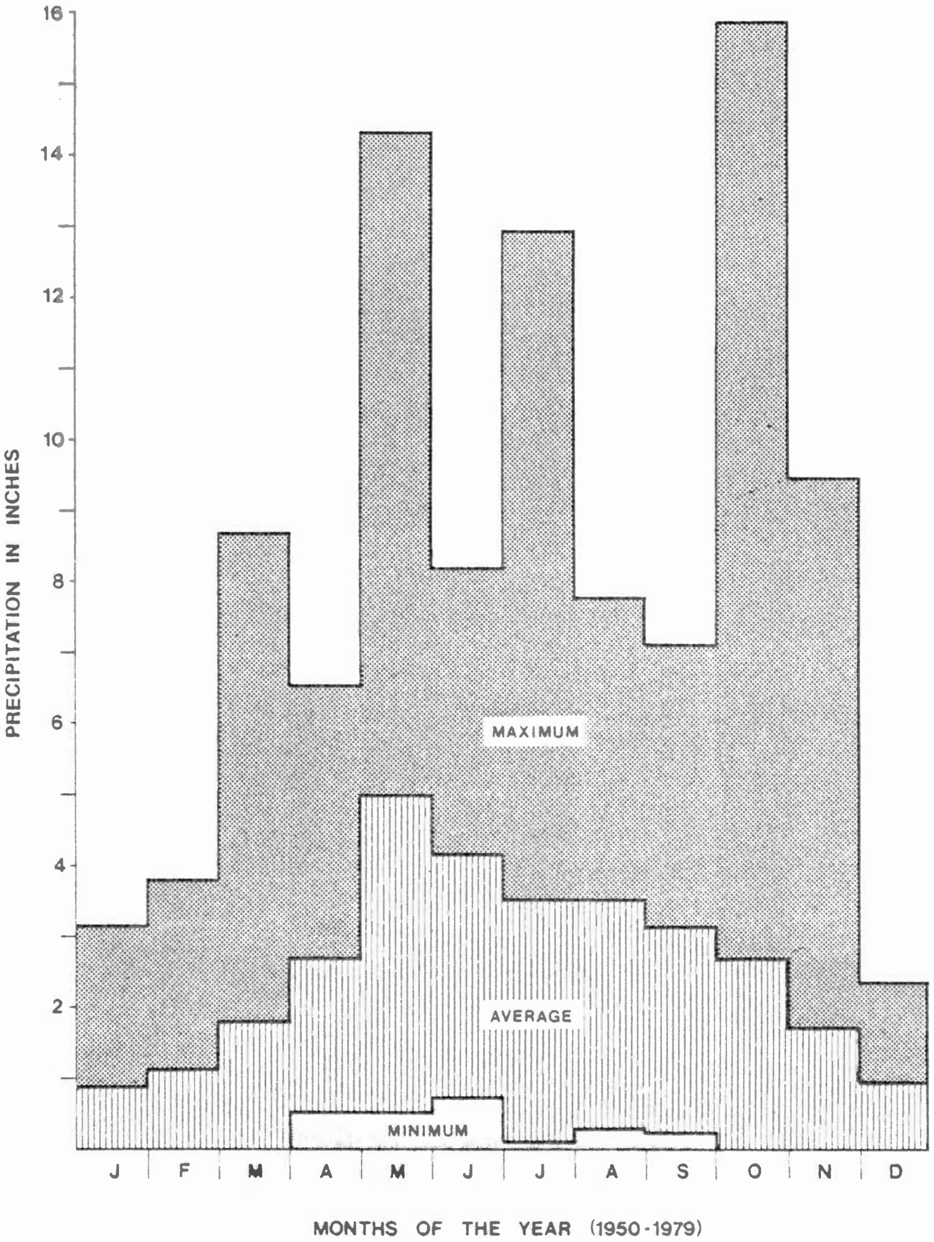

Figure 11. Monthly Precipitation at Enid, Oklahoma 1950-1979

they are very similar and together they make up the western half of the Enid Isolated Terrace Aquifer.

Morton (1980, 1981) recognized the Cedar Hills Sandstone Formation as having aquifer potential. In areas to the northwest of the study area, this unit has been used as a ground-water source with established well fields; however, these wells were later abandoned due to the heavily mineralized quality of ground-water.

Water Supply and Irrigation

Due to the nature of the area, ranching, farming and oil refining are the three main industries. Wheat, oats, barley, grain sorghum, and alfalfa are the dominant crops grown within the area. Pasture grasses are grown during the fall, spring and summer months.

Farm cultivation takes place in those areas devoid of aeolian dunes and not deeply incised by the dendritic drainage of the area. The greatest concentration of cultivation occurs in the west-central, southwestern, east-central and northeastern parts of the study area. The irrigation period for the above mentioned crops is June through September.

The City of Enid makes up the greater portion of the south-central portion of the study area. Enid, with a population of 45,000, is characterized by one-family dwellings with light industry interspersed throughout this region.

The main source of water, for the City of Enid, is from municipal wells located in the isolated terrace and also from wells located on the Cimarron terraces southwest of Enid. Of the 90 wells used for data collection, fifty percent of these were municipal wells used by the City of Enid.

Surface Recharge

Recharge is the major source of water to the aquifer in the area. Due to the sandy nature of the area a high infiltration rate can be expected. The recharge rate will vary depending upon many factors: rainfall intensity and duration, vegetation, soil type, permeability of unsaturated zone, temperature, wind, topography and depth to water-table.

A value of 2.3 inches per year recharge has been calculated for the area based on well hydrographs and precipitation hydrographs. This figure should represent a minimum value because throughout the period of study pumping took place somewhere within the aquifer.

The average annual rainfall for the area has been established at 31.11 inches per year as shown in Figure 10. The percentage of rainfall recharging the aquifer through infiltration and percolation has been estimated to be seven percent of the averaged annual rainfall. This estimate is based on well hydrographs and precipitation records for the area (Figure 12). The calculation of this recharge percentage is shown on Table I. The percentage of rainfall as recharge for each given year was calculated by dividing the estimated recharge using the hydrograph by the total rainfall for the year. The seven percent estimate represents an average value which was determined by averaging the percent of rainfall for the years between 1950 and 1955.

Subsurface Recharge

Subsurface recharge to the aquifer represents a minor, yet significant element in maintaining aquifer equilibrium. The subsurface flow is most prevalent in the western half of the area where the Cedar Hills Sandstone Formation is adjacent to and in hydraulic continuity with the Quaternary terrace deposits.

Water Quality

Ground-water quality is dependent on initial rain-water quality and chemical reactions which may occur during downward percolation the aquifer. In the Enid area, the ground-water has been analyzed and tested at several sites for Total Hardness (TH), Total Dissolved Solid (TDS), Sulfate (SO_4) and Chloride. This data is shown in Table II. Concentration of these dissolved minerals are a result of the period of contact between the ground-water and geologic formations and as a result of natural and man-made pollution.

All the Permian units and lower parts of the Quaternary material within the area contain some calcium carbonate ($CaCO_3$) which in turn provides the source for calcium (Ca^{++}) in the ground-water. The amount of Ca^{++} present in the water is reflected through total hardness. Waters containing a total hardness of less than 75 mg/l are considered to be soft, between 75 and 150 mg/l are moderately hard, 150-300 mg/l are hard and greater than 300 mg/l are very hard. Mean total hardness for the study area has been established at 193 mg/l. Using these parameters, waters analyzed from the Enid terrace are considered hard.

