COMPUTER SIMULATION OF THE ALLUVIAL AQUIFER ALONG THE NORTH FORK OF THE RED RIVER IN SOUTHWESTERN OKLAHOMA

By

ERIC JOHN PAUKSTAITIS

Bachelor of Arts

Rutgers University

New Brunswick, New Jersey

1973

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
July, 1981

COMPUTER SIMULATION OF THE ALLUVIAL AQUIFER ALONG THE NORTH FORK OF THE RED RIVER IN SOUTHWESTERN OKLAHOMA

Thesis Approved:

Douglas C. Kent
Thesis Adviser

James W. Naney

Gary F. Stewart

Zuhair Al-Shaieb

Norman N. Durham
Dean of the Graduate College

PREFACE

This study concerns the hydrogeologic properties of the alluvial aquifer associated with the North Fork of the Red River in southwestern Oklahoma. The primary objective of the study is to determine the maximum annual yield of fresh-water which can be pumped from the aquifer between July 1, 1973, and July 1, 1993. A computer model was used to simulate the hydrogeologic regime of the aquifer system and to determine the maximum annual yield based on pumpage prior to July 1, 1973 and subsequent allocated pumpage.

The author wishes to thank Dr. Douglas C. Kent, his major adviser, for his direction and support in this study. Sincere appreciation is also extended to Dr. Fred E. Witz, computer-system consultant, for his valuable assistance in modifications to the USGS ground-water model for application to the North Fork alluvium. Gratitude is extended to the Oklahoma Water Resources Board (OWRB) for providing funds for graduate research assistantships in the contract with Oklahoma State University and Dr. Kent, Principal Investigator of the project. Appreciation is extended to the following staff members of the OWRB for providing data and legal information: Mr. James Barnett, OWRB Director, Mr. J. A. Wood, Chief of Ground-water Division, and to Mr. Danny Spiser, geologist, for his aid in the field investigation. Special appreciation is extended to Dr. Gary F. Stewart, Dr. Z. Al-Shaieb, and Mr. James W. Naney, members of the thesis advisory committee, for their critique of this thesis.

Finally, very special gratitude is expressed to my wife, Arlene, without whose patience and support this study would not have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

ABSTRACT

The alluvial floodplain and terrace deposits associated with the North Fork of the Red River constitute an important ground-water aquifer supplying domestic, irrigation, and municipal needs in much of southwestern Oklahoma. The area under consideration extends over an area of approximately 575 square miles in Beckham, Greer, Kiowa, and Jackson counties.

A two-dimensional finite-differencing model was used to simulate well drawdown over a 20-year period between July 1, 1973, and July 1, 1993. The maximum annual yield of fresh-water that can be produced from the aquifer was determined based on pumpage prior to 1973 and subsequent allocated pumpage at different trial rates. Input into the model consisted of all available hydrogeologic data from a variety of sources plus information gathered during a field investigation of the area.

Model results were used to determine an annual allocation for each of three sub-basins. An annual allocation of 0.92 acre-foot per acre was determined for the entire 575 square mile area, assuming that one-half of the aquifer area would go dry during the 20-year period. On this basis, 3,358,761 acre-feet per year was established as the maximum annual yield. This annual discharge would yield a total volume of 67,175,220 acre-feet pumped between July 1, 1973, and July 1, 1993.

CHAPTER II

INTRODUCTION

The Quaternary alluvial terrace and floodplain deposits associated with the North Fork of the Red River comprise one of the major ground-water aquifers in southwestern Oklahoma. Southwestern Oklahoma is an important agricultural area, producing cotton, wheat, barley, and peanuts, as well as alfalfa, sorghum, and other feed crops. Having a semi-arid climate, this region is highly dependent on irrigation to augment natural precipitation. Ground water presently provides the bulk of irrigation demand.

The North Fork aquifer also supplies the water needs of several municipalities, including Elk City, Sayre, and Mangum, and the State Reformatory at Granite. Due to increased water demand for irrigation, this aquifer has undergone extensive pumping over the past twenty years. Consequently, water levels have declined where pumping has exceeded recharge. This trend can be expected to continue with increased use of irrigation.

Under Oklahoma Statue No. 82§1020.4 and 82§1020.5, the Oklahoma Water Resources Board (OWRB) is responsible for completing hydrologic surveys of each fresh ground-water basin or subbasin 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 Statute No. 82§1020.5 states the following:

> After making the hydrologic survey, the Board shall make a determination of 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. Transmissibility 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 (Oklahoma Legislature, 1973, pp. 51-53).

Objective

This study was undertaken in cooperation with and funded by the Oklahoma Water Resources Board to implement Oklahoma Statute No. 82§1020.5 for the North Fork of the Red River between the Texas border and northern Tillman County, Oklahoma. The objective of this study is to utilize all available hydrogeologic data to determine the maximum annual yield and annual allocation of fresh water that can be produced from the North Fork alluvial aquifer for the 20-year period between July, 1973, and July, 1993. This objective was achieved using the following methods:

1. Selection of hydrogeologic data, supplied by the Oklahoma Water Resources Board (OWRB) and from other sources, to be used as input into the mathematical model.

2. Field investigation of the area to supplement information supplied by the OWRB.

3. Assignment of spatially distributed aquifer properties to alluvial deposits based on available hydrogeologic information.

4. Calibration of an existing mathematical model and simulation of ground-water flow and corresponding changes in hydraulic head in an unconfined alluvial aquifer over a 20-year period.

Previous Investigations

Portions of the North Fork alluvial and terrace deposits were mapped and briefly described in early studies of the bedrock geology of southwestern Oklahoma (Gould, 1905, 1926; Sawyer, 1924; Gouin, 1927; Clifton, 1928). More detailed mapping of the alluvial deposits was undertaken by later investigators (Scott and Ham, 1957; Merritt, 1958; Murphey, 1958; Meinert, 1961; Johnson, 1963, 1969; Smith, 1964).

The first comprehensive study of the alluvial deposits of the North Fork basin was undertaken in 1951 by the U.S. Geological Survey (USGS) in cooperation with the Oklahoma Water Resources Board. In that year the USGS initiated an exploratory drilling program in central Beckham County to determine the character of the alluvial sediments and to estimate the total amount of water available from these deposits. In that same year, Shell Oil Company drilled a series of exploratory wells in the alluvium to locate a reliable ground-water source for their refinery in eastern Beckham County. A report based on the results of these drilling programs plus an inventory of domestic and irrigation wells was published by the OWRB (Burton, 1965). The report includes bedrock, water table, and saturated thickness maps based on available well data. The OWRB also completed ground-water studies of Elk and Otter Creek basins, which are tributaries of the North Fork (Hollowell, 1965).

A summary of the geology, soils, ground- and surface-water availability and quality, as well as present and projected water needs, was published by the OWRB in "Appraisal of the Water and Related Land Resources of Oklahoma, Region One," (1967). Engineering properties of soils, alluvial materials, and bedrock of southwestern Oklahoma were summarized by the Oklahoma Highway Department (Oklahoma Highway Dept., 1969). The most recent summary of the geology and water resources of southwestern Oklahoma was completed for the Clinton quadrangle in 1976 (Carr and Bergman, 1976) and for the Lawton quadrangle in 1977 (Havens, 1977) by the Oklahoma Geological Survey in cooperation with the U. S. Geological Survey.

This present study consists of data processing for and calibration of an existing mathematical model to predict changes in the potentiometric head (water table) due to pumping. A finite-difference model (Trescott and Pinder, 1976) was used to simulate those changes in the North Fork alluvial aquifer. The model used in this study evolved from Pinder's original model (1970) which was designed to simulate changes in potentiometric head for two-dimensional aquifer problems, and from modifications made by Pinder (1969) and Trescott (1973). Further modifications and addition of a Print/Plot option (Witz, 1978) allow data and results to be selectively stored and printed in map form.

In the present study aquifer coefficients of permeability and specific yield are assigned to layered sediments described on drillers logs. This approach, which is based on work in the Washita River alluvium, (Kent et al, 1973), was used successfully in a computer model simulation of the Tillman Terrace alluvium (Kent and Naney, 1978; Al-Sumait, 1978). A sensitivity analysis of the vertical variability of these aquifer properties, using a similar digital model, was completed by Loo (1972) and DeVries and Kent (1973).

CHAPTER III

DESCRIPTION OF THE STUDY AREA

Location

The study area is located in the southwestern Oklahoma counties of Beckham, Greer, Kiowa, and Jackson (Figure 1). It includes parts of T2N through T11N and R17W through R26W. It is bounded on the west by the Texas border and on the south by Tillman County, Oklahoma. The aquifer extends over an area of approximately 575 square miles.

Climate

The study area is characterized by a warm, continental climate with generally mild winters and long hot summers. The average annual temperature at Sayre, Oklahoma (based on 30 years of record) is 63°. Prevailing winds are from the southeast at 1 to 12 mph. The average annual precipitation recorded at Sayre for the period 1951 to 1977 is 22.78 inches per year (Figure 2). It can be seen that rainfall deviated considerably from the average during the 1950's with drought conditions occurring during the early 1950's and heavier than average rainfall occurring in the late 1950's and early 1960's. The heaviest precipitation generally occurs in May and the lightest in January (Figure 3). A weighted average precipitation of 24.28 inches per year for the entire project area was obtained using the Theissen polygon method (Hjelmfelt and Cassidy, 1976). Average annual precipitation recorded at surrounding stations (Figure 4) is shown in Table I.

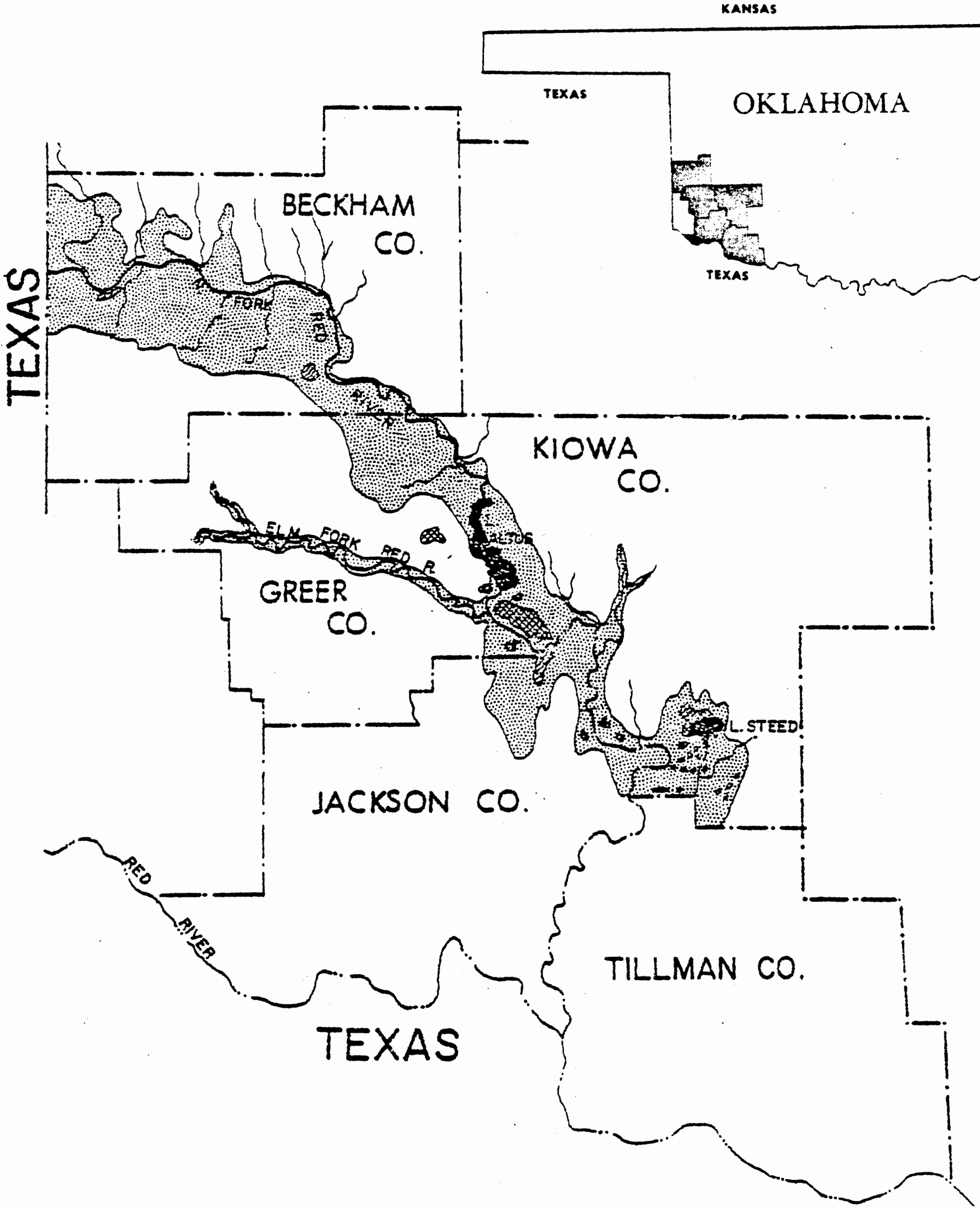


Figure 1. Location Map

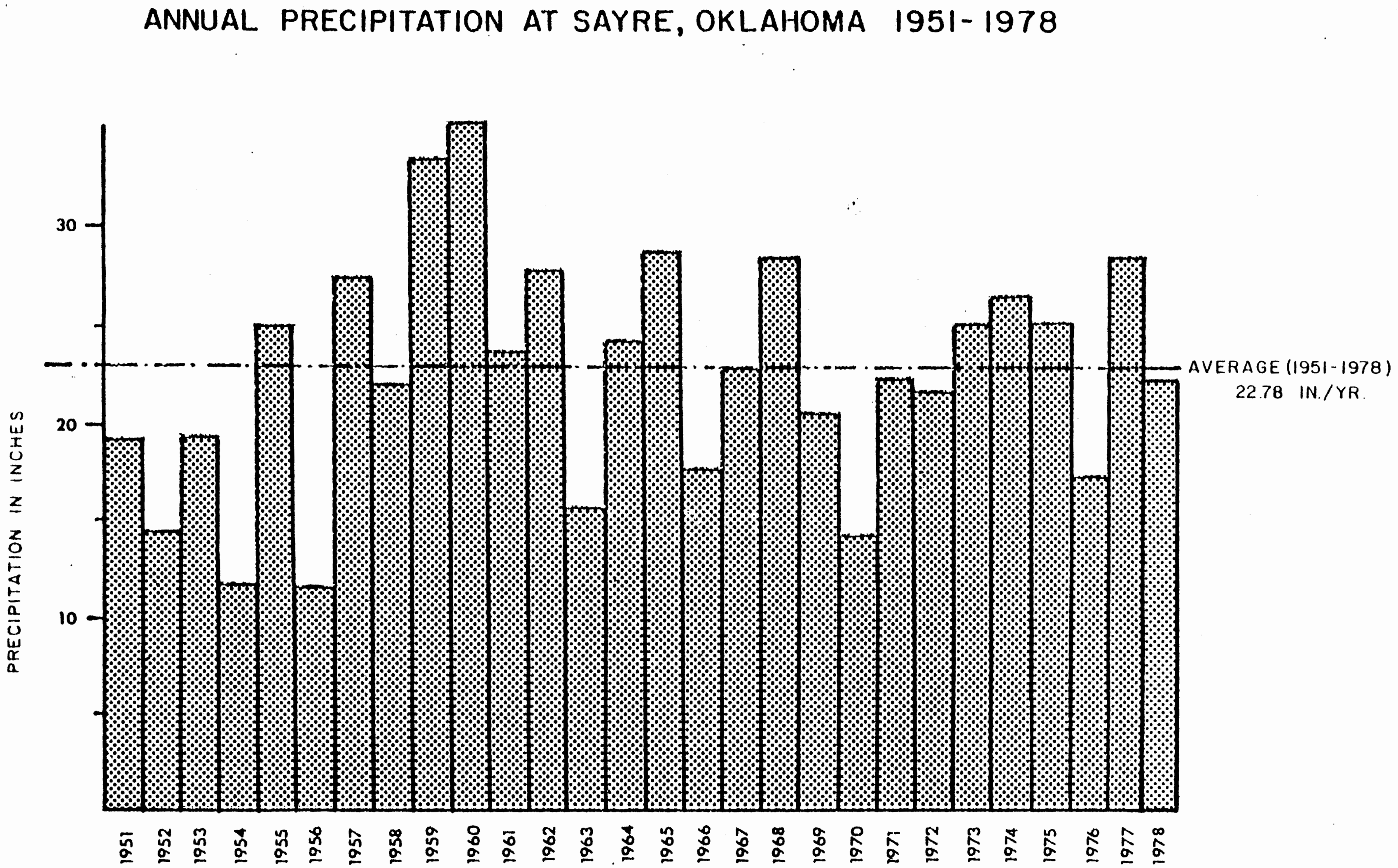


Figure 2. Annual Precipitation at Sayre, Oklahoma 1951-1978

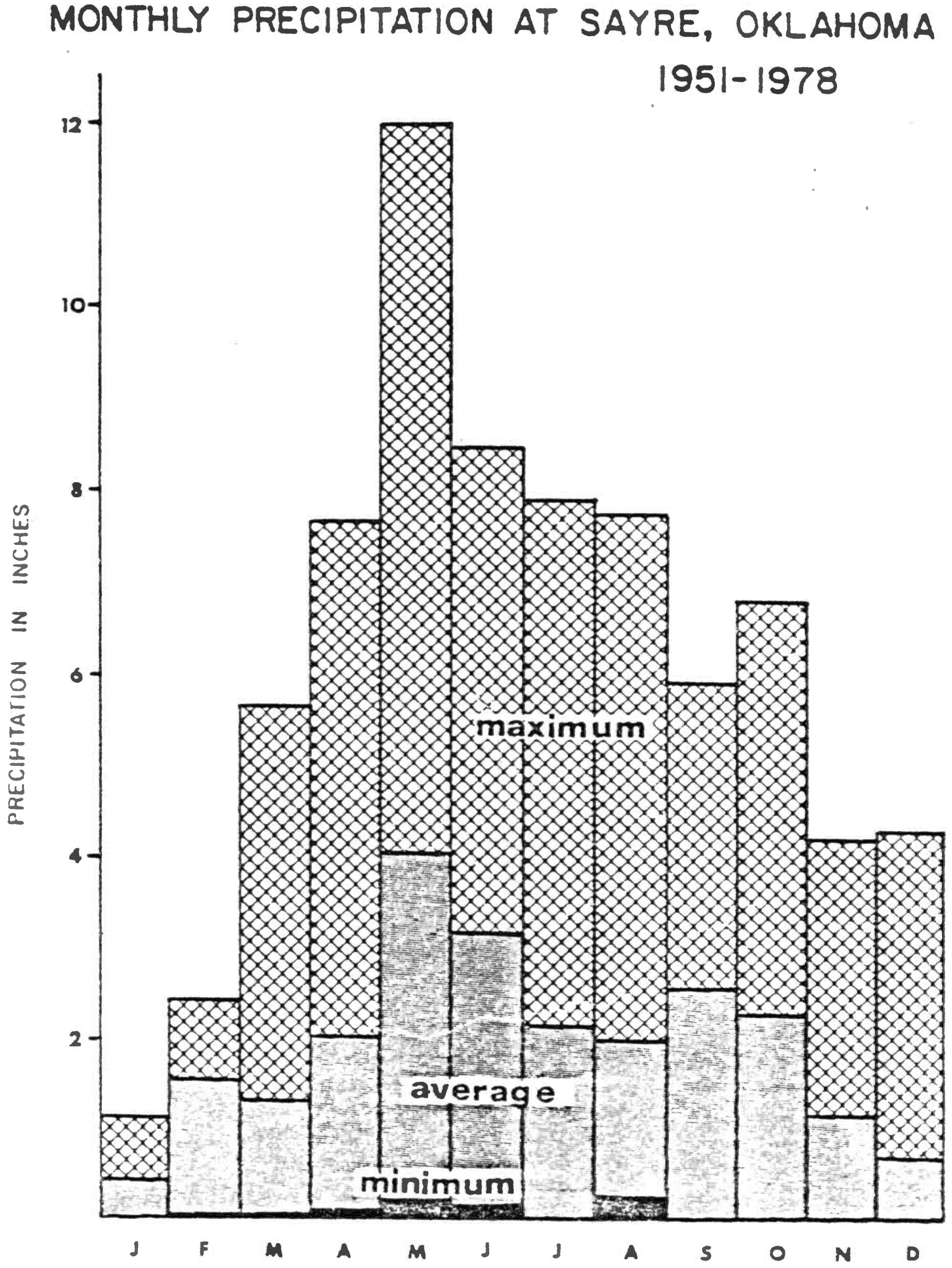


Figure 3. Monthly Precipitation at Sayre, Oklahoma 1951-1978

TABLE I

WEIGHTED ANNUAL AVERAGE PRECIPITATION

Station	Average Precipitation	Area	Percentage of Area	Weighted Average
Shamrock	22.75 in/yr	42 mi^2	6.7%	1.52 in/yr
Erick	24.35	120	19.0	1.64
Sayre	22.78	91	14.4	3.2
Moravia	25.02	99	15.7	3.93
Mangum	25.27	19	3.0	0.76
Altus Dam	23.81	130	20.6	4.91
Altus	24.68	29	4.6	1.14
Roosevelt	26.12	19	3.0	0.79
Snyder	26.37	81	12.9	3.39
		630 mi^2	99.9%	24.28 in/yr

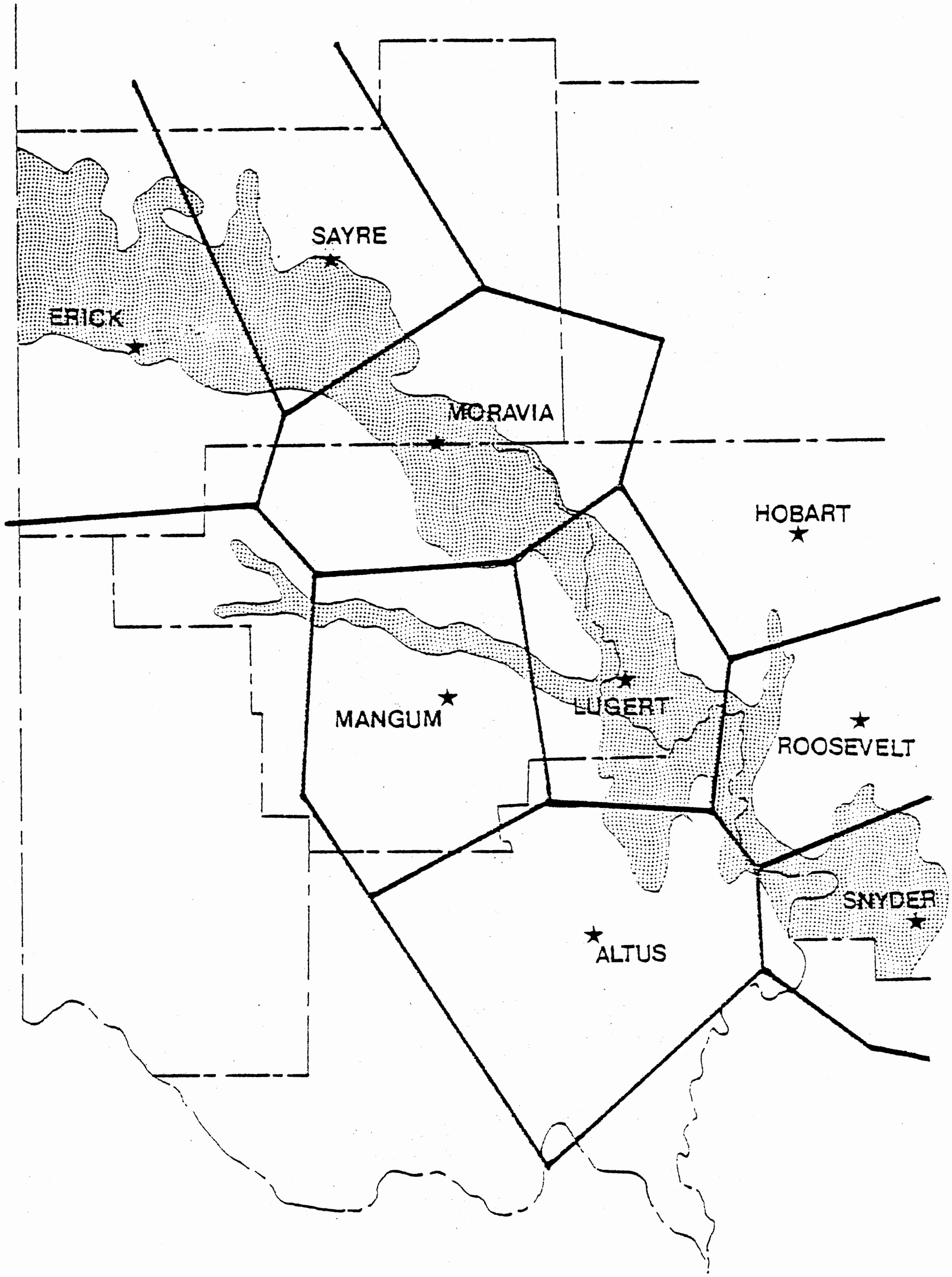


Figure 4. Theissen Polygon Method Using Weather Stations in Southwestern Oklahoma

Geology

The rocks exposed within the study area range in age from Cambrian to Quaternary (Figure 5). The oldest rocks found are the gabbros and granites associated with the Wichita Mountains which were apparently uplifted during Pennsylvanian time. These rocks are exposed as isolated barren hills ranging in height from a few feet to over a thousand feet above the surrounding plain. These units are highly fractured and, although springs are common at the intersection of joints, the total yield of water from these units is small.

Following the Wichita Uplift and removal of overlying early and middle Paleozoic units by erosion, sediments were laid down during Permian time in a shallow sea which apparently advanced from the southwest. The oldest sediments found within the study area are those of the Garber Formation. This formation consists of an arkosic conglomerate derived from Cambrian outcrops and is usually found within six miles of these exposures. This unit grades laterally into a red-brown shale containing deposits of salt, gypsum, anhydrite, and some dolomite. Exposures of the Garber Formation are found in the southeastern portion of the study area.

Overlying the Garber Formation is the Hennessey Formation, which is characterized by reddish-brown argillaceous shales and siltstones. This unit outcrops extensively over large portions of the southern part of the study area. The Hennessey Formation does not yield significant amounts of water although low to moderate yields can be obtained locally from isolated sandstone lenses.

The Duncan Sandstone overlies the Hennessey Formation and consists of a very fine-grained, silty, lenticular sandstone interbedded with thick, reddish-brown shales. The shales increase in thickness westward and the sandstone pinches out near the center of the study area.

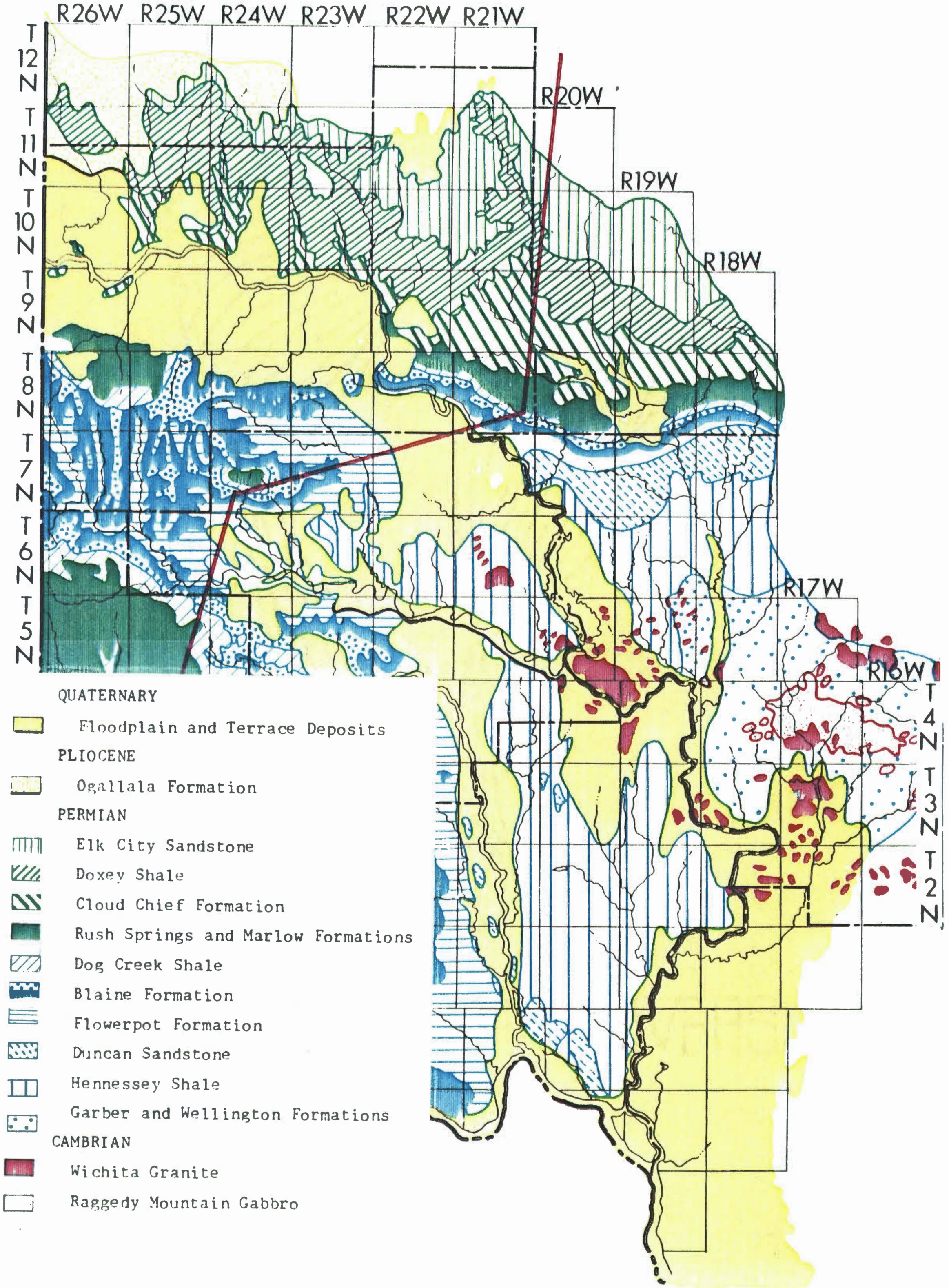


Figure 5. Surficial Geology of the Project Area

The Flowerpot Formation consists predominately of reddish-brown shale with minor amounts of thin, interbedded, greenish-gray shale, siltstone, gypsum, and dolomite and some large deposits of salt. The Flowerpot Formation outcrops in southern Beckham and northern Greer counties. While some springs occur in the Duncan Sandstone and Flowerpot Shale along the Elm Fork of the Red River, the ground-water contribution from these units is small and of poor quality.

Overlying the Flowerport Formation is the Blaine Formation. The Blaine Formation consists of cyclic shale and gypsum beds averaging 140 to 200 feet in thickness. Outcrops are found in southern Beckham and northern Greer counties. This formation serves locally as an aquifer where solution channels in the gypsum beds are encountered. Only moderate ground-water yields of somewhat highly mineralized water are produced.

The Dog Creek Formation overlies the Blaine Formation and consists of salty, red-brown shales and some thin dolomites and gypsum. The Dog Creek Formation locally yields minor amounts of fair to poor quality water.

Upper Permian rocks occur predominately in the northern part of the project area. The Whitehorse Group consists primarily of a soft, reddish-orange, massive to locally crossbedded, very fine-grained to silty sandstone containing a few thin shales and gypsum layers. The group outcrops in southern Beckham County. Eastward from Beckham County, the strata of the Whitehorse Group can be distinguished as the Rush Springs and Marlow formations which are mapped separately throughout the rest of the Anadarko Basin. The Rush Springs Sandstone is a good aquifer supplying moderate to large quantities of good quality water to wells. The Rush Springs Sandstone, however, probably makes only a minor contribution to the ground-water budget of the North Fork alluvial aquifer due to limited hydraulic continuity with that system.

The Rush Springs is overlain by the Cloud Chief Formation. The Cloud

Chief is an orange-brown shale and siltstone containing some sandstone, dolomite and gypsum. Thickness of the formation is highly variable. The division between the Cloud Chief Formation and the overlying Doxey shale is defined primarily on the basis of color change. The Doxey is a red-brown, highly impermeable shale and siltstone. Both of these units outcrop extensively north of the study area.

The Elk City Sandstone, which is the youngest Permian formation in Oklahoma, outcrops north of the study area. It is a fine-grained, orange-brown sandstone which serves as a good aquifer but has no known hydraulic continuity with the North Fork alluvial aquifer.

The Pliocene Ogallala Formation outcrops in the northeastern corner of the study area. This formation is a partially indurated, fine- to medium-grained quartz sand. The Ogallala is generally a very good aquifer but is believed to make only a small contribution to the North Fork water budget because it is relatively thin in this area and has limited hydraulic contact with the North Fork aquifer.

The Quaternary deposits found in the study area consist of alluvial and eolian sands associated with the North and Elm forks of the Red River. These deposits consist of discontinuous layers of sand, silt, clay, and gravel derived from the Permian and Cambrian bedrock through which the river has eroded. They are generally poorly sorted.

The surface of the alluvial deposits ranges from flat to gently undulating and slopes generally toward the river. At some locations, particularly in the northern part of the area, several alluvial terrace levels may be observed but are partially obscured by wind-blown sand. Elevations of these terraces range from approximately 1,300 to 2,200 feet above sea level with a maximum height of approximately 100 feet above the river bed. Test drilling indicates that the thickness of the alluvial deposits averages 40 feet and attains a maximum approximately 100 feet above the river bed. Test drilling indicates that the thickness of the alluvial deposits averages 40 feet and attains a maximum thickness of over 150 feet.

Ground-Water Regime

The alluvial floodplain and terrace deposits along the North Fork of the Red River form an unconfined aquifer except where relatively impermeable zones create localized confined or perched conditions. Maps showing past and present water-table configurations are shown in Figure 6 through 10. The North Fork is generally a gaining stream (effluent) within the project area, i.e. ground water from the terrace deposits supplies water as base flow to the river throughout most of the year.