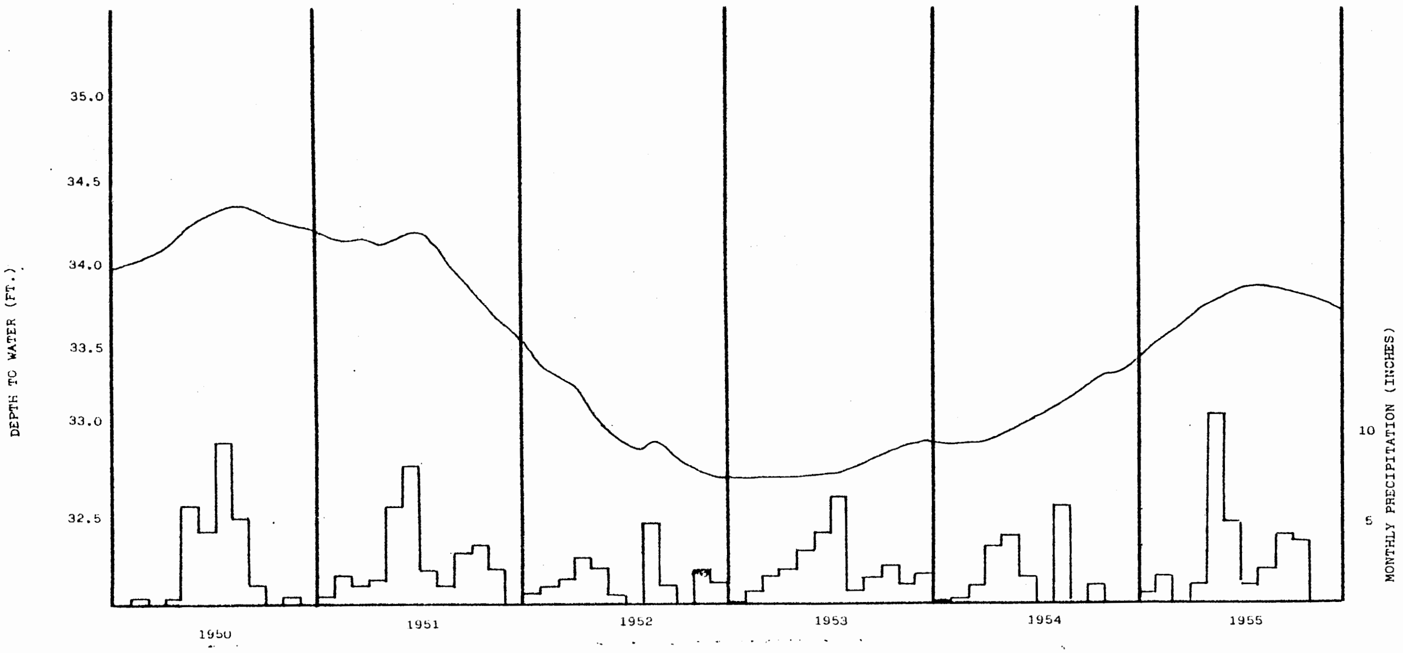

Figure 12. Well Hydrographs and Precipitation Data at Enid, Oklahoma 1950-1955

TABLE I

CALCULATION OF GROUND-WATER RECHARGE AND RELATIVE PERCENT OF ANNUAL RAINFALL

Year	Change in Water Table (inches) (From well hydrograph)		Average Specific Yield (Sy)		Ground-water Recharge (inches)	Total Rainfall for Year (inches)	Percent of Rainfall as Ground-water Recharge
1950	4.2	x	.295	=	1.2	28.8	4.2
1951	7.8	x	.295	=	2.3	32.8	7.0
1952	9.6	x	.295	=	2.8	18.5	15.3
1953	2.4	x	.295	=	.7	25.8	2.7
1954	5.8	x	.295	=	1.7	18.8	9.1
1955	5.5	x	.295	=	1.6	32.1	5.1
						Mean Percent as Recharge	7.2

TABLE II

WATER QUALITY FOR SELECTED WELLS

Location	Total Hardness (1)	Dissolved Solids (2)	Sulfate (as SO_4) (3)	Chloride (3)	Oklahoma Water Board Sample Number (4)
	milligram per liter mg/l				
SW SW NE 31 23N 6W	212	388	16	29	0539
SW NW NE 31 23N 6W	221	372	20	45	0541
SW SW SW 30 23N 6W	211	344	15	29	0540
SE SW SE 30 23N 6W	205	384	19	40	0542
NW NE SW 1 22N 7W	164	300	15	21	0522
NW SW SE 1	192	468	26	37	0523
NE NW SE 1	217	408	27	83	0524
SE NW SE 1	265	594	48	110	0525
SE NE SE 1	246	512	52	70	0526
NE NE SE 1	204	400	23	37	0527
NE SE NE 1	247	412	28	40	0528
SE SE SE 16 23N 7W	122	232	16	26	0532
SW SE SW 21	126	252	16	23	0535
NW NW NW 21	194	428	34	36	0552
SE SE NW 17	168	316	22	52	0553
NE NE SE 17	122	220	12	12	0554
SW SW SE 17	236	508	36	78	0551
NE NE NE 26	143	288	13	18	0534
NW NW NE 26	188	368	18	52	0533
SW SW NW 27	187	368	17	14	0529
NE NE NW 27	120	304	13	17	0531
NE NE NE 27	135	284	12	24	0536
NE NE NE 28	146	320	20	24	0530
SW SE NE 36	339	652	33	114	0537
NE NE NE 36	224	328	14	26	0538
	$\overline{X}$=193	$\overline{X}$=378	$\overline{X}$=22	$\overline{X}$= 42	

1. Reported as $CaCO_3$
2. 500 mg/l recommended maximum rejection limit
3. 250 mg/l recommended maximum rejection limit
4. Sample period August 1973

The mean total dissolved solids for the area is 378 mg/l. This value represents the total quantity of dissolved mineral matter in the ground-water. A recommended maximum value of 500 mg/l has been established by the United States Environmental Protection Agency for drinking water containing total dissolved solids.

Mean values for sulfate and chloride are 22 mg/l and 42 mg/l, respectively. The source of sulfate is associated with halite and gypsum deposits occurring in the Permian formations. Chloride is a common constituent of ground-water. Both values for sulfate and chloride fall well below the recommended maximum rejection limit of 250 mg/l, as set by United States Public Health Department. An areal distribution of these mean values is shown in Plate 3.

Permeability

Under normal conditions, aquifer test data are used to determine the coefficient of permeability and related transmissivity values for the study area. Unfortunately, aquifer test data are unavailable for the 90 wells located within the area. Therefore, an indirect method was used to generate the coefficient of permeability and transmissivity (Kent et. al. 1973). Information related to thickness and lithology of the terrace deposit was obtained from drillers logs of the 90 wells. The lithology is divided into four ranges: range one is associated with clay and silt; range two is very fine to fine sand; range three is fine to coarse sand; and range four is associated with coarse sand and gravel. A weighted average permeability was introduced by multiplying a weighting factor for the four size ranges by the percentage of saturated thickness for each range and summing up the total for all the ranges. The method is described for selected wells within the study area in Table III. The weighting factors for each range were obtained from the coefficient of permeability grain-size envelope developed by Kent et. al. (1973) as shown in Figure 13. The values of permeabilities were converted from gpd/ft^2 to units of feet/second by using a multiple of 1.55 x 10^{-6}.

In an attempt to ascertain that these values of permeability and transmissivity were correct this 'envelope' analysis was run on several wells completed in the Cimarron River terraces outside the study area (Reed 1952). Aquifer test data and very complete well logs were available for the chosen wells. The lithology of these wells was very similar to those encountered in the Enid area. A comparison of these two methods is shown on Table IV. Kent's envelope method was shown to be very accurate in ascertaining transmissivity and permeabilities when compared with aquifer test data.

Two average values of permeability were assigned to the Enid Isolated Terrace Aquifer based on subsurface geologic interpretation. These are shown in Figure 14. The Permian surface represents a highly eroded, unconformity surface. The Cedar Hill Sandstone Formation overlies this unconformable surface. The extent of the Cedar Hills Sandstone Formation is based on the well log data and discussions with Fay (1981) and Morton (1981). A channel fill of Cedar Hills Sandstone appears to exist in the mid-western portion of the study area. The channel fill underlies the thickest sections of Quaternary terrace material and permeability values were characteristically higher within this area. Therefore, the study area was divided into

TABLE III

CALCULATION OF WEIGHTED COEFFICIENT OF PERMEABILITY (K)

Location of Well	Well Log	From	To	Saturated Thickness (ST)	Range	Multiplier (M)	Coefficient of Transmissivity (T x M)
		ft.	ft.	ft.			gpd/ft
SW SE SE 28 21N 9W-2	Sand	0	10	0			
	Clay, gray	10	15	0			
	Clay, sandy	15	20	0			
	Sand, fine	20	35	11	2	300	3,300
	Clay, sandy	35	40	5	1	5	25
	Sand, Coarse	40	60	20	4	1,500	30,000
	Red beds	60	-				
				36			33,325

$$\text{Weighted K} = \frac{\Sigma\ T}{\Sigma\ ST} = \frac{33325}{36} = 925\ \text{gpd/ft}^2$$