The major source of recharge to the aquifer is from precipitation. The sandy soil of the eolian and alluvial deposits has a high infiltration capacity. The presence of discontinuous layers of clay and caliche near the surface apparently have a negligible effect on regional infiltration, but in some localized areas may reduce it. Hydrologic studies by the Oklahoma Water Resources Board (OWRB) have assumed an average of nine percent of precipitation as an estimate of net recharge to the water table. Multiplying the average of 24.28 inches annual precipitation for the entire project area by the nine percent recharge figure yields a recharge rate of 2.2 inches per year. This results in an annual recharge of 67,000 acre-feet per year when the recharge rate is prorated over the 367,520 acres of the project area.

Other sources of recharge to the North Fork ground-water system include inflow from the alluvial deposits in Texas, leakage from the river and lakes, and underflow from bedrock units underlying and adjacent to the alluvial valley. The ground-water contribution to the alluvial aquifer from the bedrock units is

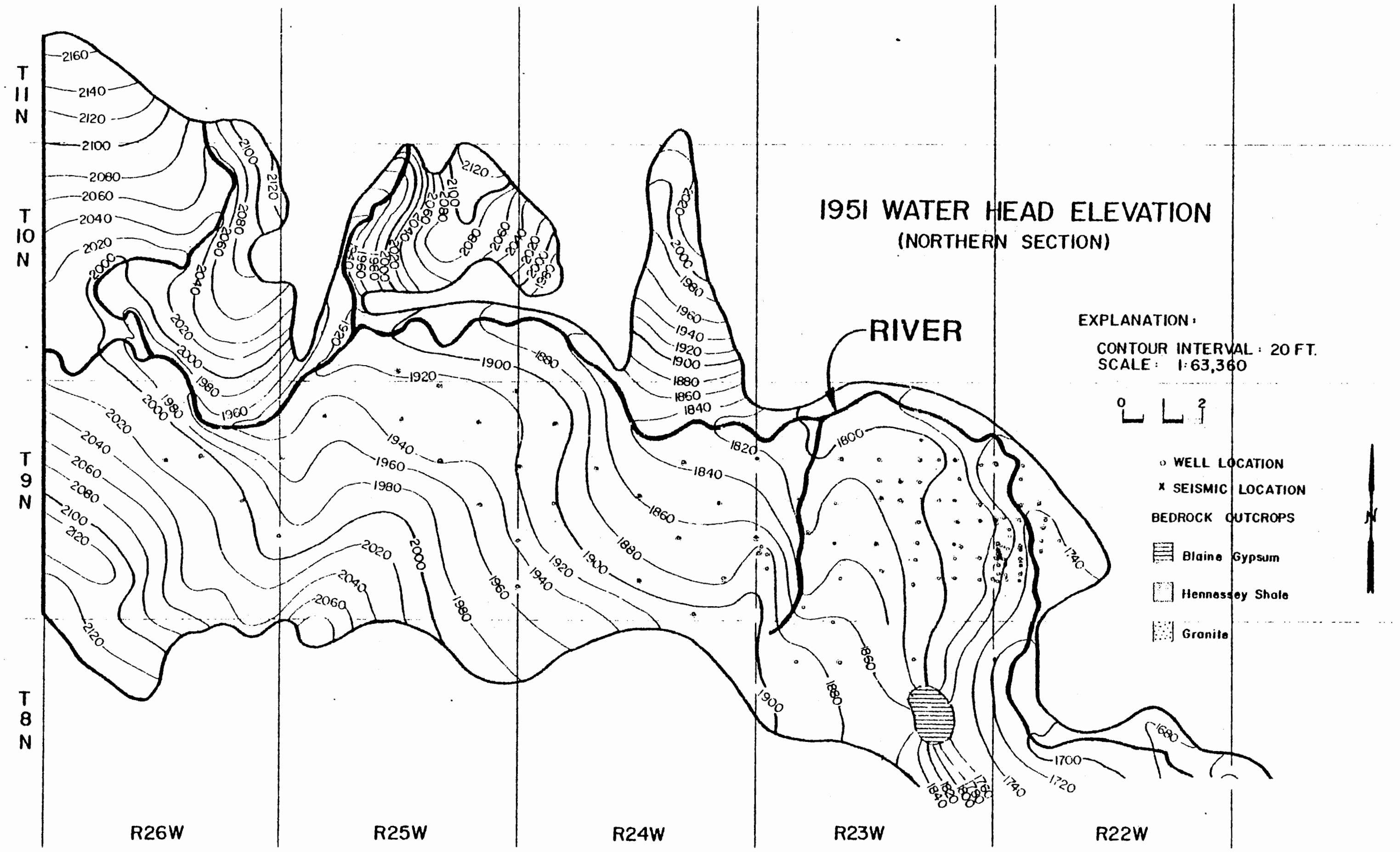


Figure 6. 1951 Water Head Elevation (Northern Section)

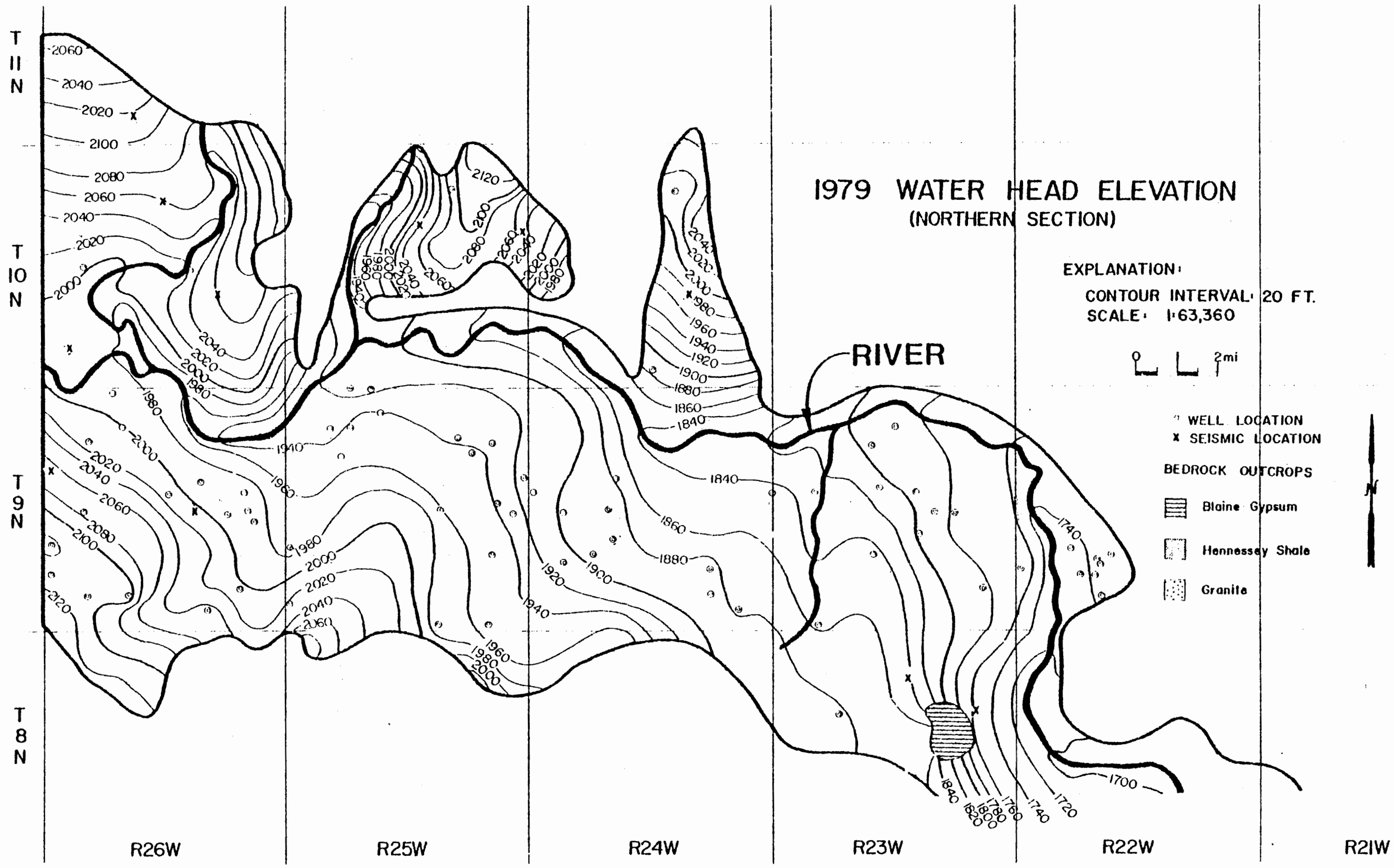


Figure 7. 1979 Water Head Elevation (Northern Section)

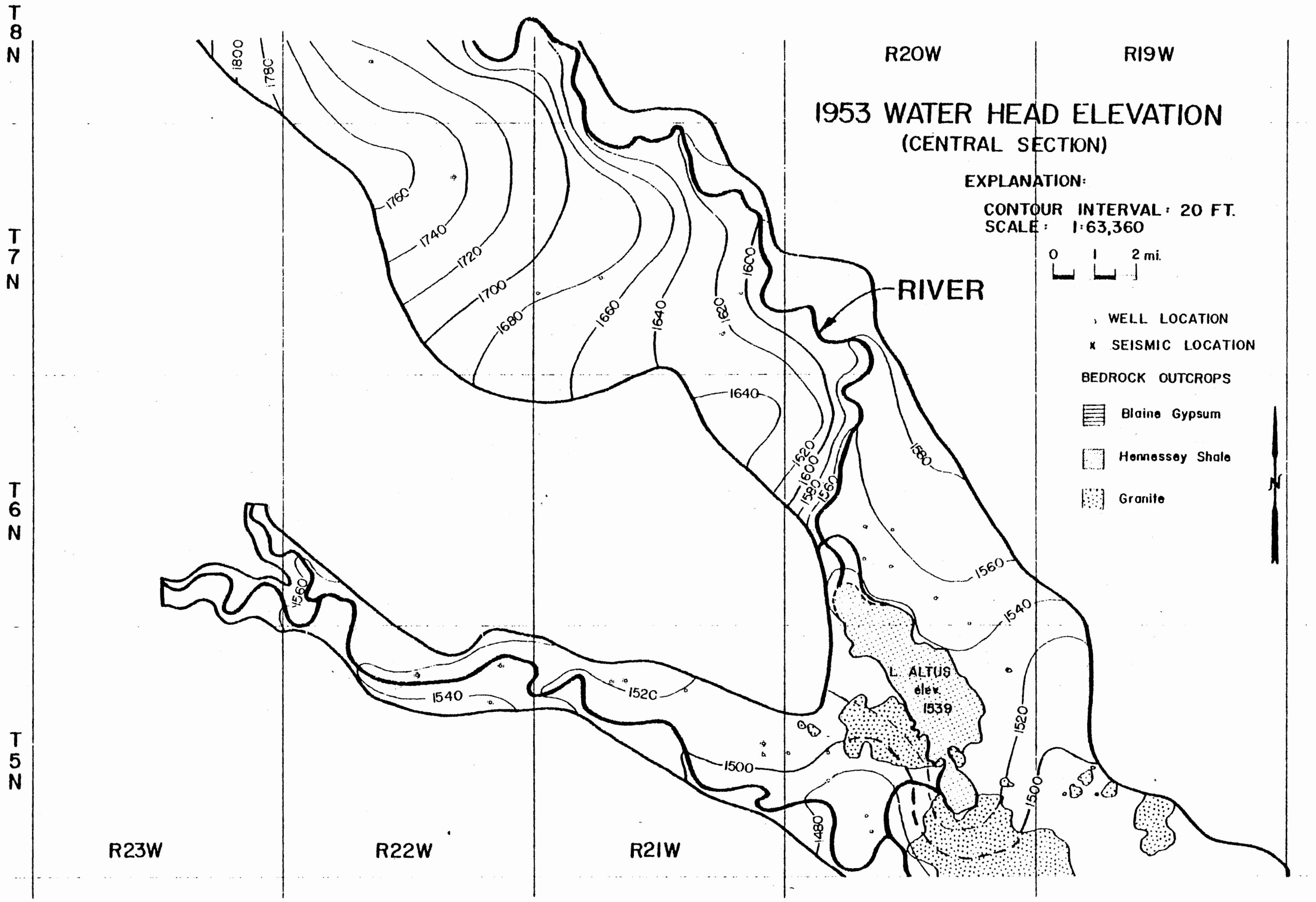


Figure 8. 1953 Water Head Elevation (Central Section)

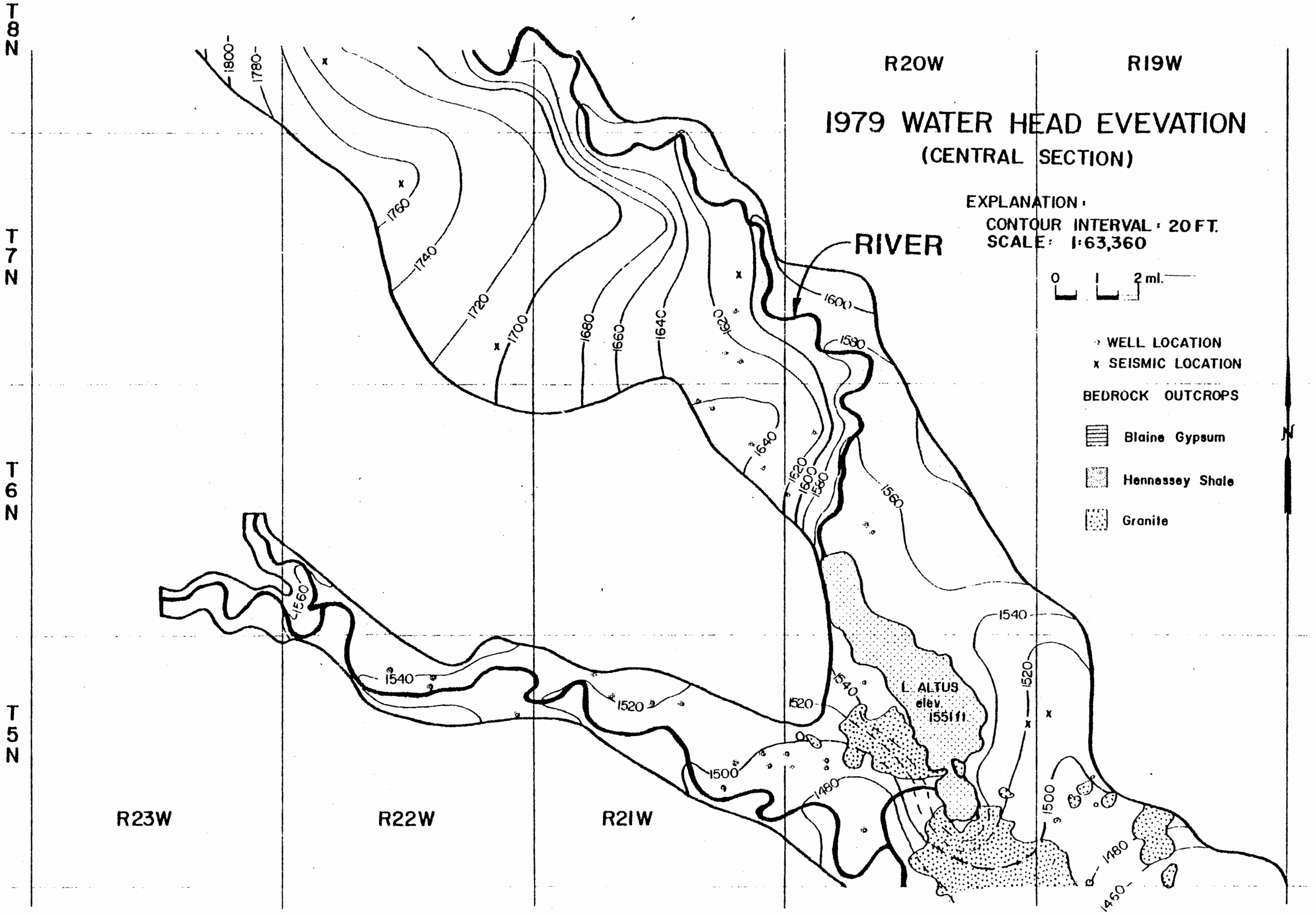


Figure 9. 1979 Water Head Elevation (Central Section)