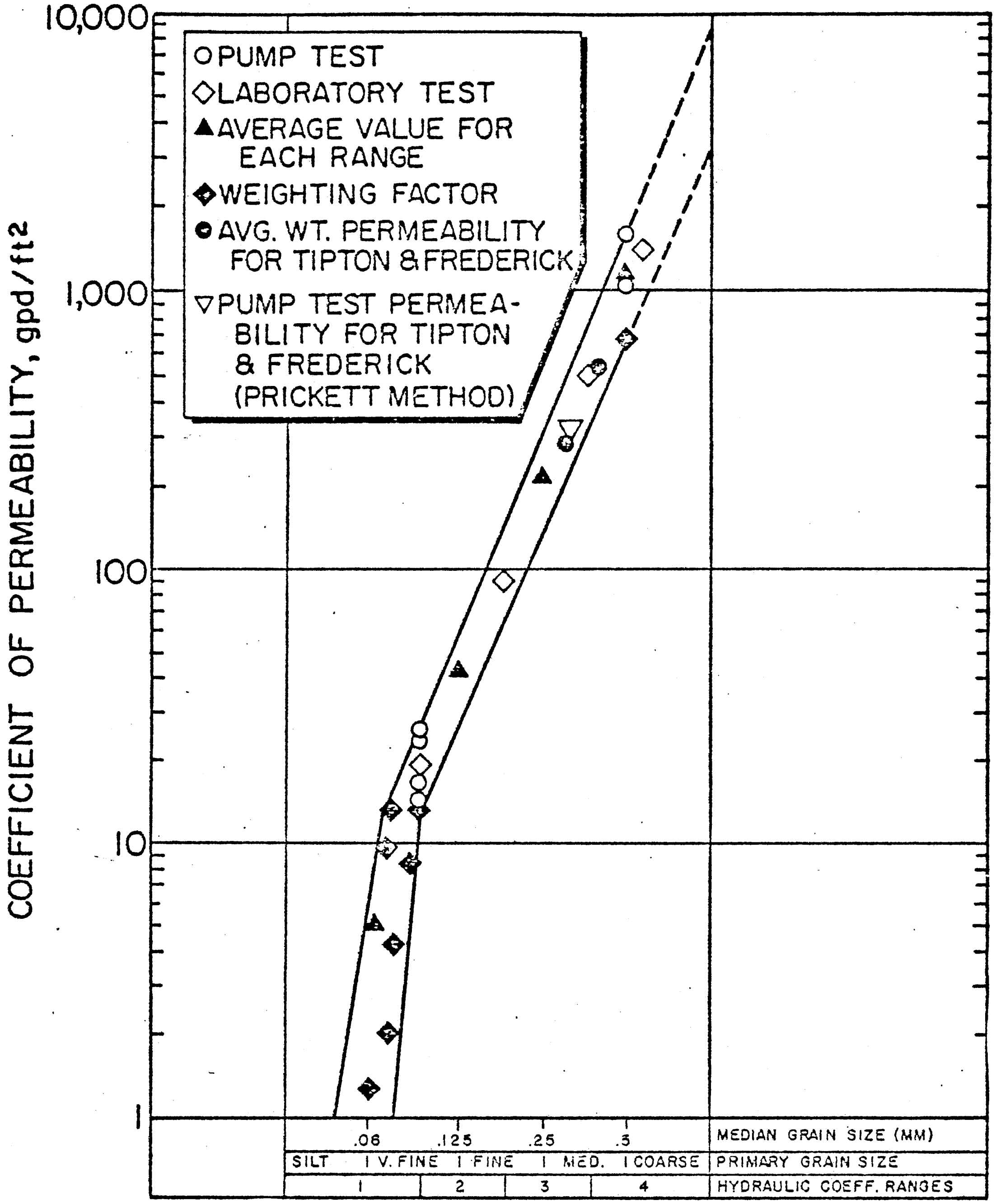

Figure 13. Coefficient of Permeability vs. Grain Size Envelope (after Kent, 1975)

TABLE IV

COMPARISON OF AQUIFER TEST DATA (Reed, 1952) WITH WEIGHTED COEFFICIENT OF PERMEABILITY (K) (Kent, 1975)

Well Location	Aquifer Test Values from Reed (1952)		Envelope Method from Kent (1975)	
	Coefficient of Transmissivity (gpd/ft)	Coefficient of Permeability (gpd/ft^2)	Coefficient of Transmissivity (gpd/ft)	Coefficient of Permeability (gpd/ft^2)
SEC 27 19N 8W-2	60,000	1,100	56,700	1,000
SEC 5 20N 9W-2	46,000	800	46,000	800
SEC 28 21N 9W-2	31,000	900	33,000	900
SEC 20 21N 20W-3	52,000	800	49,000	700

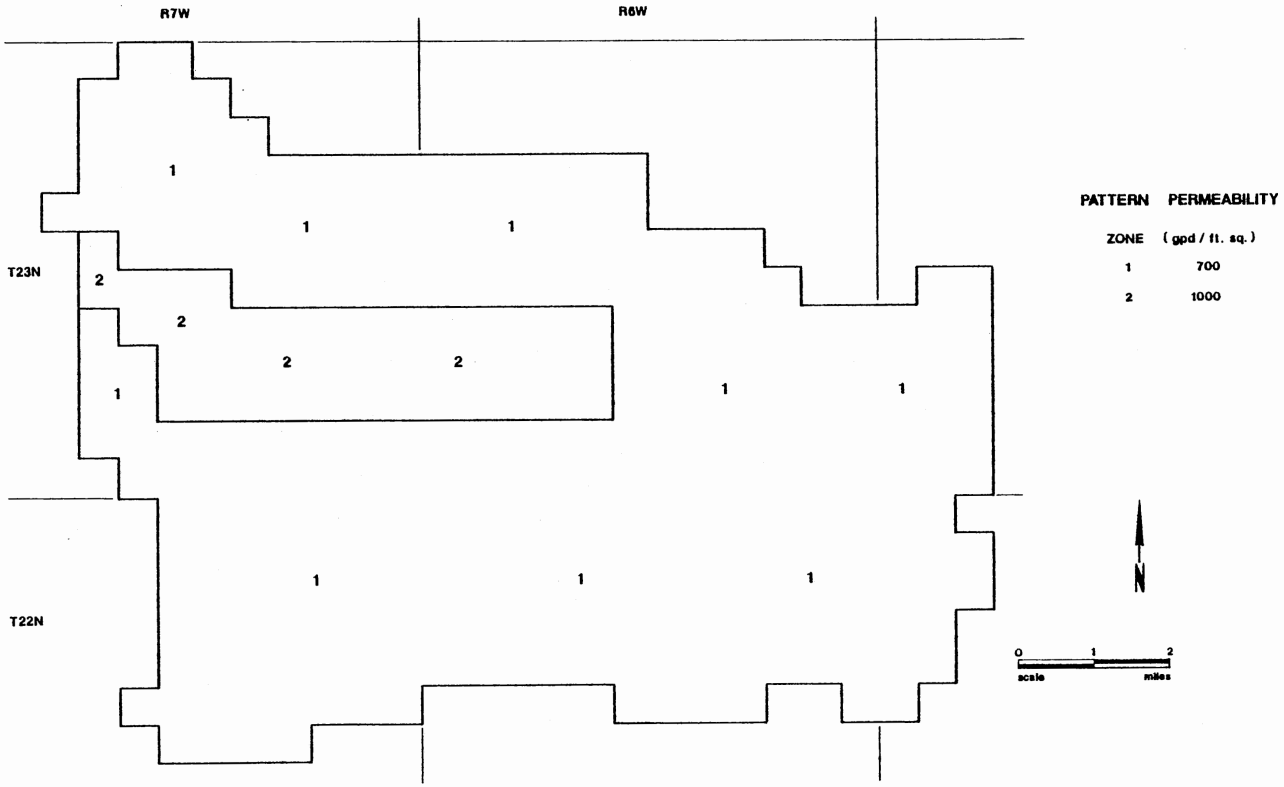

Figure 14. Patterned Permeability

two regions based on permeability. Areas of the aquifer which overlie the channel fill were assigned a value of 1000 gpd/ft^2. All other areas were assigned a permeability value of 700 gpd/ft^2. These values represent an average of the 90 wells used in this study.

CHAPTER IV

COMPUTER METHODOLOGY

General

In order to model the Enid Isolated Terrace Aquifer, quantitative values were assigned to hydrogeologic parameters. These numerical values were either generated by the computer system or were assigned directly by the modeler based on hydrogeological data.

The modeling program used in this report 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 for the Enid Isolated Terrace Aquifer. For a more complete explanation concerning the mathematical theory of this model, the reader is referred to Pinder (1970) and Trescott, Pinder, and Larson (1976).

Assumptions

In order to model the area, several assumptions concerning the aquifer were made. These are shown in Figure 15. The aquifer is assumed to be a quasi-homogeneous, unconfined system having a leaky lower boundary through which ground-water can percolate into the Permian bedrock.

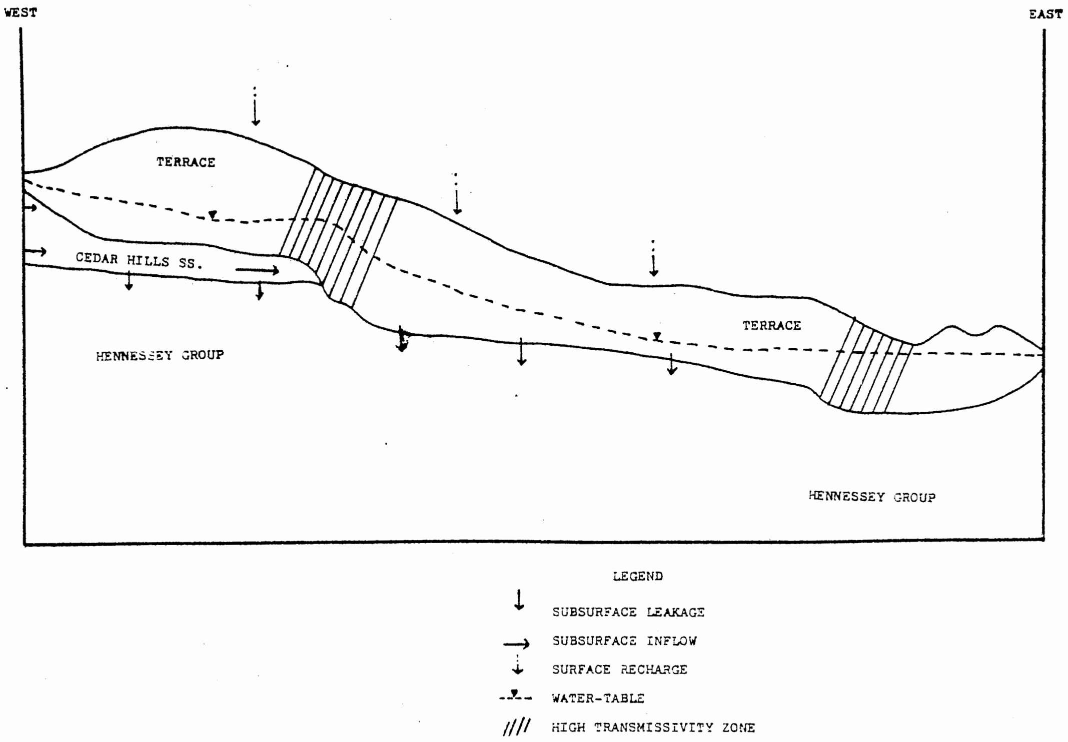

Figure 15. Conceptual Hydrogeologic Model

On a micro-scale, the Enid Isolated Terrace Aquifer is not homogeneous in the pure sense of the word. Vertical variations within the terrace occur throughout the area. Hydraulic characteristics also change as can be seen by noting the patterned permeability. Therefore, on a macro-scale the aquifer was subdivided into two zones of permeability. Each zone is represented by an averaged value of permeability used to represent homogeneous conditions within that zone.