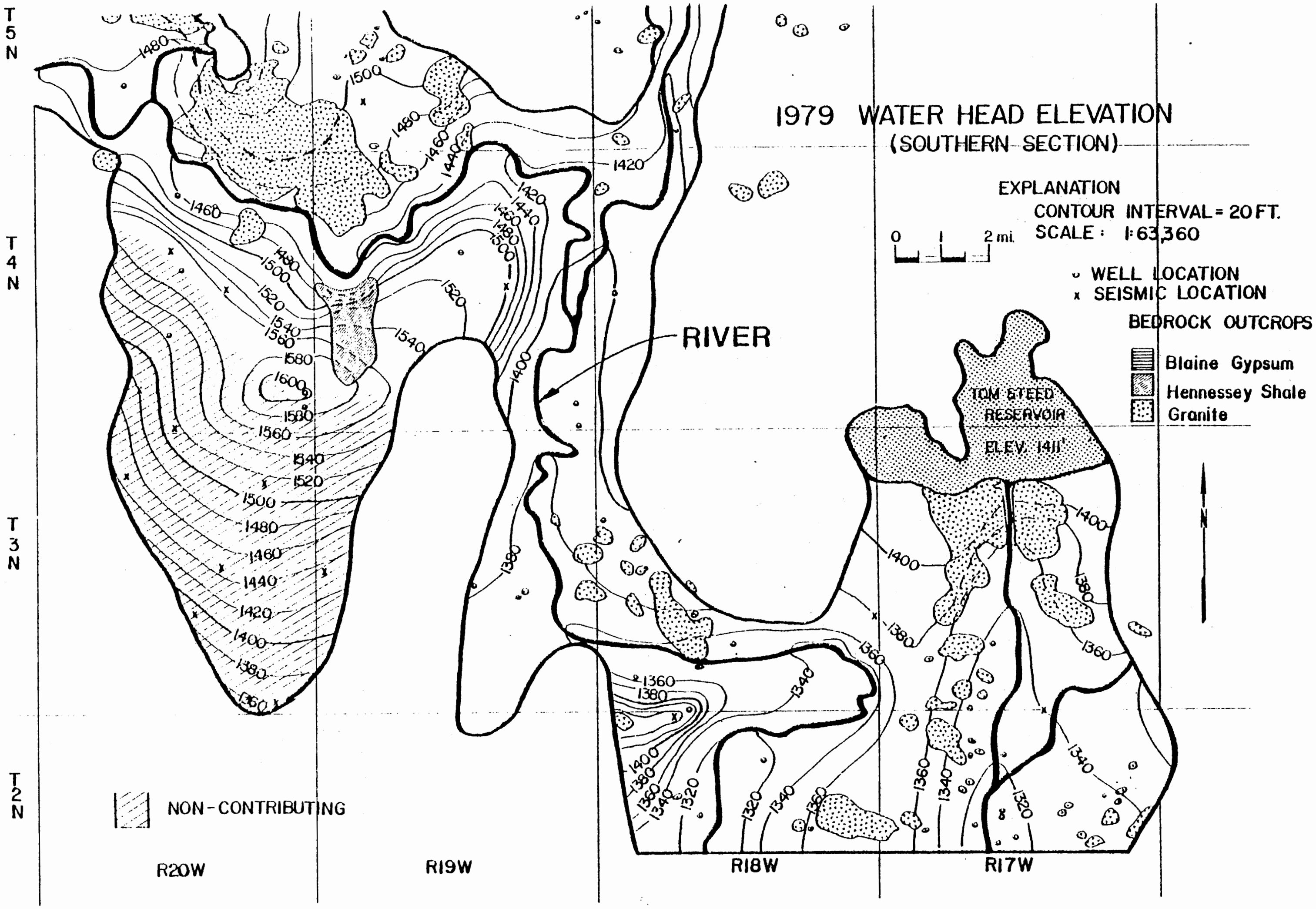


Figure 10. 1979 Water Head Elevation (Southern Section)

Water Quality

Ground-water quality within the alluvial deposits is generally fair to good. Average values of total dissolved solids within the aquifer vary from 843 parts per million (ppm) in Jackson, Kiowa, and southern Greer counties to 419 ppm in northern Greer and Beckham counties (Carr and Bergman, 1976; Havens, 1977). Twenty-five percent of the sampling points are higher in concentration than those indicated above.

Ground water within the project area is generally of better quality than surface water, which contains high concentrations of total dissolved solids. Stream quality is variable between high and low flows and between northern and southern areas (Table II). The higher salinity concentrations in the southern portion of the project area results from high sulfate and sodium chloride concentrations derived from Permian redbed formations (Dog Creek Shale, Blaine Gypsum, and Flowerpot Shale) particularly along the Elm Fork of the North Fork.

TABLE II

GROUND- AND SURFACE-WATER QUALITY NORTH FORK OF THE RED RIVER

Average Total Dissolved Solids (TDS)

	Ground Water	Surface Water	
	TDS (ppm)	TDS (ppm)	Flow (cfs)
Northern Section	419	1519	252
		2195	1.3
Southern Section	849	1210	649
		6465	19

CHAPTER IV

METHODOLOGY

General

Hydrogeologic data from various sources were reviewed and analyzed to determine the ground-water characteristics of the North Fork aquifer. A field investigation was undertaken to fill "gaps" where additional hydrogeological data was needed. The field investigation consisted of (1) a seismic survey to determine bedrock and water-table elevations, (2) a field check of alluvial boundaries and bedrock outcrops, and (3) an aquifer test used to verify estimated permeabilities based on drillers logs. These data were analyzed and spatially distributed over the study area. The data were then contoured and digitized for computer processing.

The study area was divided into three sub-areas or sections as shown in Figure 11. This was done to reduce the amount of data necessary for computer simulation and to accommodate boundary conditions. Although data for each section were processed separately, continuity of data distribution between sections was maintained; thus, continuity of ground-water flow between sections was provided in all computer simulations.

Steps employed in the use of the model for desired results are summarized in Figure 12. The input data were divided into matrix and constant parameters. The matrix parameters include: bedrock, water head, top, and land elevations; coefficient of permeability; specific yield; thickness and hydraulic conductivity of the river bed; and well pumping rate. The constant parameters include

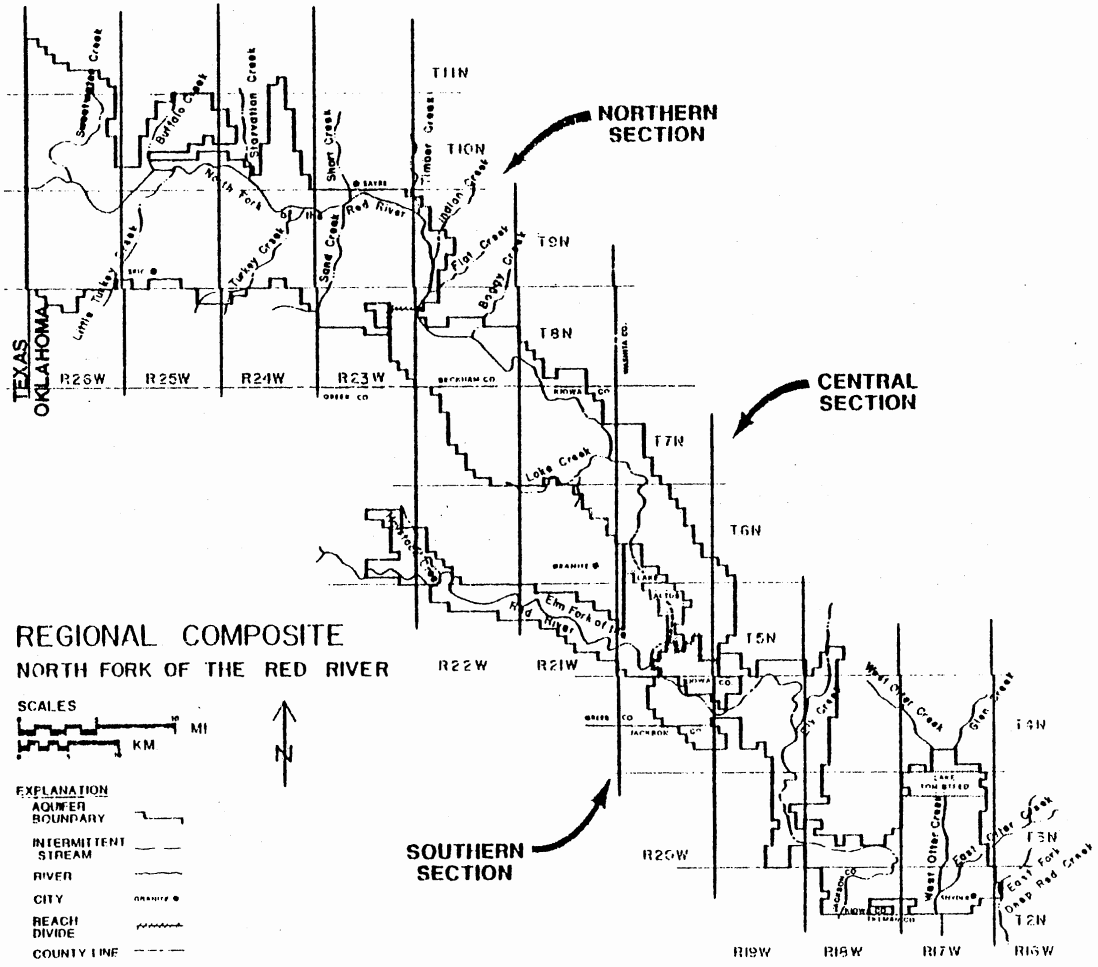


Figure 11. Regional Composite-North Fork of the Red River

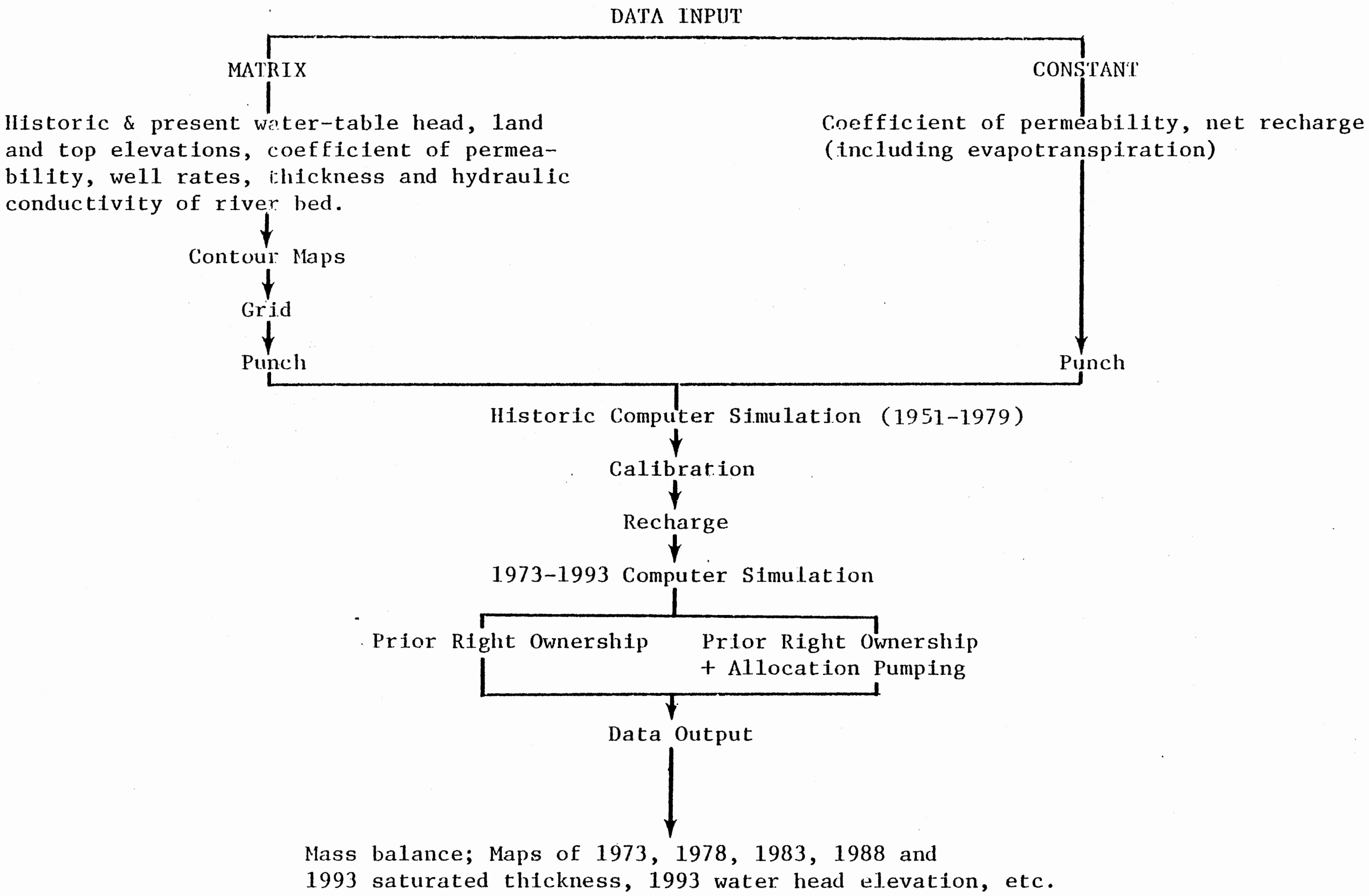


Figure 12. Data Input-Output Flow Chart

storage coefficient of the river bed, and rate and depth of evapotranspiration.

To calibrate the model, a 29-year computer simulation was performed for the Northern section using historic water level data and prior appropriative pumping rates. Calibration was achieved by adjusting the recharge rate so that the simulated 1979 water-table elevations were within five feet of those observed in 1979.

Following calibration, a 20-year computer simulation was conducted for the period 1973 to 1993 for each section. Various pumping rates were used to establish an annual allocation rate that would assure a minimum basin life of 20 years. Three trial computer simulations were made for each area based on these different pumping rates.

Data output was plotted in map form using the computer printer (Witz, 1979). Maps were plotted for each 5-year interval of the 20-year simulation period. Computed output data include transmissivity, saturated thickness, and water-table elevations.

Input Data

The hydrogeologic data supplied by the Oklahoma Water Resources Board include: well locations, past and present water levels, depth to bedrock, prior appropriative pumping rates, and drillers logs. Data were also obtained from the Oklahoma Geological Survey, the U.S. Geological Survey, the Bureau of Reclamation, the Oklahoma Highway Department, and the Soil Conservation Service. These data were reviewed and analyzed for use as input into the computer model.

Bedrock and Water-Table Elevations

Records of bedrock depth, as well as historic and present water-table depths, were made available by the Oklahoma Water Resources Board (OWRB). These records are based on drillers logs and field measurements collected by OWRB personnel. Aquifer boundaries were determined from Oklahoma Geological Survey (OGS) hydrologic atlases (Carr and Bergman, 1976; Havens, 1977) and checked during the field investigation. The bedrock surface at the base of the alluvium (Figures 13 through 15) was considered to be an impermeable boundary with no net water gain to or loss from the alluvial deposits.

Depths to water and bedrock were subtracted from surface elevations, (determined from USGS topographic maps), to obtain water-table and bedrock elevations. These elevations were then plotted on base maps and contoured. A quarter-mile grid, drawn at the same scale as the base maps, was overlaid onto each contour map. Values were assigned to each node of the grid by a perimeter-averaging technique developed by Griffen (1949). This method involves averaging the values at the corners and center of each node to obtain an average value for that node.

Field Investigation - Seismic Survey

Several large areas for which no water-table and bedrock information was available occur within the project area. A seismic survey was undertaken to provide data where this information was lacking. A 12-channel refraction seismograph recorder produced by Electro-Technical Laboratories of Houston, Texas (Model ER-75-12), was used in the study. Seismic shot locations are shown in Figures 7, 9, 10 and 13 through 15.