Another assumption made was the bottom boundary represents an aquitard through which ground-water in the terrace leaks into the underlying fractured bedrock.

A recharge-discharge equilibrium is assumed to occur within the aquifer. Historical water-level measurements for selected wells seem to reflect this phenomena by noting the negligible change which occur between these 1950 wells and 1975 wells. The result of using this assumption can be recognized by comparing the prior rights water-table maps for 1973 and 1993 (Plate 1 and Figure 16); a negligible change in the two water-tables can be noted.

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 format is shown in Plate 4. The scalar values used are:

1. Specific yield (Sy)
2. Recharge rate (QRE)
3. Permeability of flow to river (RATE)
4. Effective distance from river (M)

5. Number of pumping periods in the total simulation time (NPER)
6. Number of days in period (TMAX)
7. Grid spacing in X-direction (DELX)
8. Grid spacing in Y-direction (DELY)
9. Number of rows in the model (DIML)
10. Number of columns (DIMW)
11. Length of time step in hours (DELT)

Matrices used are as follows:

1. Land surface elevations (LAND)
2. Bottom of aquifer elevations (BOTTOM)
3. Water-table elevations (STRT)
4. Permeability of the terrace material (PERM)
5. Prior appropriative pumping (WELL)
6. Constant gradient nodes (GRAD)

The permeability matrix was entered as a pattern. Bottom of river elevation (TOP) and river water elevations (RIVER) are generated by the program.

The initial recharge rate from precipitation was calculated to be seven percent of precipitation, as indicated by well hydrographs and rainfall data. Return flow from irrigation is estimated to be 25 percent of the total water pumped and is initially subtracted from the amount of water pumped in the model.

An average land elevation was identified for each quarter section and assigned to each node using the 15-minute United States Geological Survey Enid Quadrangle topographic map. Water-table and bedrock surface elevations of the aquifer were assigned to each node using a water-table contour map and a contour map of the base of the aquifer.

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

The coefficient of permeability for the aquifer was determined using the grain size envelope (Kent 1975), as discussed previously. The value of specific yield (Sy) was computed using a curve matching procedure. Values of permeability were matched with corresponding Sy values using the curve shown in Figure 18.

Constant gradient nodes were used as subsurface recharge elements and represent the change in head between constant gradient nodes and adjacent nodes. The calculation of the inflow from the constant gradient was made by a modification of the Darcy equation:

$$Q = K(W \times D)(\Delta H \div L)$$

where:

Q = the amount of inflow

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

W = cross sectional width of the node

L = distance between centers of nodes

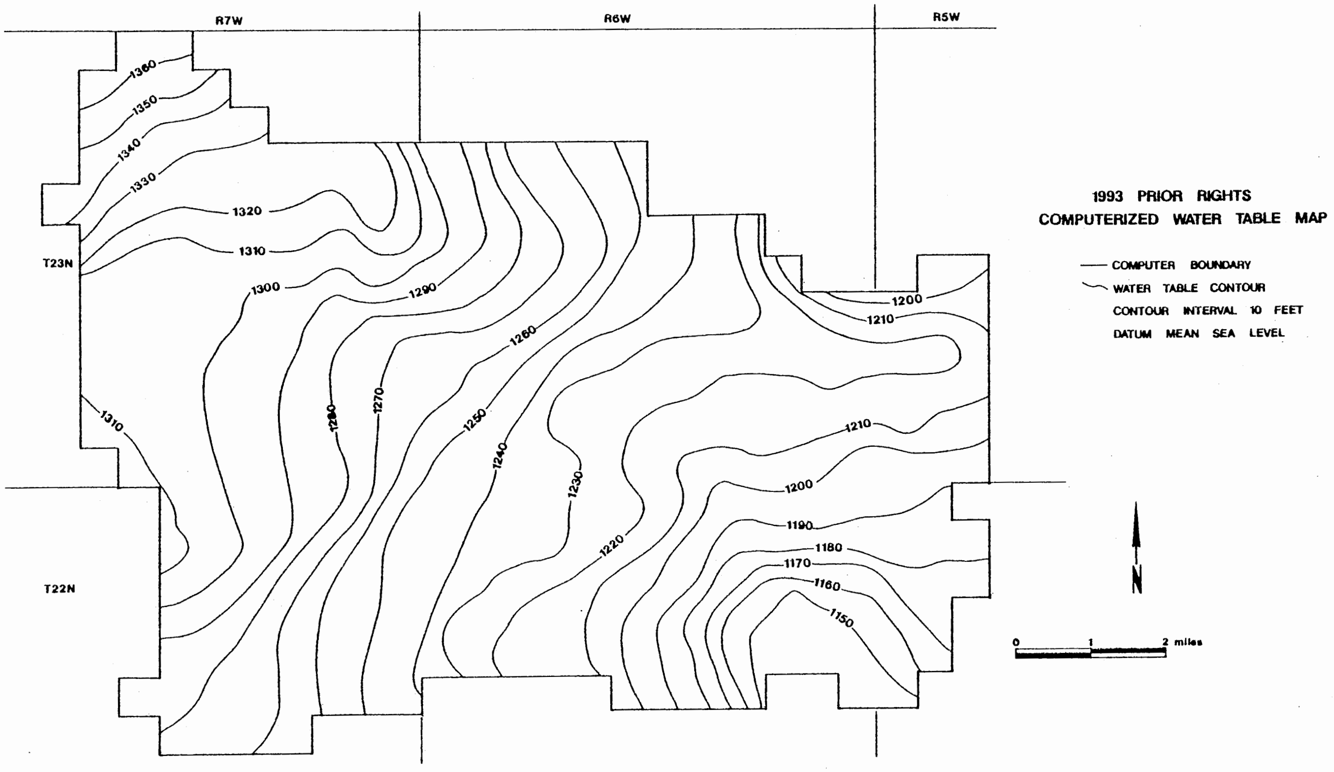

Figure 16. 1993 Prior Rights Computerized Water Table Map

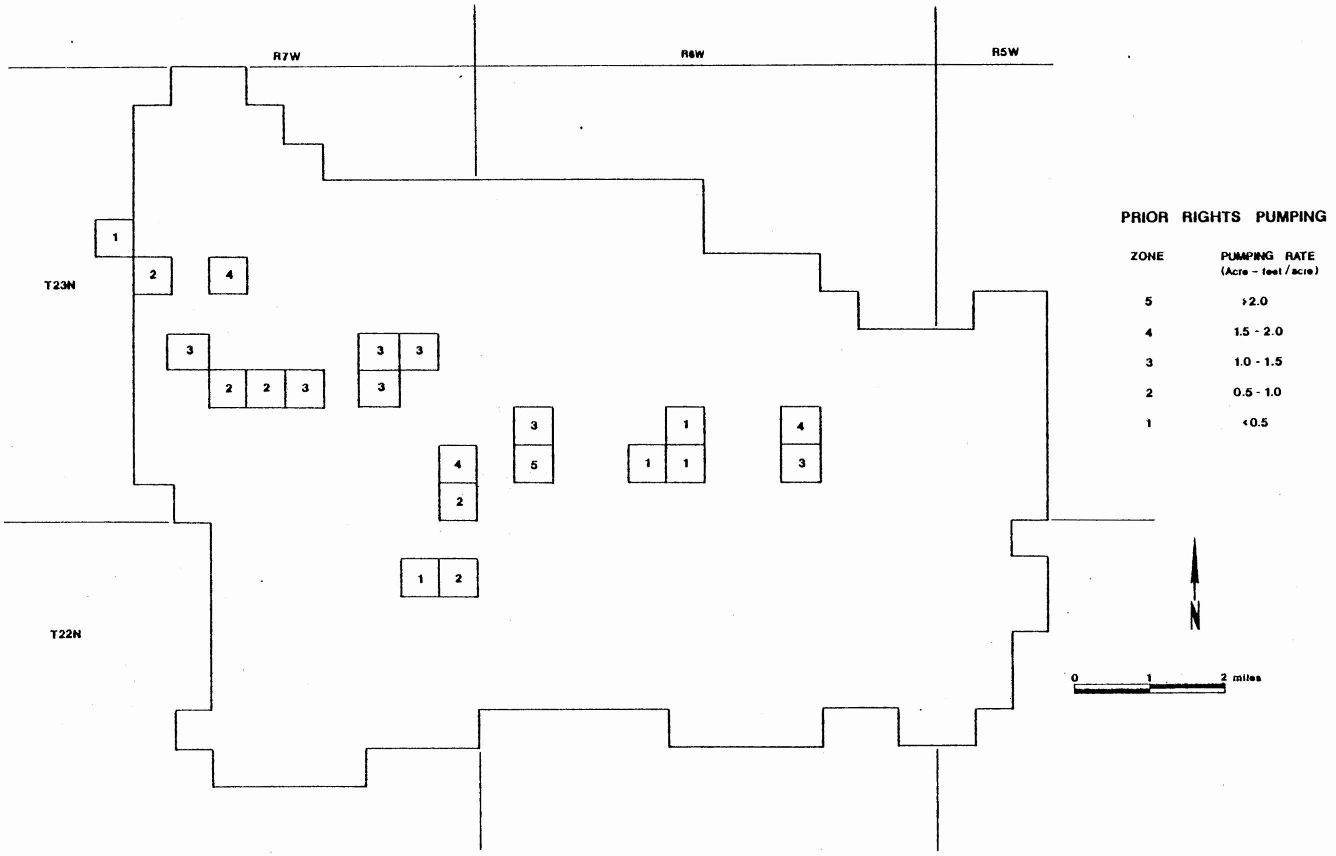

Figure 17. Prior Rights Pumping for Irrigation, Municipal and Industrial Use

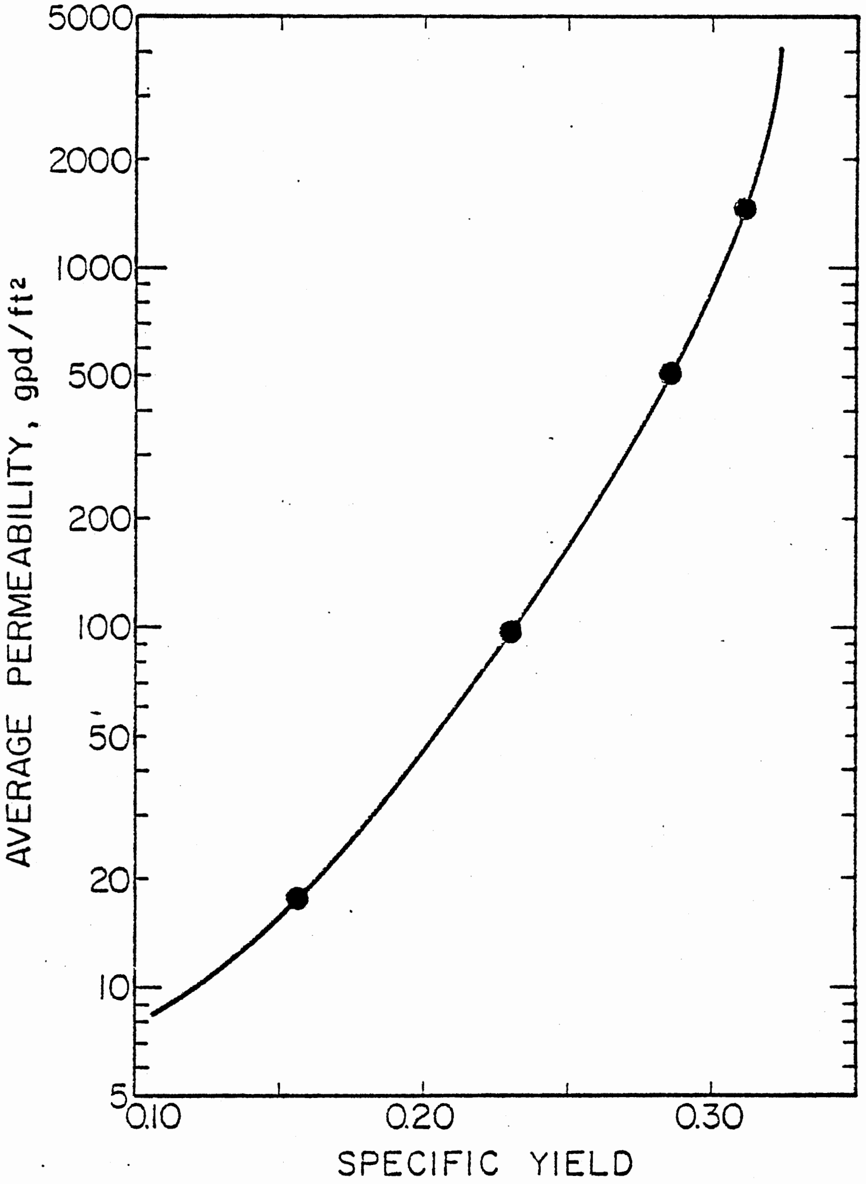

Figure 18. Relationship Between Permeability and Specific Yield (after Kent, 1978)

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.

Time Periods

The model was used to simulate pumping and corresponding water level changes over a one-year and a twenty-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 Statute 82, section 1020.4 and 1020.5 requires that new annual pumping allocations be assigned based on a minimum aquifer life of twenty years.

The simulation period was subdivided into 41 pumping periods (NPER) and a time step of ten days was used. A time step (DELT) 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 repeated 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 twenty-year simulation included two simulation runs: (1) prior appropriative rate only; (2) prior appropriative rate with allocation pumping.

Check Program

All of the matrices are loaded into the IBM computer using a time-sharing terminal. A check program is run to correct digitizing and contour errors. Saturated thickness is computed by subtracting the bottom elevations from the water-table elevations and shown on corresponding maps for each quarter section node (Figures 19, 20 and 21). Transmissivity is calculated in the model by multiplying the value of permeability for each node by the saturated thickness for the same node (Figures 22 and 23). 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.

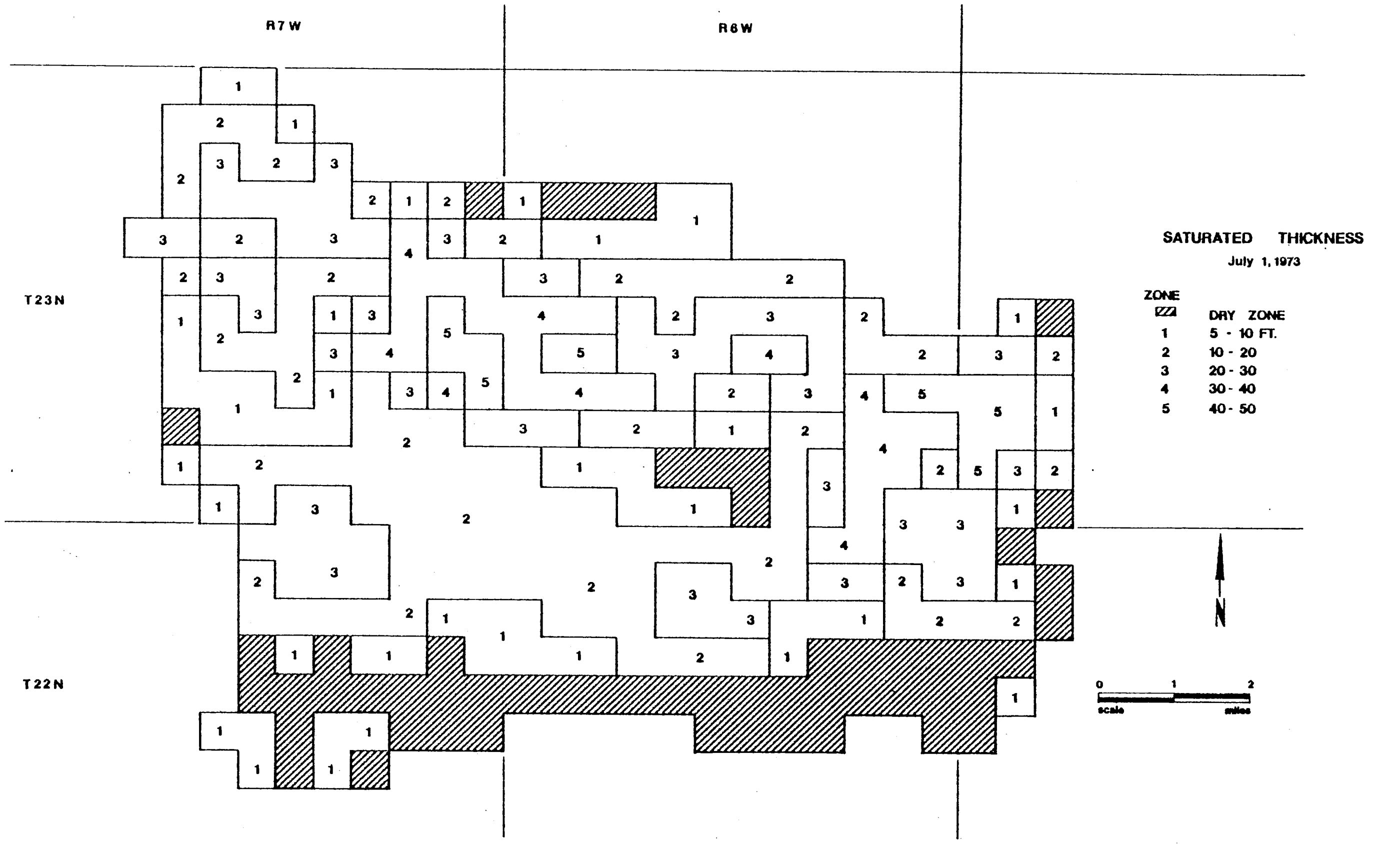

Figure 19. 1973 Saturated Thickness

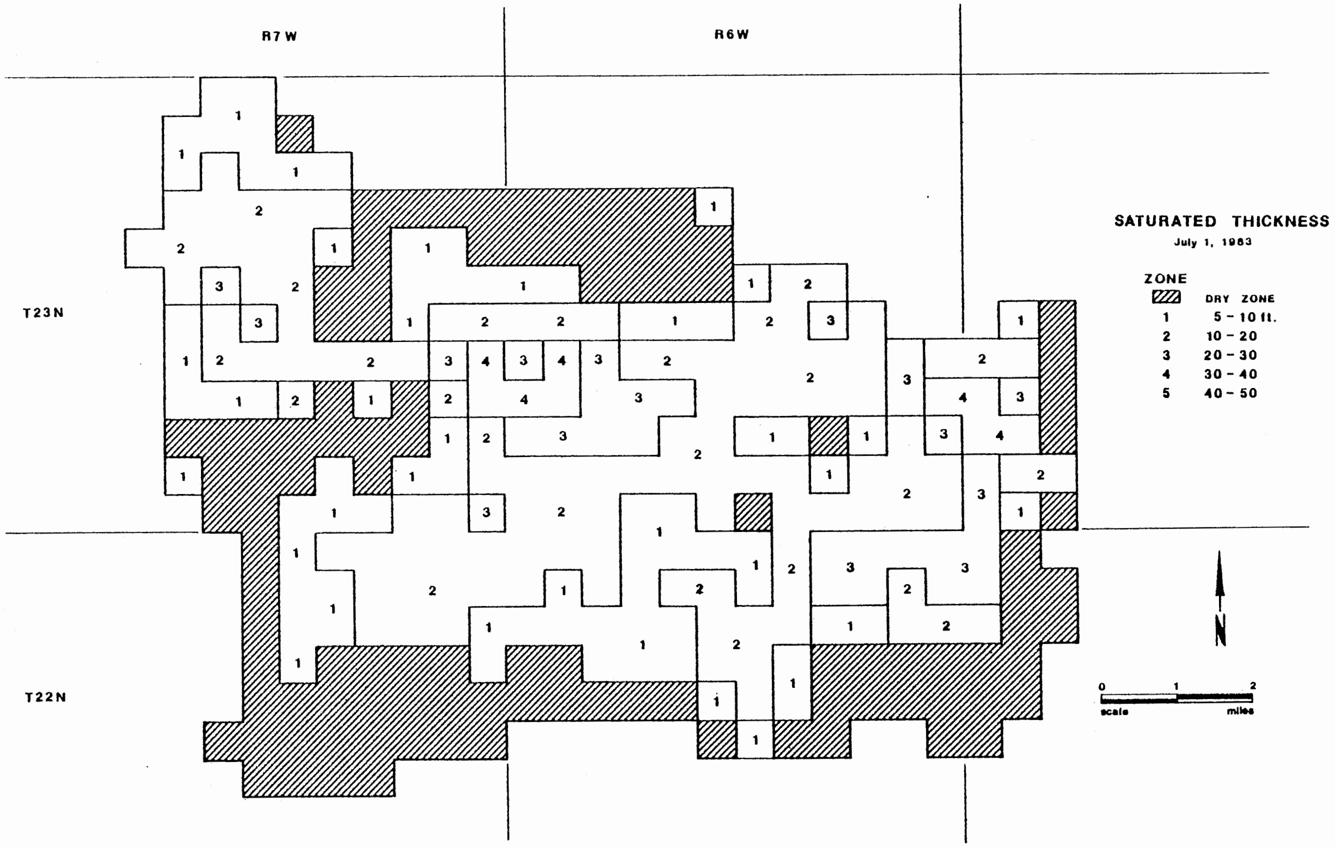

Figure 20. 1983 Saturated Thickness

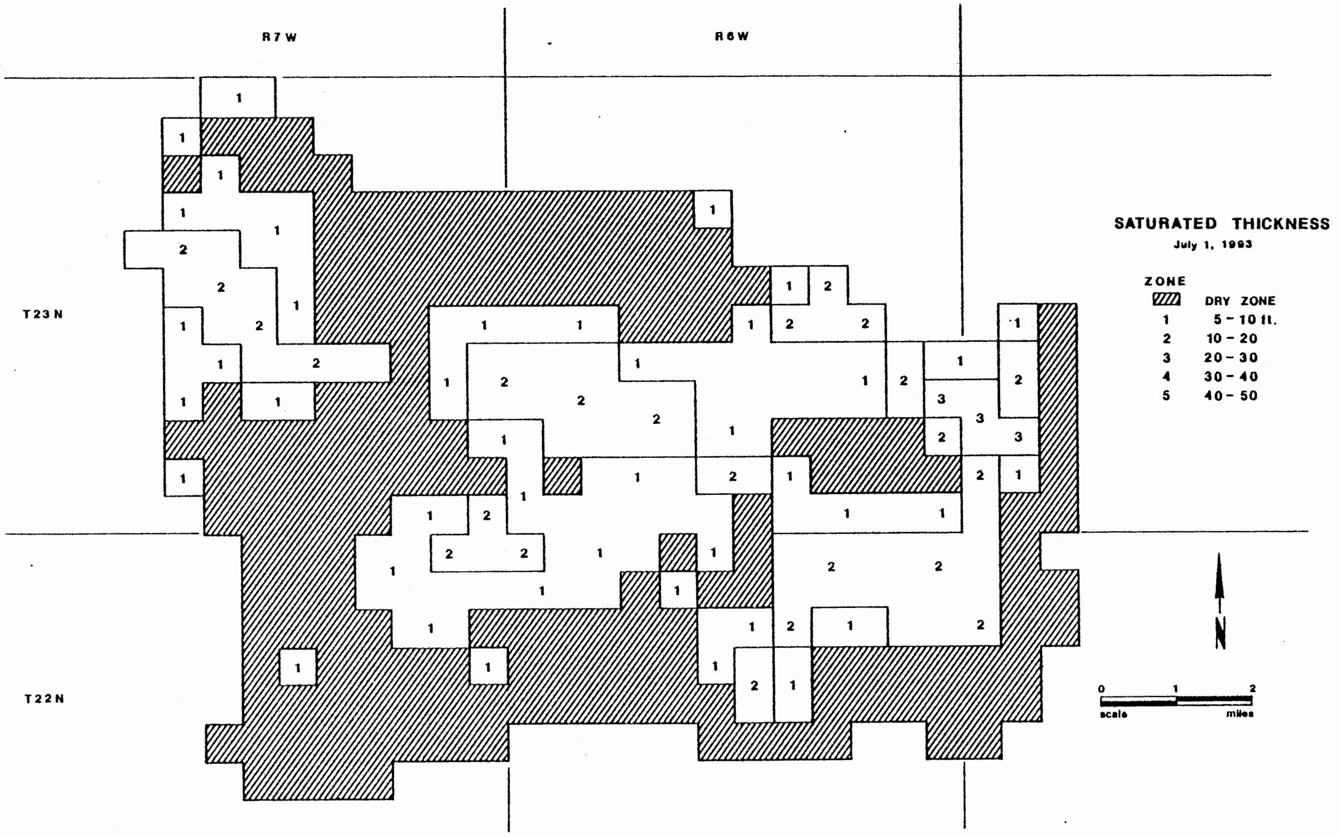

Figure 21. 1993 Saturated Thickness

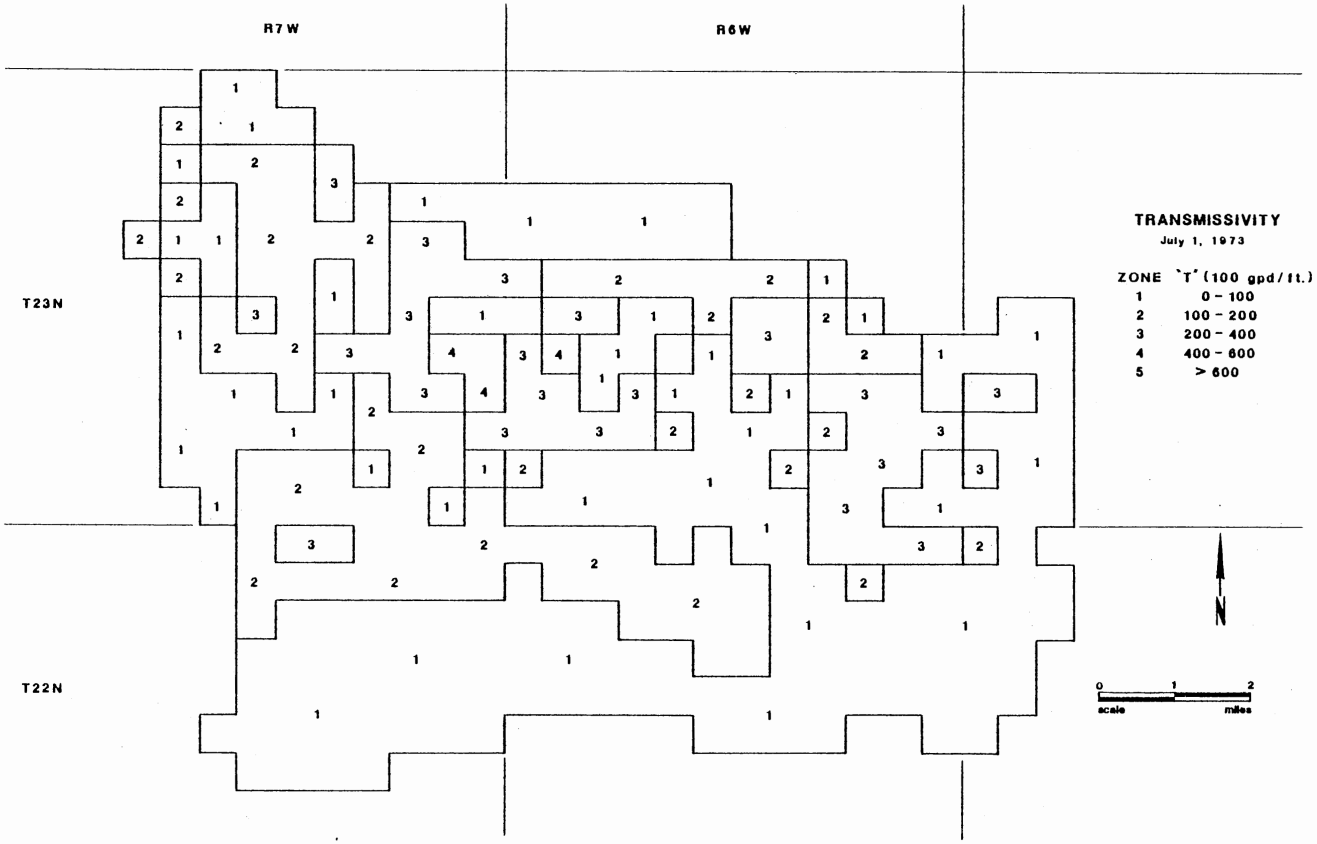

Figure 22. 1973 Transmissivity

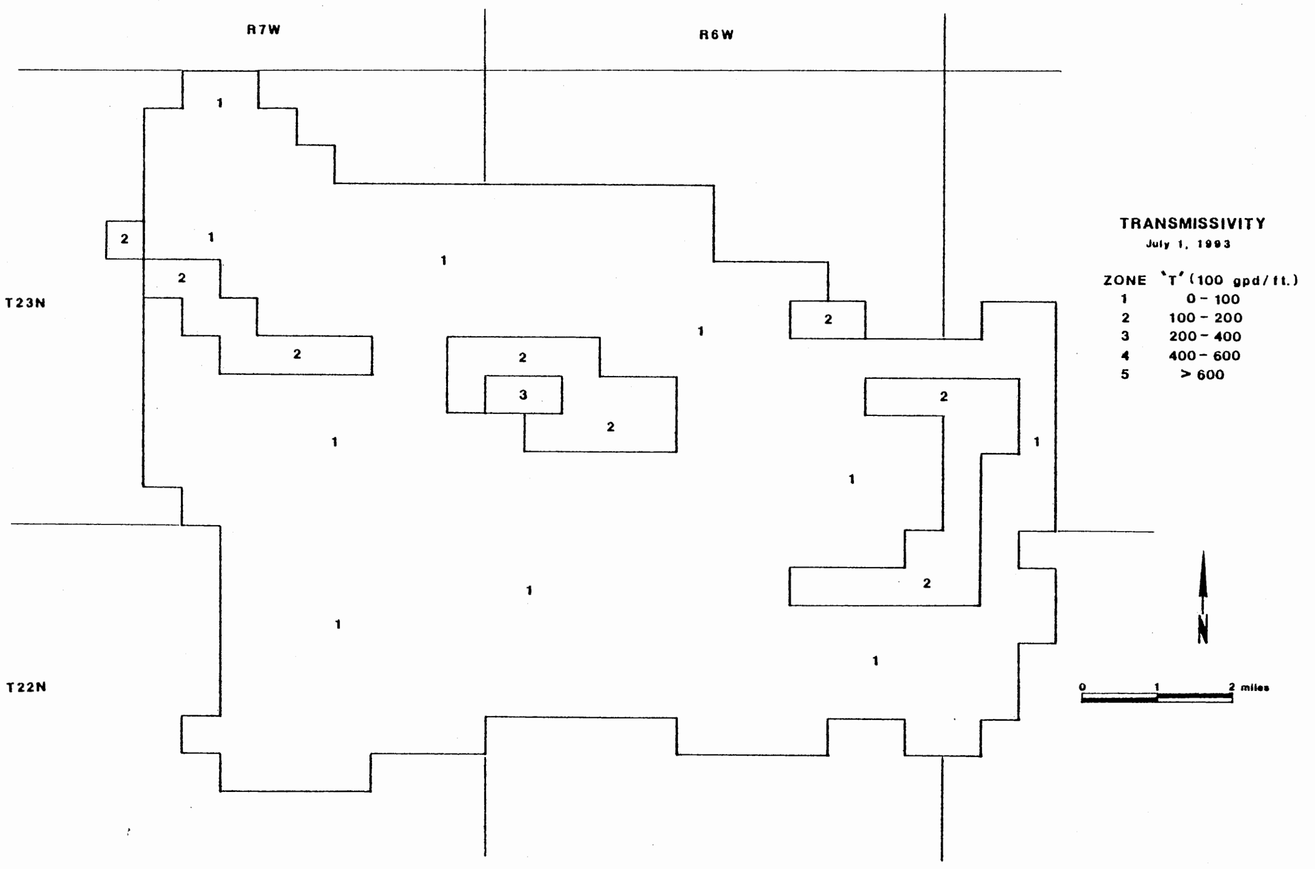

Figure 23. 1993 Transmissivity

CHAPTER V

RESULTS

Calibration

The Enid Isolated Terrace Aquifer is considered to be a quasi-homogeneous aquifer occurring in a recharge-discharge equilibrium. The main objective, in calibration of the model, was to maintain this recharge-discharge equilibrium. Equilibrium is established when the mass balance shows the inflow and outflow as being equal and is indicated by negligible fluctuations in the water-table elevations.

To calibrate the model, a river program option was used to simulate ground-water discharge into the intricate network of intermittent streams which are present in the area. This river option was used as an alternative to setting transient evapotranspiration parameters or constant gradient discharge node values. The river was deemed to be more appropriate to the geologic setting and was therefore used in simulating boundary discharge through seepage as well as discharge into streams.

Because the river option only handles relatively shallow water, a problem arose in the mid-central portion of the study area. Using the river option, it was noted that a mound build-up occurred after a one-year simulation run. This mound created a water excess of 4000 acre-feet. Assuming the Hennessey Group may represent a semi-permeable boundary, an attempt was made to program the model to remove this water excess by including a factor for bottom leakage. This attempt proved unsuccessful. Evidence for bottom leakage was supplied by Fay (1981) and Reed (1952). Fay, in a personal communication, described collapse features occurring in the Hennessey Group. Reed comments on solution cavities found within the Permian units.

The existence of the excess water causes the model to be in a state of nonequilibrium. Water would build up over the twenty-year run. Assuming that this excess is discharged into the bedrock units, the model should be calibrated. Because this was not accomplished, due to ground-water excess storage, the results must represent an upper limit.

Allocation