A typical seismograph "spread" showing geophones aligned at predetermined intervals from the "shot point" is illustrated in Figure 16a. Seismic waves are produced by detonation of an explosive charge. When the

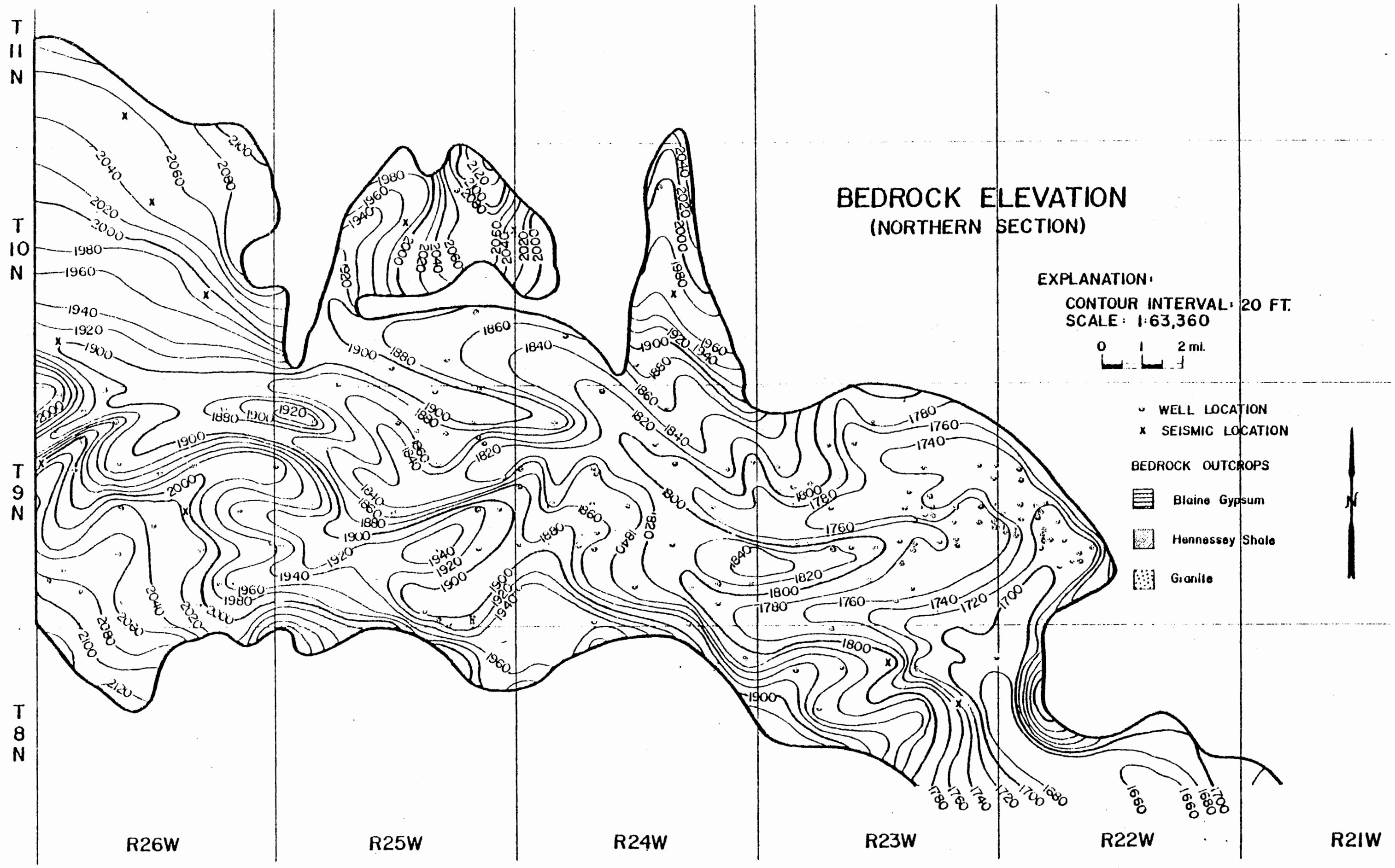


Figure 13. Bedrock Elevation (Northern Section)

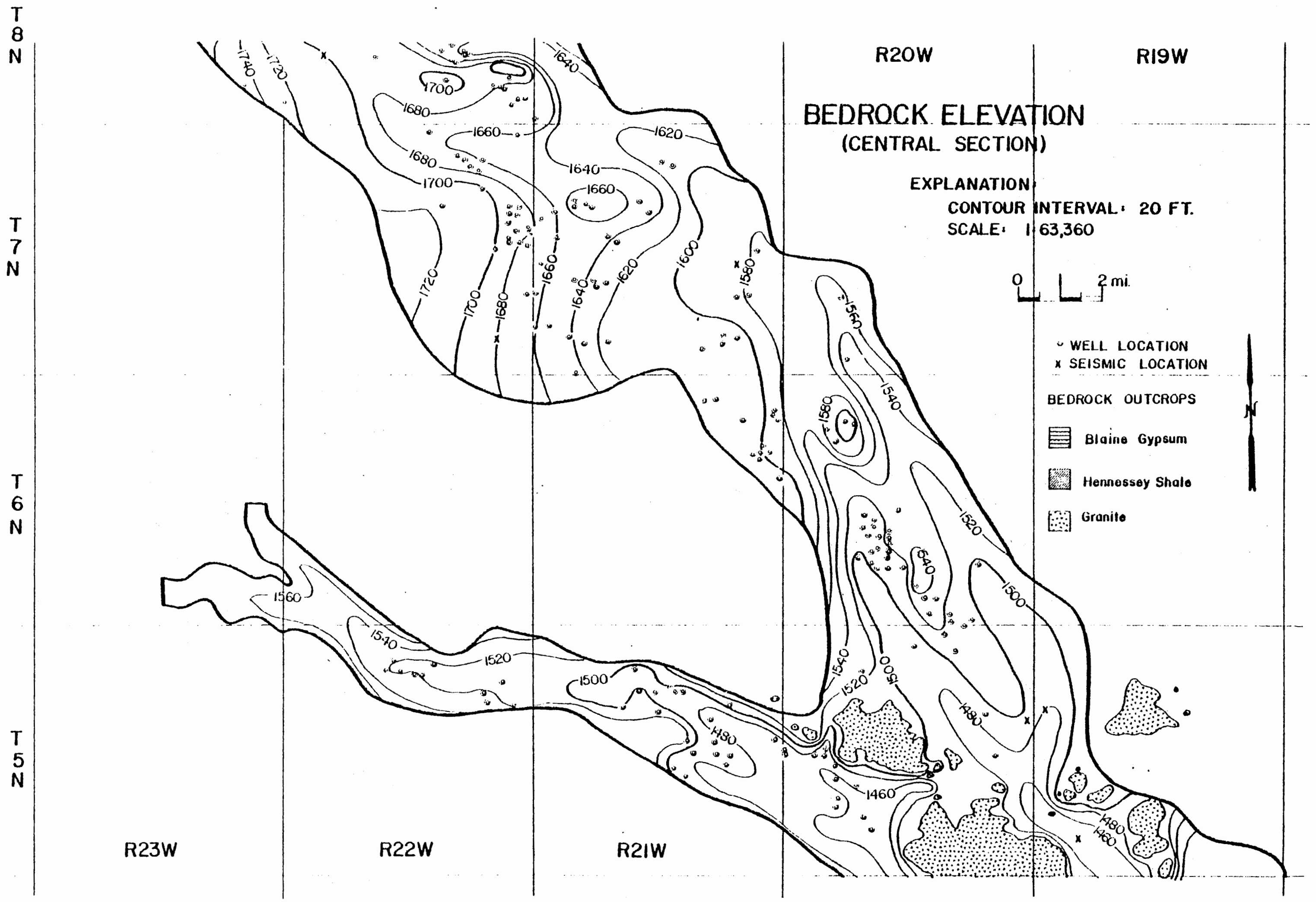


Figure 14. Bedrock Elevation (Central Section)

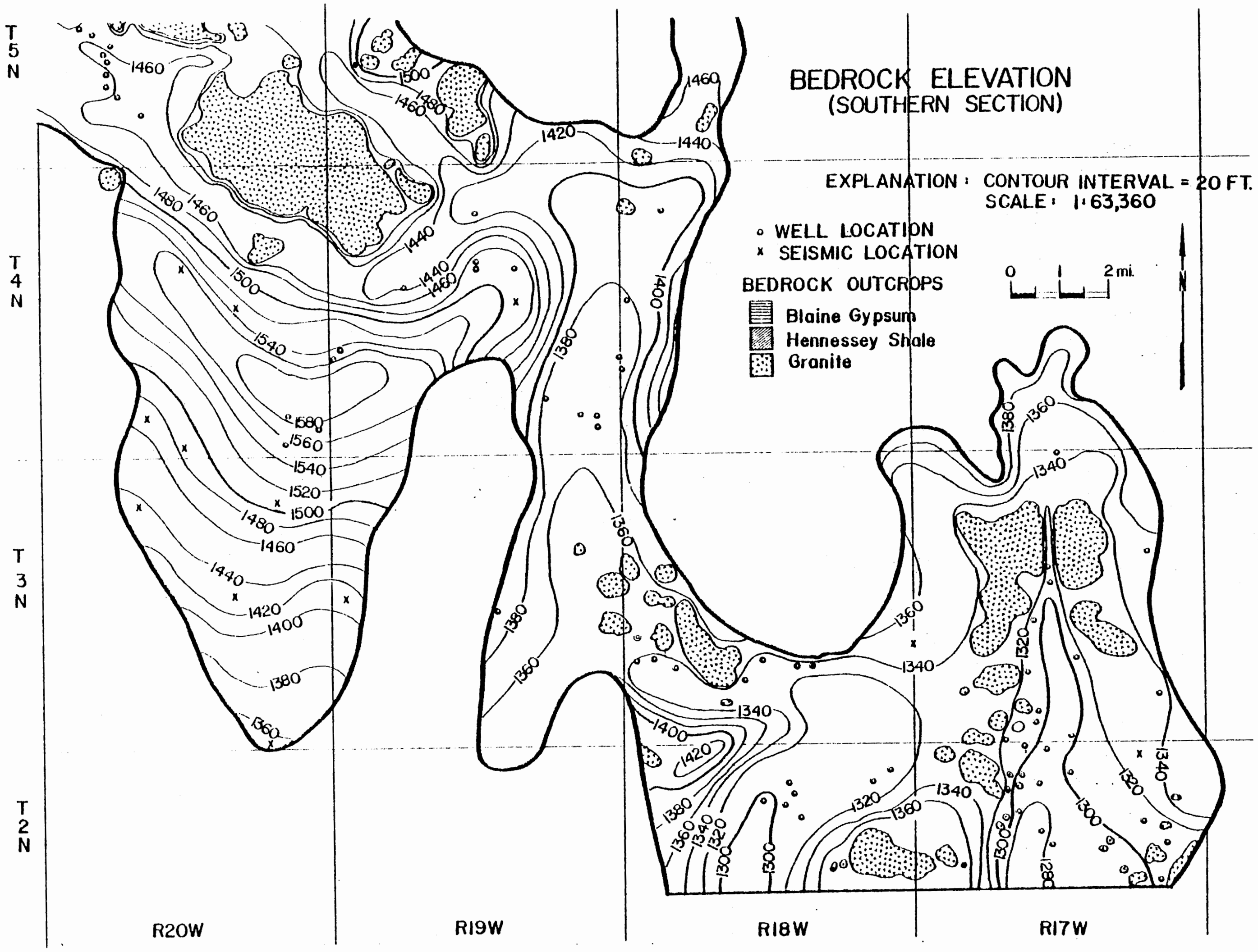


Figure 15. Bedrock Elevation (Southern Section)

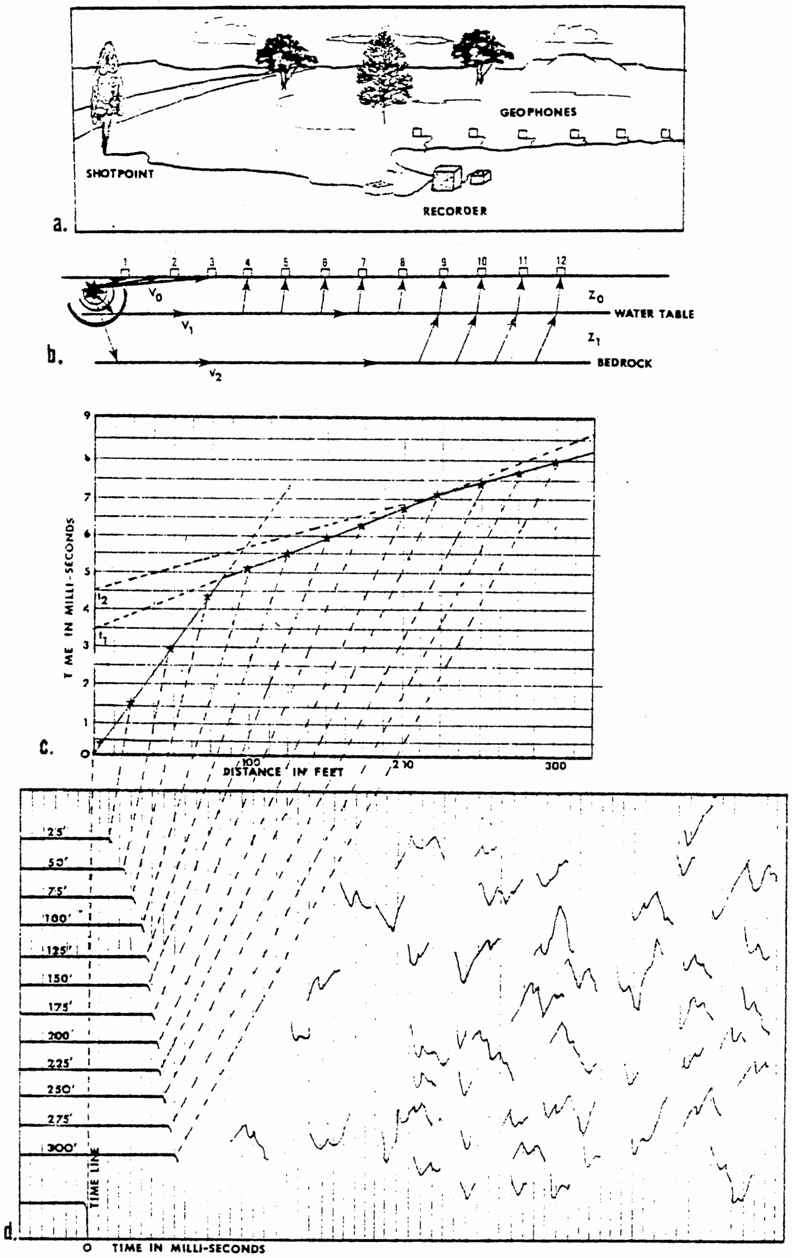


Figure 16. Seismic Investigation

charge is exploded, the exact instant of denotation is recorded as "shot-time" and is represented as a time line in Figure 16d. Energy from the explosion moves outward and downward from the point of impact as a spherical wave front. Seismic velocities through various materials are shown in Table III. Because of the short travel path, direct or horizontal waves moving through the low-velocity unsaturated overburden are the first to reach the geophones nearest the impact point. The "first arrival" is recorded on film as a deflection of the time line corresponding to those geophones (Figure 16d).

As the spherical wave front spreads downward, higher velocity zones are encountered. These zones may be either saturated overburden (water-table), or bedrock characterized by velocities corresponding to rock type and texture as shown in Table III. The change in velocity causes some of the energy to be refracted along the higher velocity zone before returning to the surface (Figure 16b). The travel time for the energy to reach the surface is greatly decreased because of the higher velocity. Consequently, the refracted wave soon overtakes the slower horizontal wave. This occurs between geophones 3 and 4 as shown in the example in Figure 16b. Until this time, all that had been recorded by the first three geophones is the wave through the unsaturated overburden. The refracted energy which arrives at geophones 4 through 8 ahead of the horizontal wave is recorded as the "first arrival". Geophones 9 through 12 record energy which has been refracted by an even deeper, higher velocity zone.

Figure 16d illustrates a seismic trace as recorded on Polaroid film by the seismograph unit. The wavy horizontal lines are galvanometer traces. The vertical lines represent 0.1 second intervals. As the wavefront arrives at each geophone, an electrical impulse is recorded on the galvanometer trace. The traces continue but are of such amplitude that they can not be seen on the record for approximately 0.5 second. This amplitude is the result of arrival of reflected energy. First arrival information, however, is all that is necessary for depth-to-water and bedrock computations.

First arrivals are measured in milli-seconds from the time line. These points are then plotted on arithmetic graph paper to form a time-distance curve. "Best fit" lines are drawn through the points as shown in Figure 16c. Seismic velocities are computed from the curve by dividing the station distance from the shotpoint by the intercept on the time axis. Determination of the type of material through which the wave is passing can be made by comparing the computed velocity to the characteristic velocities of the various materials shown in Table III.

Depth to the water table was computed using the intercept formula as follows:

$$z = \frac{t}{2} \frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}}$$

where: z = depth to water table

t = intercept time (intercept along "t" axis)

V_0 = velocity (unsaturated zone)

V_1 = velocity (saturated zone)

Depth to bedrock was calculated using the critical distance formula:

$$z = \frac{x}{2} \sqrt{\frac{V_1 - V_0}{V_1 + V_0}}$$

where: z = depth to bedrock

x = critical distance (distance along "x" axis)

TABLE III

SEISMIC VELOCITIES IN VARIOUS GEOLOGIC MATERIALS

Material	Velocity (feet/second)
Sand and Gravel (unsaturated)	1,000-4,000
Sand and Gravel (saturated)	4,000-6,500
Clay	4,000-9,500
Shale	7,200-13,500
Limestone	13,500-17,500
Granite	13,000-23,000

Source: Dobrin, 1976

V_0 = velocity (saturated alluvium)

V_1 = velocity (bedrock)

Water-table and bedrock elevations obtained from the seismic survey were used in conjunction with well data to produce bedrock and water-table contour maps of the area.

Coefficient of Permeability

The hydraulic properties of the aquifer are needed as input in the model. This information cannot, however, be obtained directly from drillers logs. The coefficient of permeability-grain size envelope shown in Figure 17, which was developed by Kent et al. (1973), was used to assign hydraulic properties to lithologies described on the drillers logs. The permeability-grain size envelope was developed from research conducted on the Washita River alluvium and is based on aquifer testing and laboratory determinations of permeability.

Lithologies shown on drillers logs are assigned to one of four grain size ranges shown along the abscissa of the envelope in Figure 17. Each range is identified with a permeability value corresponding to the median grain size of that range. An average weighted permeability is determined for each driller's log by multiplying the permeability of each range by the percentage of the total saturated thickness represented by that range and summing the total for all ranges. An example of this technique is shown in Table IV. Weighted average permeabilities were computed by this method for approximately 200 wells within the area. The values were placed onto a grid and digitized.