The final twenty-year computer simulation was conducted for the 1973 to 1993 period for the Enid Isolated Terrace Aquifer using pumping rates by prior appropriative right owners. This procedure was repeated using prior rights pumping and allocation pumping in order to establish a legal, annual allocation for the Enid Isolated Terrace Aquifer.

The maximum annual yield was determined by adjusting the amount of allocated pumpage that would cause approximately 50 percent of the nodes to go "dry" by the end of the twenty-year simulation period. A saturated thickness of five feet was considered "dry" due to the size limitations of a submersible pump, capable of pumping 300 gallons per minute, and set at the bottom of a fully penetrating well.

A sequence of values were used in trial simulation runs to ascertain their effect during the twenty-year simulation. The effects of these different allocations are shown in Table V. As the allocation is increased, the number of nodes going "dry" over the whole area increased. In order to obtain the required 50 percent "dry" area, 162 out of the 325 total nodes would go "dry." This situation was best approximated using the 0.5 acre-feet allocation. This corresponds to a maximum annual yield of 374,000 acre-feet and an annual allocation of 0.5 acre-feet per acre was determined.

In order to fully understand the implications of transmissivity on the annual allocation, initial transmissivity was zoned as either high or low transmissivity (Figure 24). The effects of zoning on various allocation rates are shown on Table V.

The results show that, even with a zoned transmissivity, the increase in allocation pumping is negligible. The annual allocation is increased from 0.5 acre-feet to 0.6 acre-feet in the high transmissivity zone whereas the allocation remains at 0.5 acre-feet in the lower transmissivity zone.

Saturated thickness maps for 1973, 1983 and 1993 are shown in Figures 19, 20 and 21, respectively. Those nodes which are located near the boundary tend to go "dry" during the computer simulation run except for those nodes in the northwestern corner where thicker sediments and subsurface inflow occur.

None of the prior right owners went "dry" using a 0.0 acre-foot allocation over a twenty-year run. However, seven of the twenty-one prior rights owners were effected by the annual allocation of 0.5 acre-feet over the twenty-year run.