Aquifer Test

To supplement the permeability data and to verify computed values, an aquifer test was conducted during March 15-18, 1979. A 16-inch well was

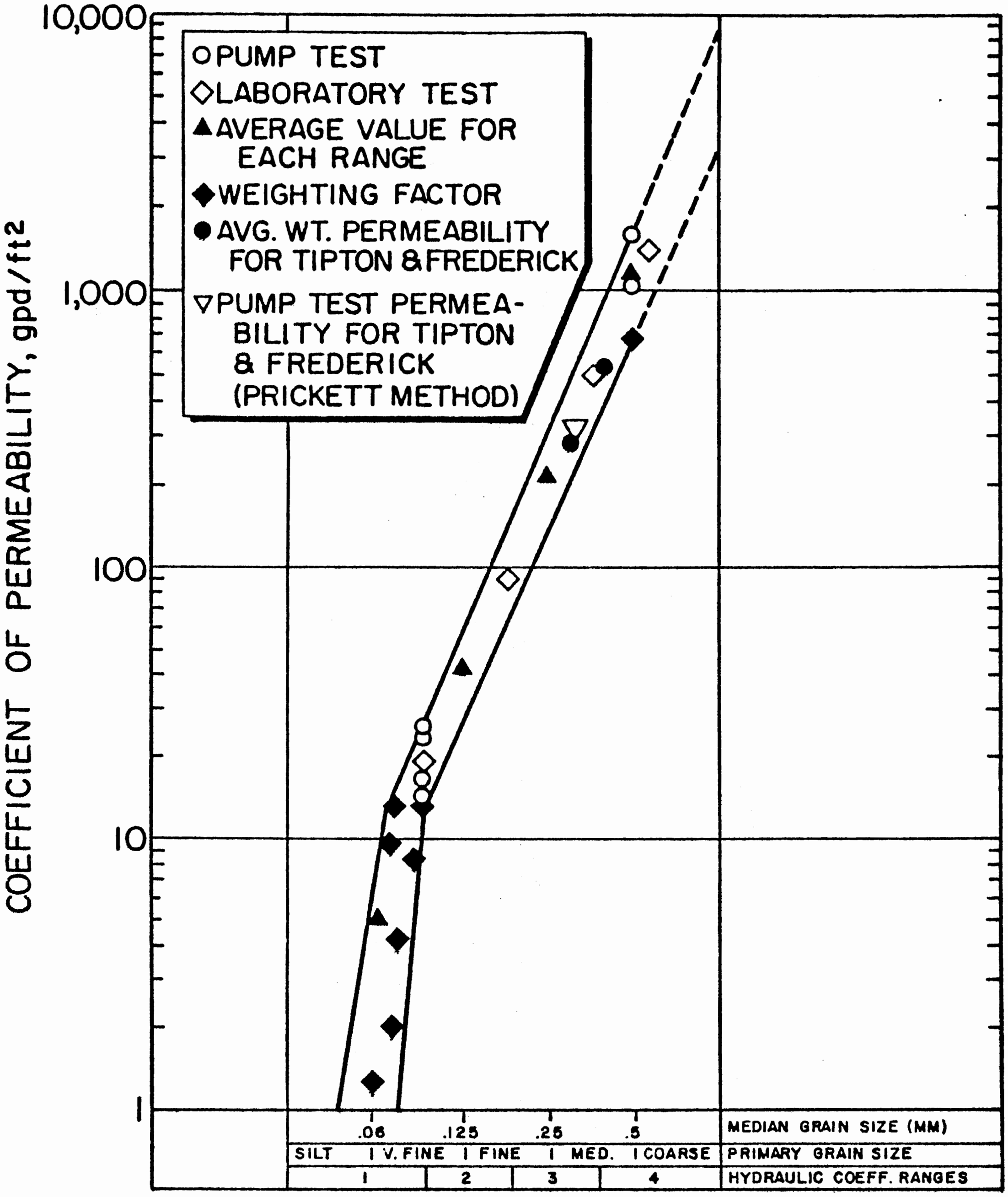


Figure 17. Coefficient of Permeability versus Grain-Size Envelope (Kent et al., 1973)

TABLE IV

WEIGHTED AVERAGE PERMEABILITY REFORMATORY WELL FIELD

Range	Average Coefficient of Permeability (gpd/ft^2)	Interval Thickness	% Thickness	Weighted of Permeability Coefficient (gpd/ft^2)
1	18	12	33.3	6
2	97	0	0	0
3	516	0	0	0
4	1,484	24	66.6	990
		36	99.9%	996*

* The weighted permeability of the section represented by the driller's log at this location is 996 gallons/day/square foot.

installed at the State Reformatory near Granite and located in NW ¼, Sec. 28, T.6N., R.20W. It was pumped continuously for 50 hours at a constant rate of 100 gallons per minute. Drawdown was measured in two 4-inch observation wells installed at distances of 75 and 150 feet from the pumped well.

The results of the aquifer test were analyzed using the non-artesian type-curve method (Prickett, 1965) shown in Figures 18 through 20 and by the Jacob method (Cooper and Jacob, 1946) shown in Figure 21. The Prickett method was developed for aquifer tests conducted under water-table conditions and takes into consideration delayed drainage due to gravity. The Jacob method was designed for artesian conditions, but is applicable for late-time drawdown under water-table conditions after gravity drainage becomes negligable and the aquifer test curve approaches artesian conditions.

Aquifer coefficients obtained from the Reformatory test are summarized in Table V. Transmissivity obtained from early drawdown by the Prickett method is 35,000 gallons/day/foot (gpd/ft); from late drawdown is 33,500 gpd/ft; and by the Jacob method is 26,500 gpd/ft; yielding an average transmissivity of 31,600 gpd/ft. Dividing the transmissivity values by 36 feet of saturated thickness yields permeability values of 975, 930, and 740 gpd/ft^2 respectively. The average permeability of the sediments at the aquifer test site is calculated to be 880 gpd/ft^2.

This value compares favorably with the value calculated for the same test well using the sample description and permeability-grain size envelope (Table IV). This similarity is considered justification for calculating permeability using drillers logs of wells within the project area.

Specific Yield

Specific yield values were computed automatically in the model. The

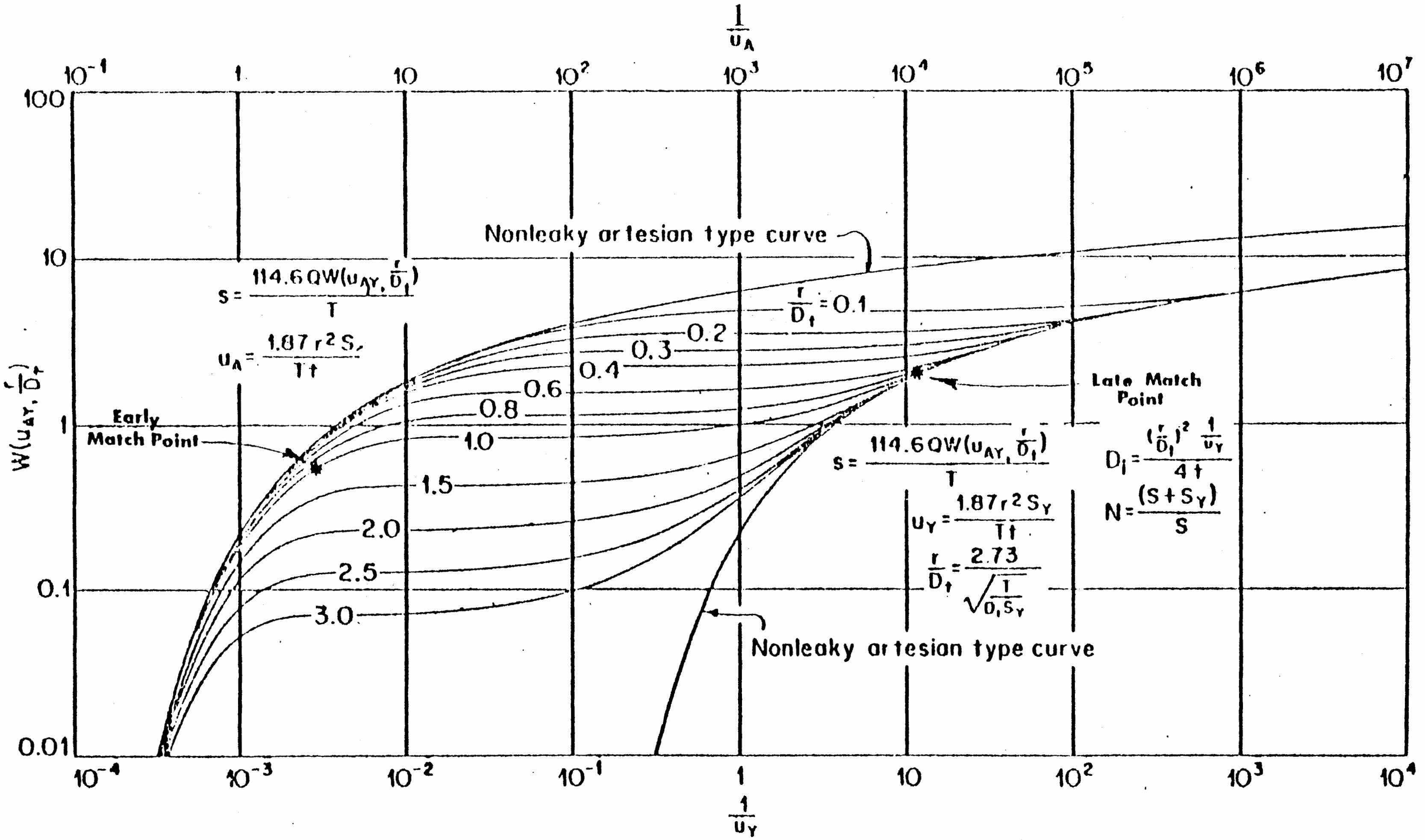
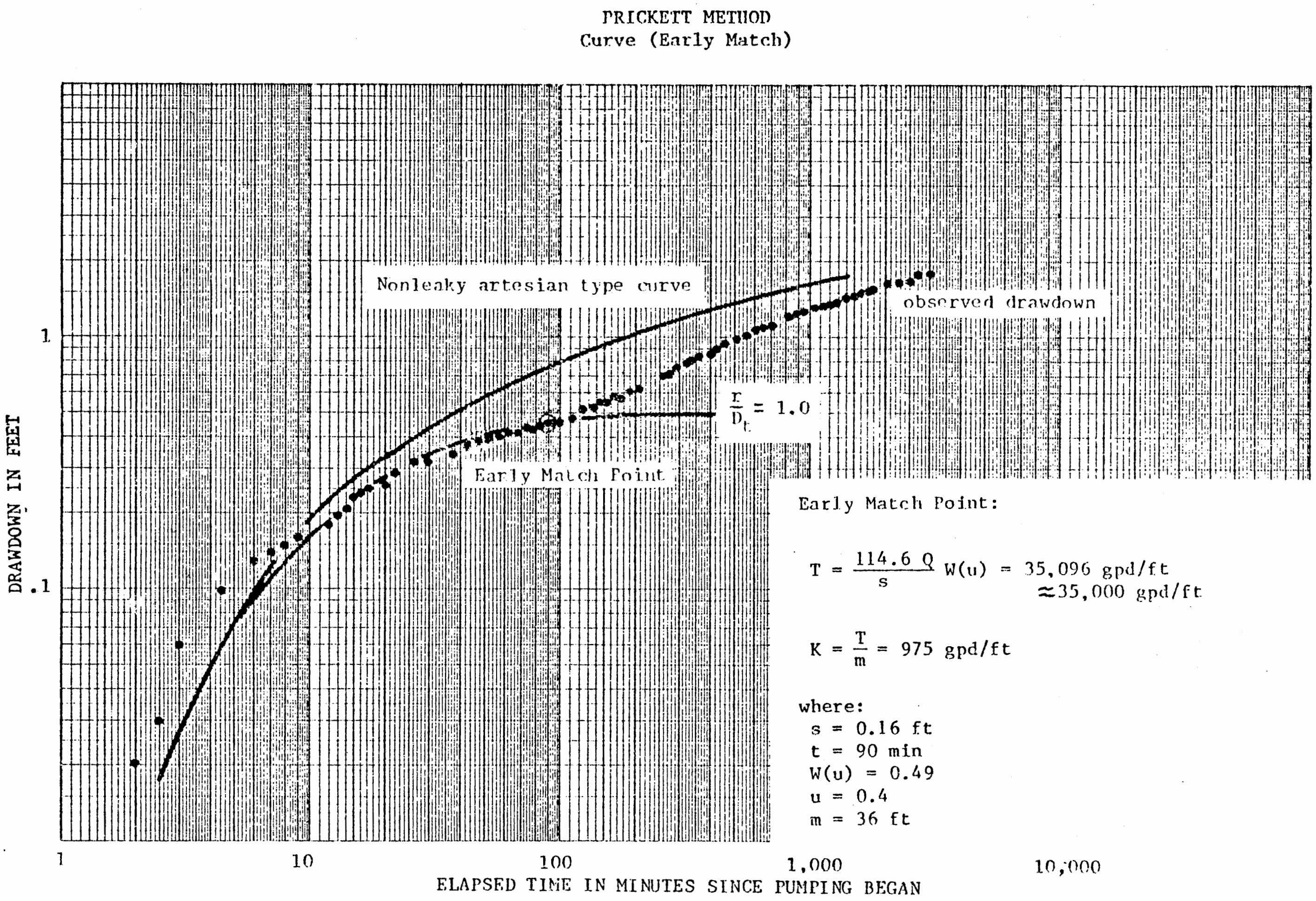


Figure 18. Water-Table, Fully Penetrating, Constant Discharge, Time-Drawdown Type-Curve



Early Match Point:

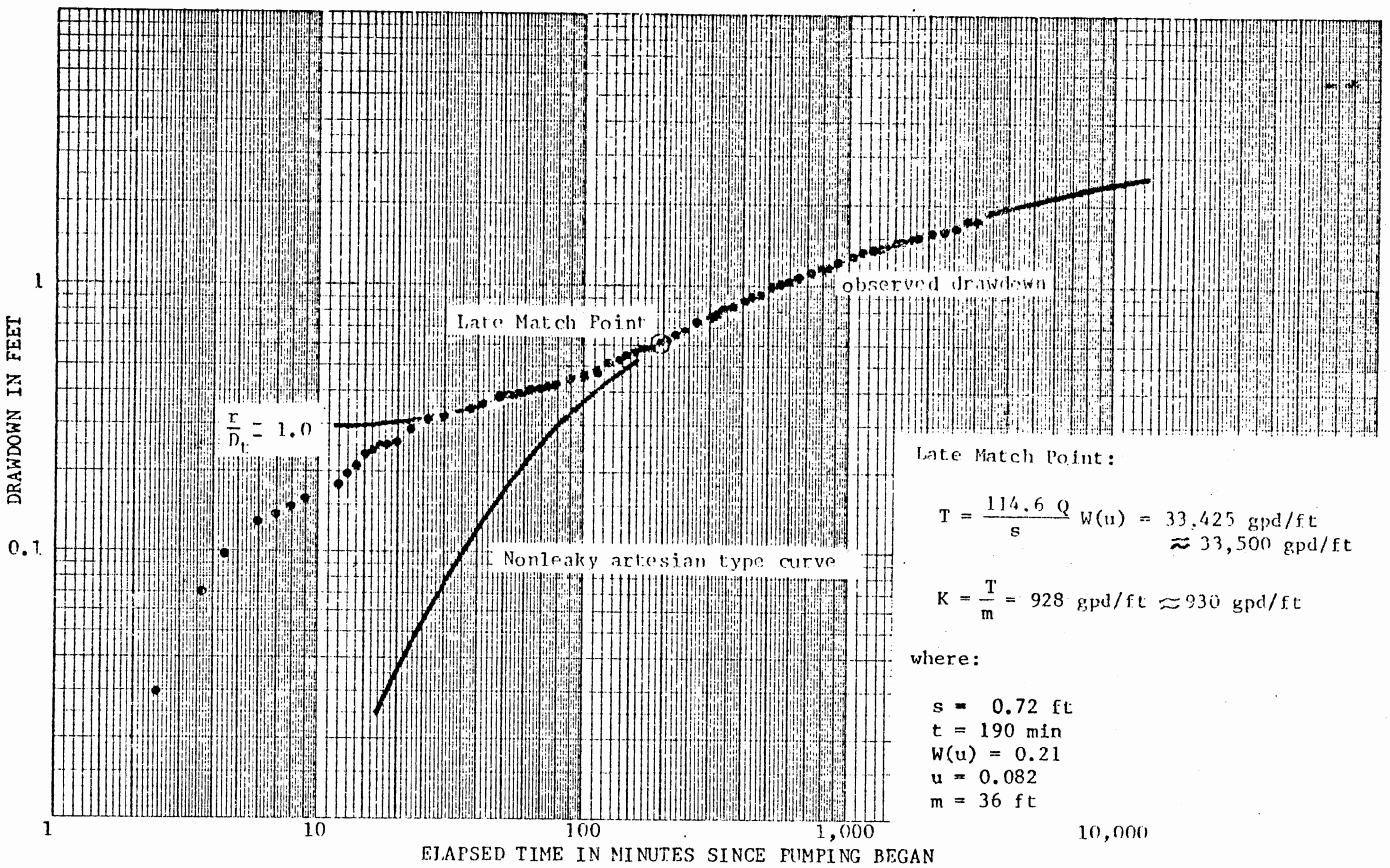
$$T = \frac{114.6\,Q}{s}\,W(u) = 35{,}096 \text{ gpd/ft}$$
$$\approx 35{,}000 \text{ gpd/ft}$$

$$K = \frac{T}{m} = 975 \text{ gpd/ft}$$

where:
$s = 0.16$ ft
$t = 90$ min
$W(u) = 0.49$
$u = 0.4$
$m = 36$ ft

Figure 19. Aquifer Test Early-Time Drawdown

PRICKETT METHOD
Curve (Late Match)