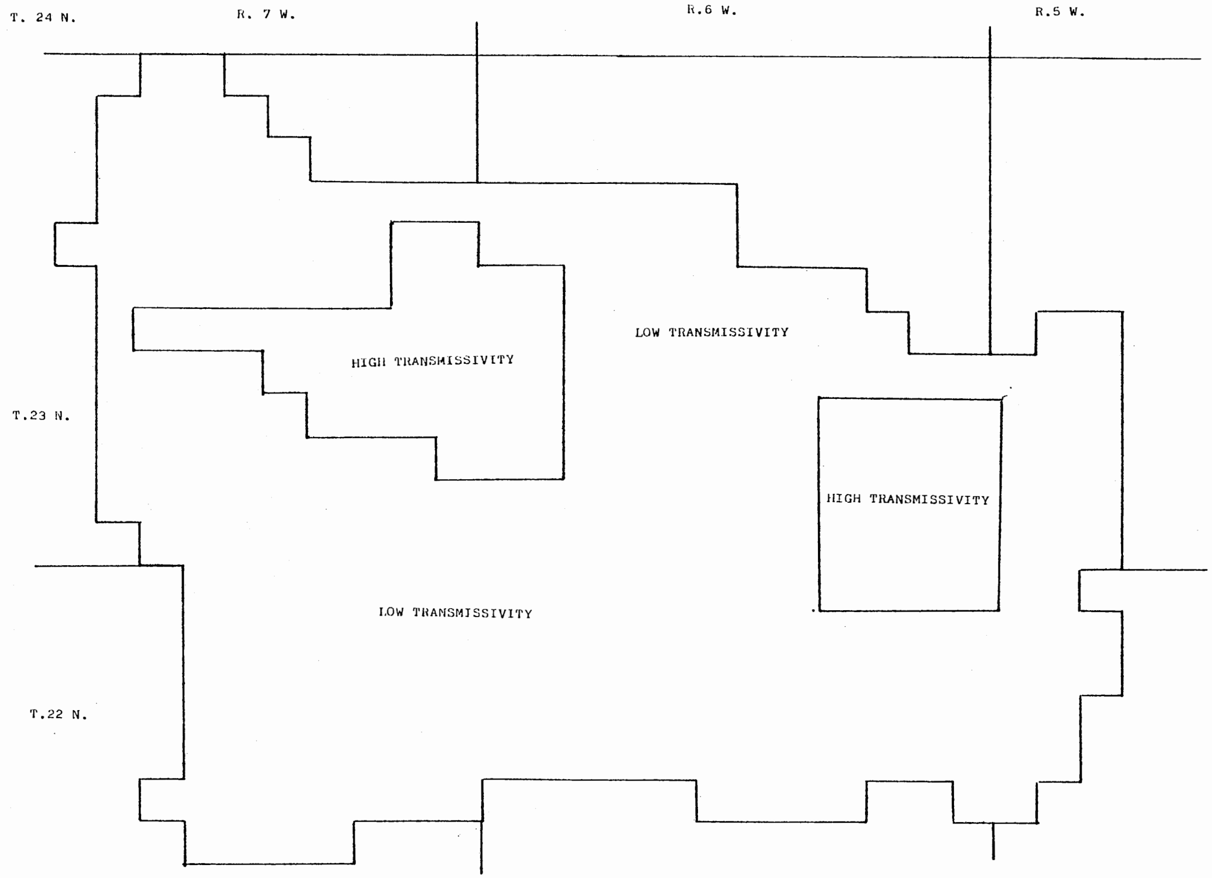

Figure 24. Zoned Transmissivity

TABLE V

PERCENTAGE OF "DRY" AREAS FOR DIFFERENT ANNUAL ALLOCATION RATES

	Total Area		High Transmissivity Zones		Low Transmissivity Zones	
Allocation (AF)	Number of "DRY" Nodes (325 possible)	% Dry	Number of "DRY" Nodes (53 possible)	% Dry	Number of "DRY" Nodes (272 possible)	% Dry
1	296	91	45	84	251	92
.8	274	84	44	83	230	84
.6	225	69	30	56	195	72
.5	168	51	21	39	147	54
.3	104	19	10	18	94	34
.0	43	13	0	0	43	15

The mass balance for prior appropriative and allocation pumping from July 1, 1973 to July 1, 1993 is shown in Table VI. Outflow during this twenty-year period is greater than the total inflow which results in a net decrease in storage. The twenty-year ground-water budget is shown in Figure 25. A net twenty-year outflow of 143,000 acre-feet occurs when the initial storage of 261,000 acre-feet is reduced to 118,000 acre-feet.

TABLE VI

MASS BALANCE OF PRIOR APPROPRIATIVE PUMPING FROM JULY 1, 1973 TO JULY 1, 1993

	Average Annual (Acre Feet)		Twenty Year Total (Acre Feet)	
	Inflow	Outflow	Inflow	Outflow
Recharge	9,966	X	199,324	X
Pumpage	X	16,734	X	334,684
River Leakage	75	1,634	1,507	32,672
Subsurface Flow	1,173		23,461	-0-
TOTALS	11,214	18,368	224,292	367,356
Net Storage		-7,154		-143,064

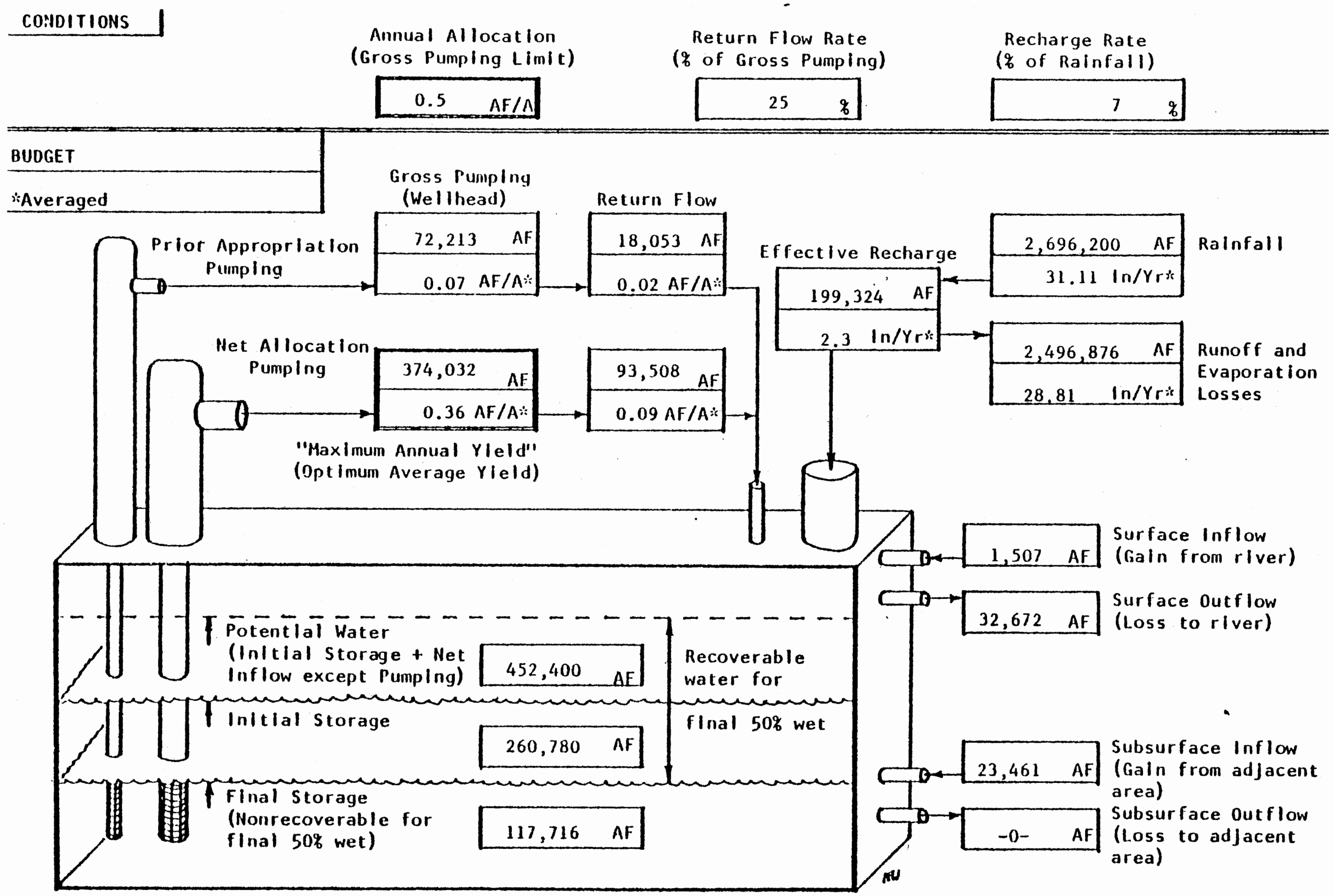

Figure 25. Twenty-year Ground-Water Budget (after Kent, 1980)

CHAPTER VI

CONCLUSIONS

General

Computer modeling has proven to be an effective tool in addressing the geologic and hydrogeologic parameters of the Enid Isolated Terrace Aquifer. The conclusions for this study are based on data acquisition by the author and quantification of the data for computer use. These conclusions are only as accurate as the raw data and the accuracy of the assumptions made.

The main assumptions used for the Enid Isolated Terrace Aquifer are as follows:

1. The Enid Isolated Terrace Aquifer is bounded vertically by the water-table above and the semipermeable Hennessey Group below. The base of the aquifer is upon an unconformable surface.
2. The Enid Isolated Terrace Aquifer forms a topographic high in the area. Variations in thickness occurs throughout the area due to the unconformable bedrock surface. Thicker terrace deposits were typically high in permeability.
3. The Enid Isolated Terrace Aquifer can be modeled as an unconfined, quasi-homogeneous aquifer in a state of

equilibrium. This condition will continue to exist unless there is increased pumping from irrigation, municipal and/or industrial wells such as assumed for allocation pumping. Two permeability zones are used to represent the homogeneous conditions.

4. Prior rights allocations were used to determine the maximum annual allocation.
5. The total number of acres for the study area is 52,000.
6. The estimated rate of recharge is 2.3 inches per year based on well hydrographs and precipitation data.
7. The base of the aquifer is considered to be a leaky bottom boundary. Water from the terrace will flow downward into the bedrock.

Conclusions arrived at after the computer twenty-year simulation runs are as follows:

1. The maximum annual yield for the area is 374,000 acre-feet.
2. The annual allocation is 0.5 acre-feet/acre.
3. The volume of water in storage in the aquifer as of July 1, 1973, is 261,000 acre-feet; the final storage as of July 1, 1993, is 118,000 acre-feet.

Recommendations

1. Transmissivity maps and zoned transmissivity can be used to identify those areas having higher well yields.
2. Annual allocations can be slightly higher if zoned transmissivities are used.

3. It will be necessary to verify the assumption that a leaky lower boundary exists. This can be achieved by recording water levels in the bedrock. Piezometers should be installed in the bedrock surrounding the study area in order to verify the direction of regional ground-water flow. If the head is lower than the base of the Enid Isolated Terrace Aquifer then the direction of vertical ground-water flow would be downward through the leaky lower boundary.

Coring of bedrock would be useful to identify secondary porosity and permeability in the form of solution cavities and fractures.

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VITA 2

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