Late Match Point:

$$T = \frac{114.6\ Q}{s} W(u) = 33{,}425 \text{ gpd/ft} \approx 33{,}500 \text{ gpd/ft}$$

$$K = \frac{T}{m} = 928 \text{ gpd/ft} \approx 930 \text{ gpd/ft}$$

where:

s = 0.72 ft
t = 190 min
$W(u)$ = 0.21
u = 0.082
m = 36 ft

Figure 20. Aquifer Test Late-Time Drawdown

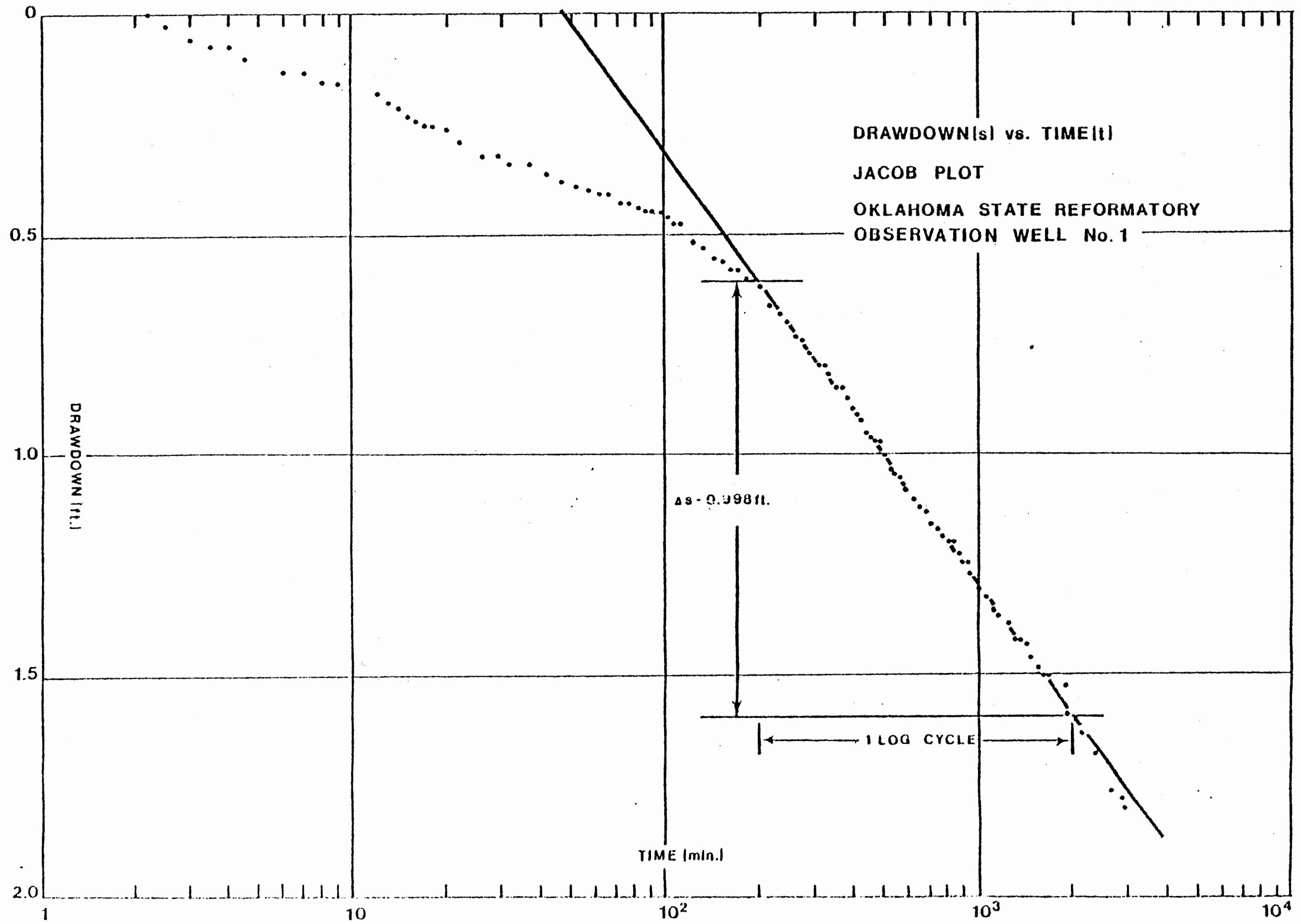


Figure 21. Aquifer Test - Jacob Analysis

TABLE V

AQUIFER COEFFICIENTS CALCULATED FROM AQUIFER TEST REFORMATORY WELL FIELD

Analysis Method	Transmissivity (gpd/ft)	Permeability (gpd/ft^2)
Prickett (Early Match Point)	35,000	975
Prickett (Late Match Point)	33,500	930
Jacob	26,500	740
Average	31,600	880

graph shown in Figure 22 (after Johnson, 1967) was used to provide a relationship between median grain size and specific yield. The dominant grain sizes in Figure 22 were considered to be equivalent to the median grain sizes of the permeability envelope (Figure 17). The values of specific yield and the corresponding permeability coefficients of the four ranges were plotted on semi-logarithmic paper to produce the relationship shown in Figure 23. This curve was stored in the model so that values of specific yield could be automatically assigned to each node corresponding to the permeability value of that node.

Other Input Parameters

To establish a reference from which depth of evapotranspiration was measured, average land elevations were assigned (using the Griffen method) to each quarter-mile node based on USGS topographic maps. It was assumed that the river bed consists of silts and clays which serve as a local aquitard. A confined aquifer condition was assumed for all river nodes. The "top" elevation is a parameter used in the model to designate the top of the confined aquifer. "Top" values which are at least two feet below land surface values are used at each river node to denote the confined condition. River bed thickness was arbitrarily set at one foot and the hydraulic conductivity of the river bed was set at 0.01 feet per second to simulate aquitard properties.

Pumping Rate

Pumping rates were entered as a variable in the model. Two matrices were used. One matrix included prior appropriative pumping as established by the Oklahoma Water Resource Board (Figures 24 through 26). This rate was used to approximate pumping prior to July 1, 1973. A second matrix was used to assign

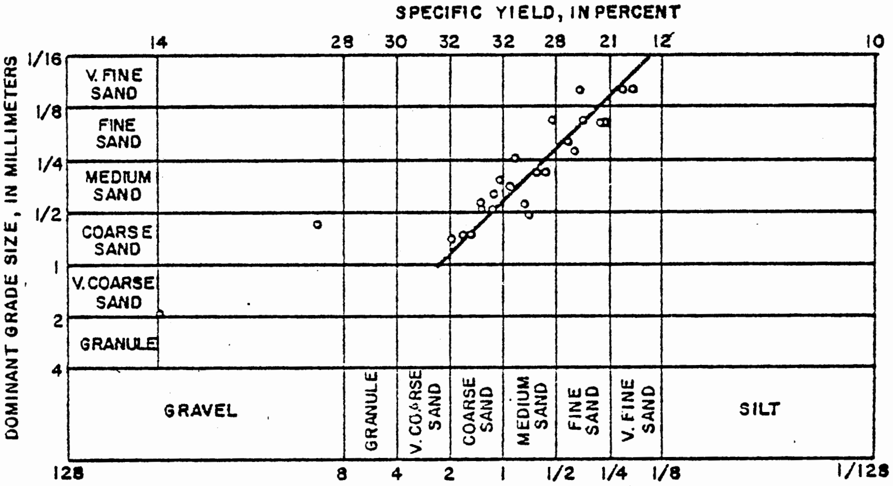


Figure 22. Specific Yield - Grain Size Relationship (After: Johnson, 1967)

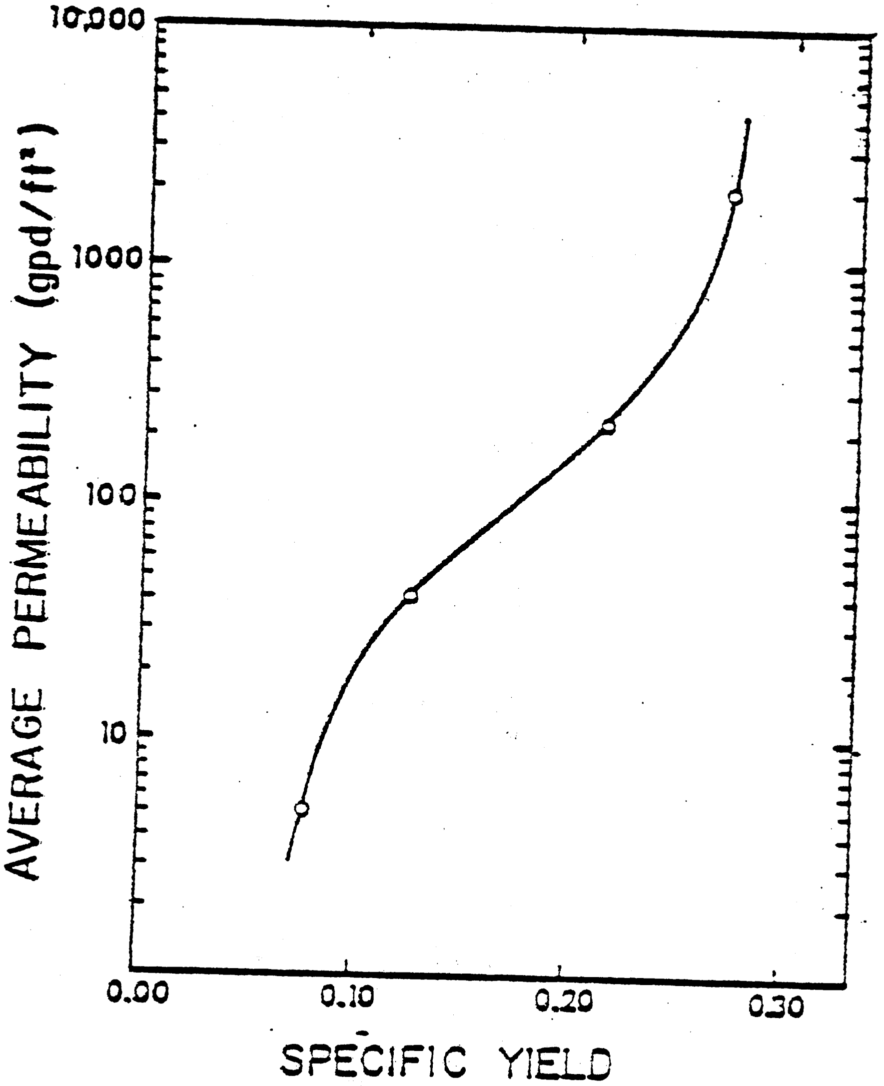


Figure 23. Specific Yield-Grain Size Relationship

a constant pumping rate to all nodes other than those with prior appropriative rights. Those nodes with prior appropriative pumping rates which are higher than the assigned constant value are retained at the higher rate.

Pumping was restricted to a 4-month irrigation season of June through September. This is followed by an 8-month period of non-pumping. Pumping rates for the 4-month period are three times the annual rate. All pumping rates included a 25 percent return flow.

Model Simulation

Calibration and simulation of each section was accomplished separately, although ground-water flow between sections is modeled by the use of constant gradient nodes at common boundaries. This report focuses on the northern section; model results for other sections, however, are also described.

Calibration

To calibrate the ground-water model, pumping and corresponding water-level changes were simulated in the northern area between October 1, 1950 and October 1, 1979. Calibration was achieved by comparing computed 1979 water head elevations with observed 1979 water head elevations. The difference between observed and computed head elevations is referred to as the calibration error. A net recharge (QRE) was adjusted for each node to reduce the calibration error to five feet or less. In areas where calibration could not be achieved using reasonable recharge values, permeability values were adjusted to reduce calibration error. Permeability controls the ability of water to move between adjacent nodes. Calibration by adjustment of permeability values is considered justified due to the relatively sparse permeability information in the area and because of the non-homogeneous nature of the alluvial sediments.

Calibration error represents the total effect of inaccuracies associated with input parameters, assumptions used, or computational error.

The mean value of adjusted net recharge is 2.28 inches per year (9.38 percent of percipitation) as compared to the original estimated 2.2 inches per year (9 percent of precipitation). The similarity between calculated and estimated recharge is indicative of a successful model calibration.

In the southern sub-section and in portions of the central sub-section calibration could not be achieved because no historical water level information is available. In these areas the recharge of 2.28 inches per year was assumed.

Simulation Period

Once calibrated, the model was used to simulate pumping between July 1, 1973, and July 1, 1993, corresponding to the dates specified under Oklahoma Statute, Sections 1020.4 and 1020.5. The 20-year simulation runs consisted of two types: one using prior appropriative pumping only, (Figures 24 through 26), the other using prior appropriative pumping plus a trial constant rate (allocation) assigned to all other nodes. Pumping at each node is designed to automatically cease if the water head elevation in that node drops to within five feet of the bottom of the aquifer. It is assumed that the bottom five feet of each well is used to accommodate a submersible pump and well screen. If the water head in a "dry" node rises above the five foot level due to recharge, pumping is automatically resumed.

Model simulation is mathematically based on computations of change in storage and corresponding water-head elevations at each node. These changes are computed simultaneously in order to represent the effects of lateral flow to and from adjacent nodes. The volume of water in each node is computed using

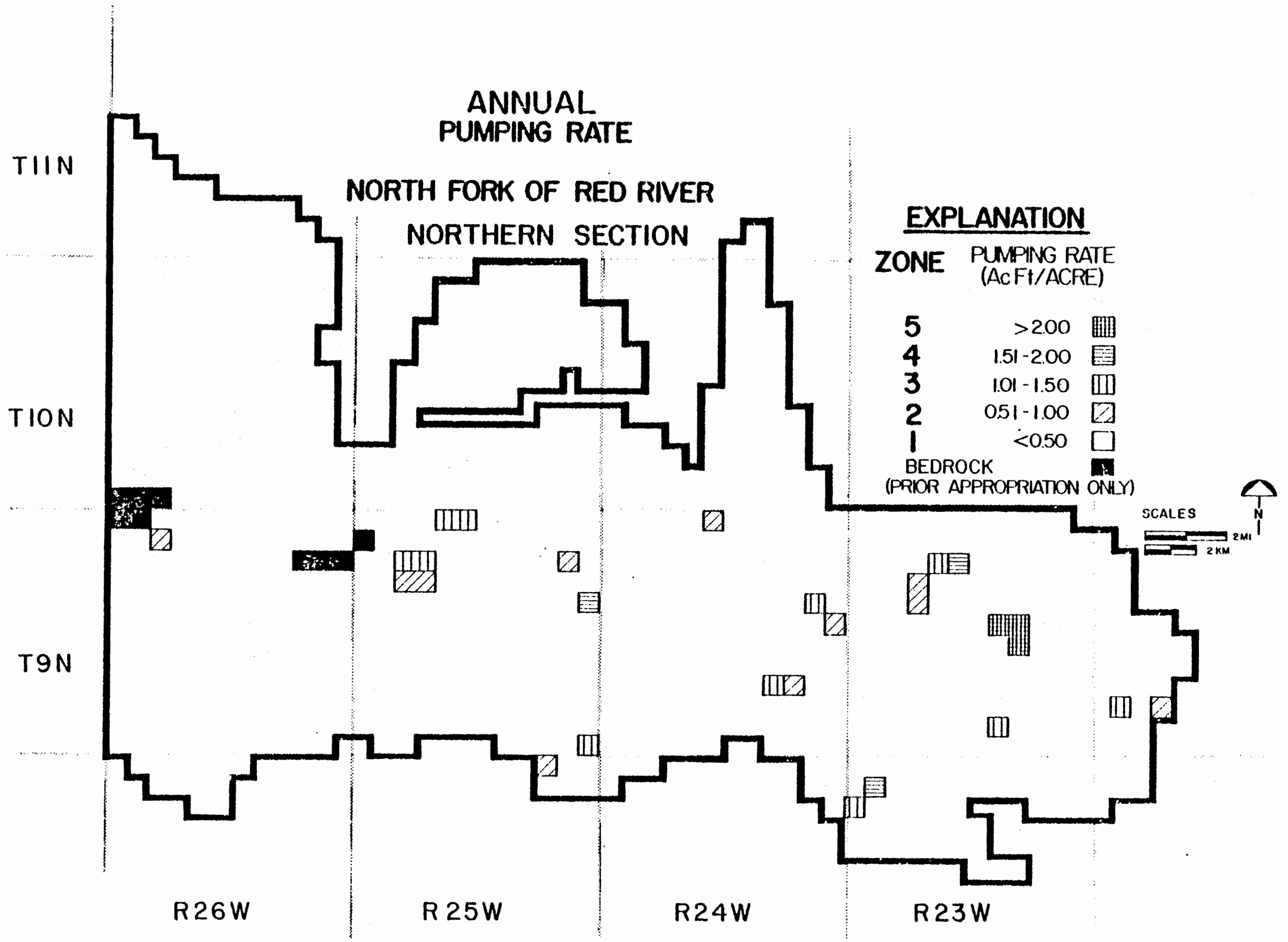


Figure 24. Prior Appropriative Pumping Rate-Northern Section

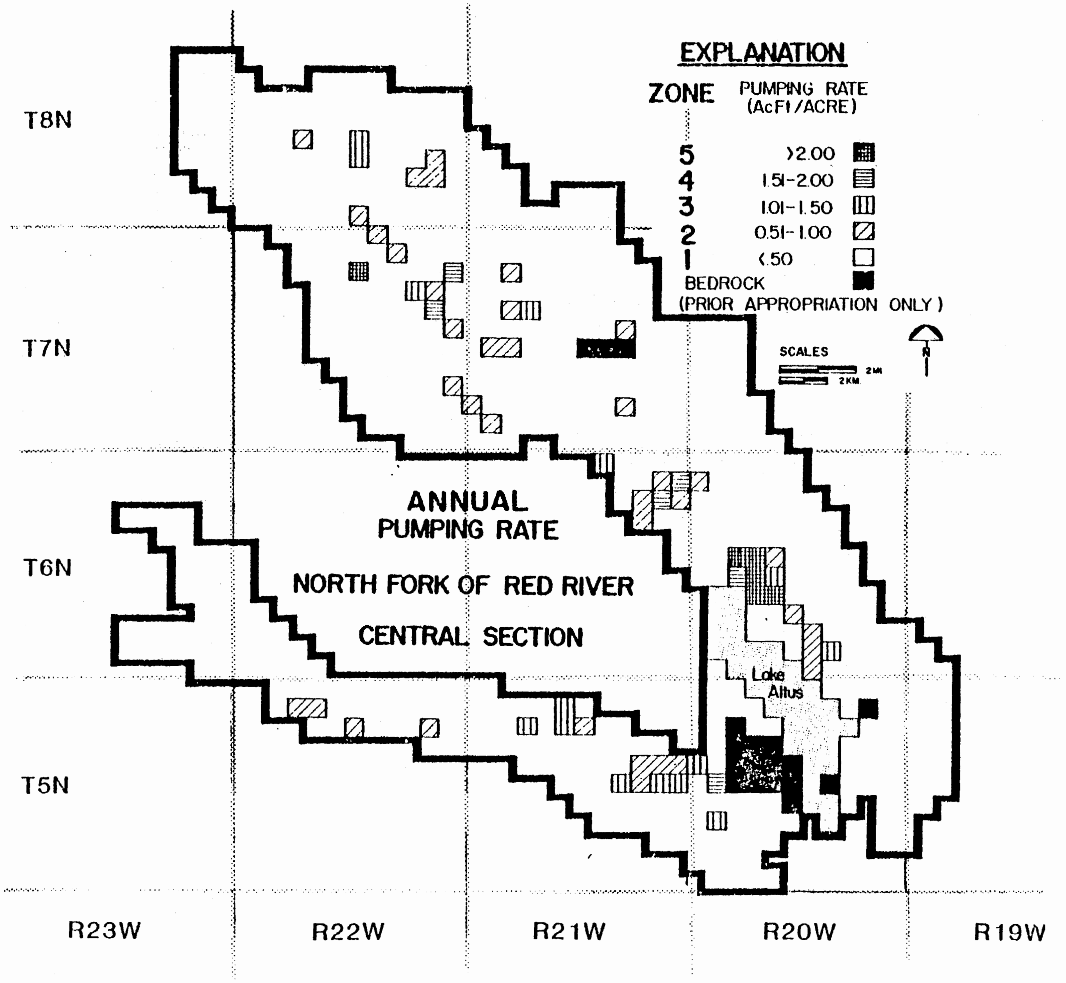


Figure 25. Prior Appropriative Pumping Rate-Central Section

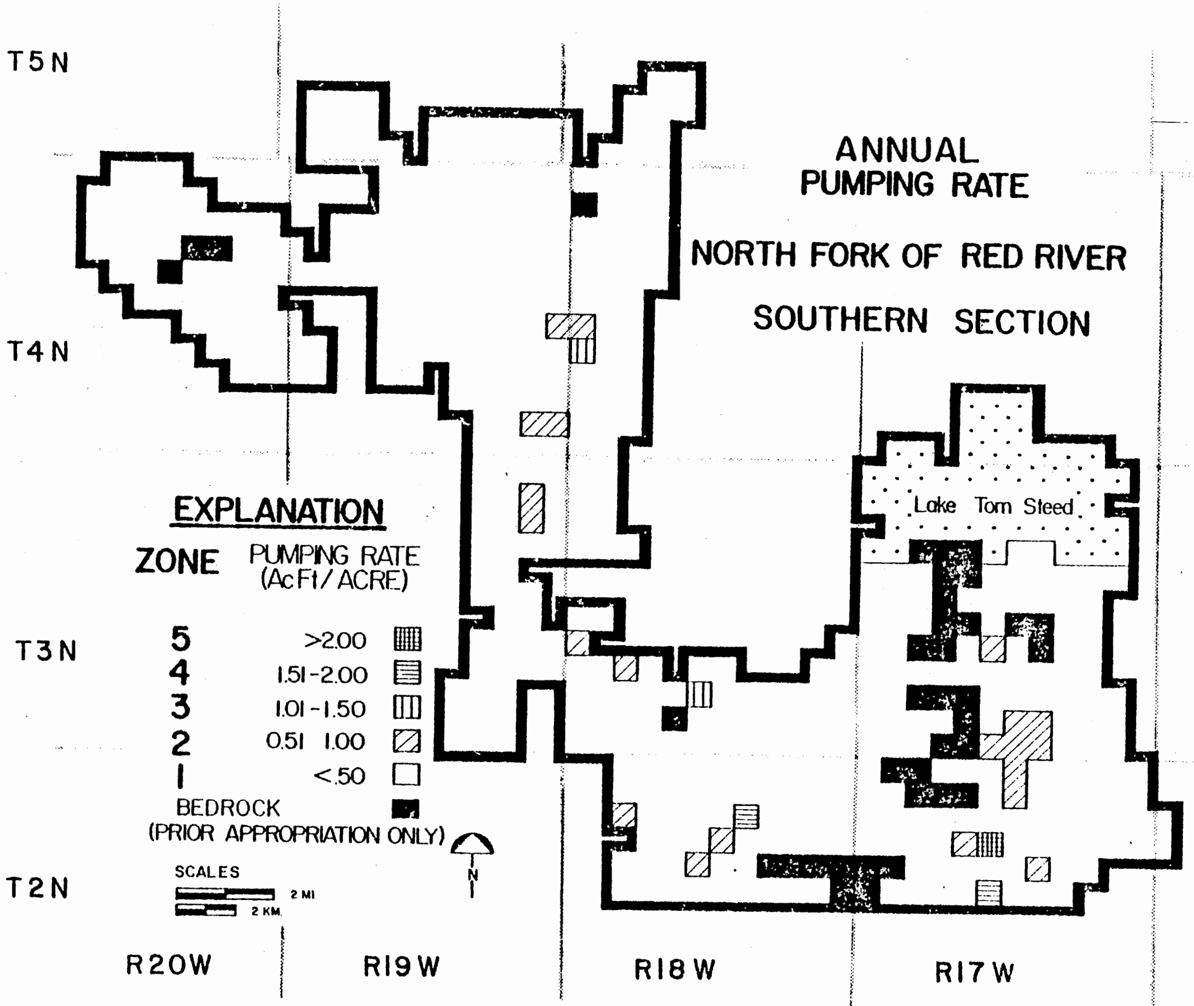


Figure 26. Prior Appropriative Pumping Rate-Southern Section

Darcy's Law to calculate lateral flow (Q) at each node face:

$$\pm Q_n = T_n I_n W_n$$

Where:

Q_n is the lateral flow of water into (+) or out of (-) the node at the n^{th} face (units in ft^3 per second).

T_n is the average coefficient of transmissivity of two adjacent nodes (units in ft^2 per second per foot).

I_n is the hydraulic gradient which is the difference in water-head elevations (feet) in two ajacent nodes divided by the distance (2,640 feet) between the two nodes.

W_n is the width (2,640 feet) of the common n^{th} node face.

Transmissivity is calculated in the model by multiplying the value of the coefficient of permeability by the saturated thickness at each node. The net flow into or out of each node is the algebraic sum of the lateral flows determined for the node faces as well as outflow due to pumpage and evapotranspiration and inflow due to surface recharge (calibration).

The computed values for inflow and outflow are summarized as a mass balance for the entire project area in Table VII. Mass-balance tables are computed for each model time step. A model time step of ten days is used for each set of computer calculations of head change. The head change is computed by the following relationship:

$$\pm H_n = (Q_{net,\, n,\, t=1} - Q_{net,\, n,\, t=2})\ Sy$$

TABLE VI

MASS BALANCE NORTH FORK OF THE RED RIVER (BETWEEN THE TEXAS BORDER AND TILLMAN COUNTY) PRIOR APPROPRIATIVE AND ALLOCATION PUMPING JULY 1, 1973, TO JULY 1, 1993

	Average Annual (Acre Ft)		Total (Acre Ft)	
	Inflow	Outflow	Inflow	Outflow
Recharge	+67,114		+1,342,283	
Pumping		-144,399		-2,887,980
River Leakage	+24,609	- 18,909	+ 492,176	- 378,182
Subsurface Flow	+ 1,567	- 1,461	+ 31,335	- 29,227
TOTALS	+93,290	-164,769	+1,865,794	-3,295,389
Net Storage		- 71,480		-1,429,595

$\pm H_n$ = change in water-head elevation (drop = (-), rise = (+)); (units are in feet).

$Q_{net, n, t=1, 2}$ = net flow into or from each nth node as computed at the end of consecutive time steps (t); (units are in cubic feet).

Sy = specific yield; (unitless).

The above relationship is used in a set of simultaneous equations which are computed for all nodes during each model time step. Subsequently, a relaxation procedure (ADIP) is used to adjust the resulting head elevation (former head $\pm H_n$) for each node to within a 0.1 foot model error.

CHAPTER V

RESULTS

The maximum annual yield for the alluvial aquifer associated with the North Fork of the Red River was determined by computer simulation of all prior appropriative and subsequent allocated pumping for the period July 1, 1973, to July 1, 1993. The maximum annual yield was determined by adjusting the amount of allocated pumping which would cause 50 percent of the nodes to go "dry" (saturated thickness equal to or less than 5.5 feet) by the end of the 20-year simulation period. Several simulation runs, using different trial pump rates, were made to obtain the 50 percent "dry" criteria.

The maximum annual yield determined for the Northern area is 2,060,725 acre-feet per year (AF/yr) using a pumping allocation of 0.995 acre-feet per acre per year (AF/A/yr). The ground-water budget of the Northern subbasin is illustrated in the conceptual mass balance shown in Figure 27. The box at the lower left represents the total ground water present in the alluvial deposits during the twenty year period, July, 1973 to July, 1993. Recharge to the ground-water system is depicted schematically as inflow pipes, and includes infiltration of precipitation (9.38 percent of total precipitation), surface inflow from the river, subsurface inflow from the alluvial deposits in Texas, and return flow from irrigation (25 percent of total pumpage). Ground-water losses from the system are depicted as outflow pipes and wells and include evapotranspiration, surface flow to the river, subsurface flow into Tillman County and pumpage. Similar mass balances are developed for the Central and

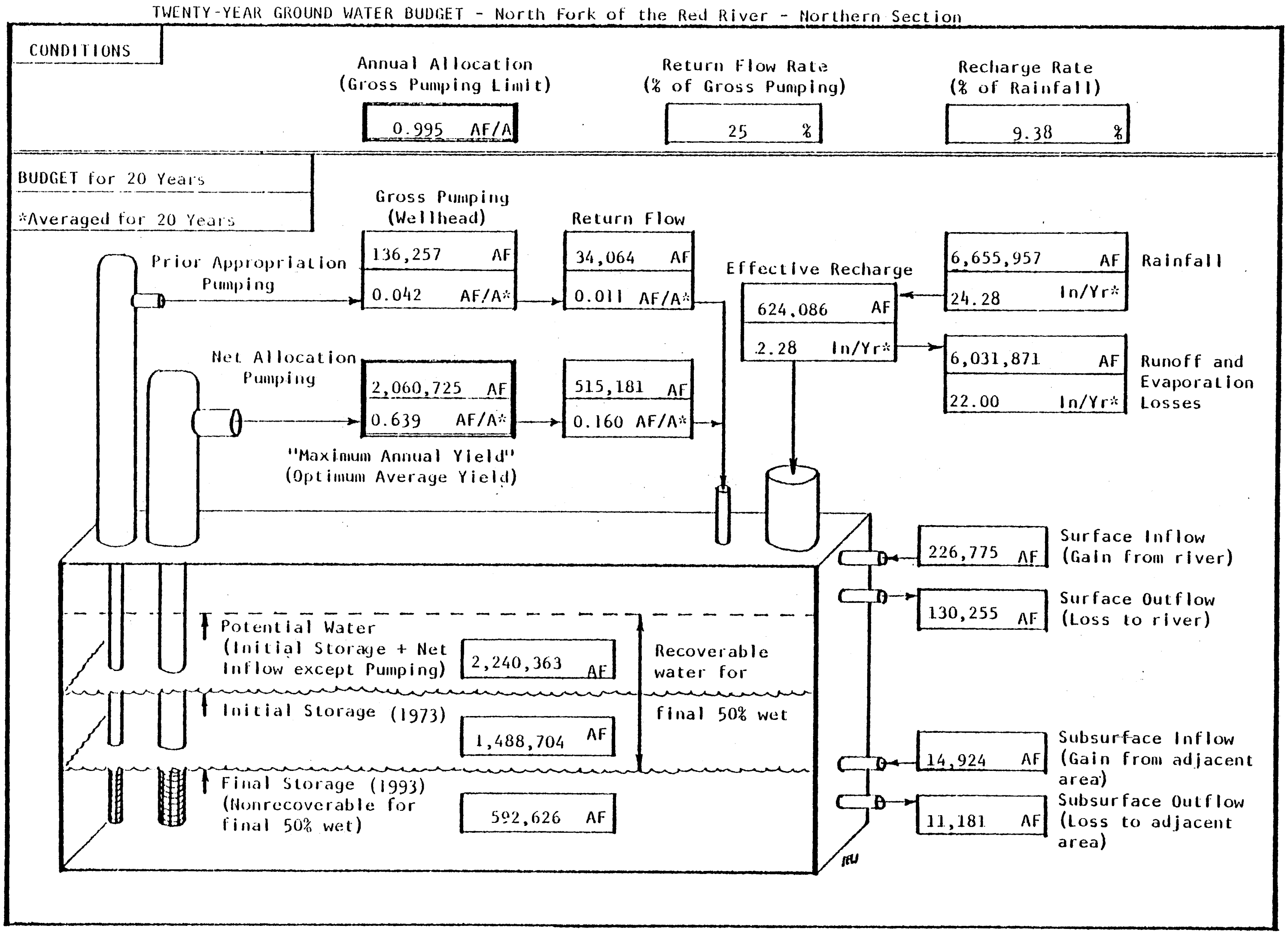


Figure 27. Twenty-Year Ground-Water Budget Northern Section

Southern areas in Figures 28 and 29.

Dividing the total recoverable water available for pumping in the Northern area by the total aquifer area produces an "optimum average yield" of 0.639 AF/A/yr. This "single bucket" approach assumes uniform aquifer properties (saturated thickness, permeability, specific yield) throughout the area. The recommended annual allocation of 0.995 AF/A/yr for the Northern area (based on the 50 percent "dry" Criteria) is computed in the model recognizing the inhomogeneity of the alluvial sediments and the non-uniform distribution of ground water within the aquifer.

The inhomogeneity of the aquifer and ground-water distribution within the system causes certain areas to become "dry" in response to pumping. Final (1993) saturated thickness maps indicating "dry" areas due to allocated pumping are shown in Figures 30, 31, and 32. A 20-year sequence of areas which become "dry" is shown on saturated thickness maps (on 5-year intervals) included in the Appendix. Initial (1973) and final (1993) water-table elevation, water depth, and transmissivity maps for each subbasin are also included in the Appendix.

"Dry" nodes are found primarily in areas of shallow bedrock (and low transmissivity resulting generally from small saturated thickness). A ground-water allocation guarantees only the right to pump a permitted volume of water, but can not guarantee its availability. Simulated pumping at the recommended allocation caused a number of prior appropriative rights owners (owners with ground-water rights established prior to July 1, 1973) to go "dry". The prior appropriative owners who are predicted go "dry" during the 20-year period (Table VII) are shown in Figure 33. This is based on a comparison of prior appropriative pumping (Figures 24 through 26) with areas which are shown to be "dry" on the saturated thickness maps. Approximately 36 percent of prior rights owners are adversely affected by additional allocated pumping. Nineteen

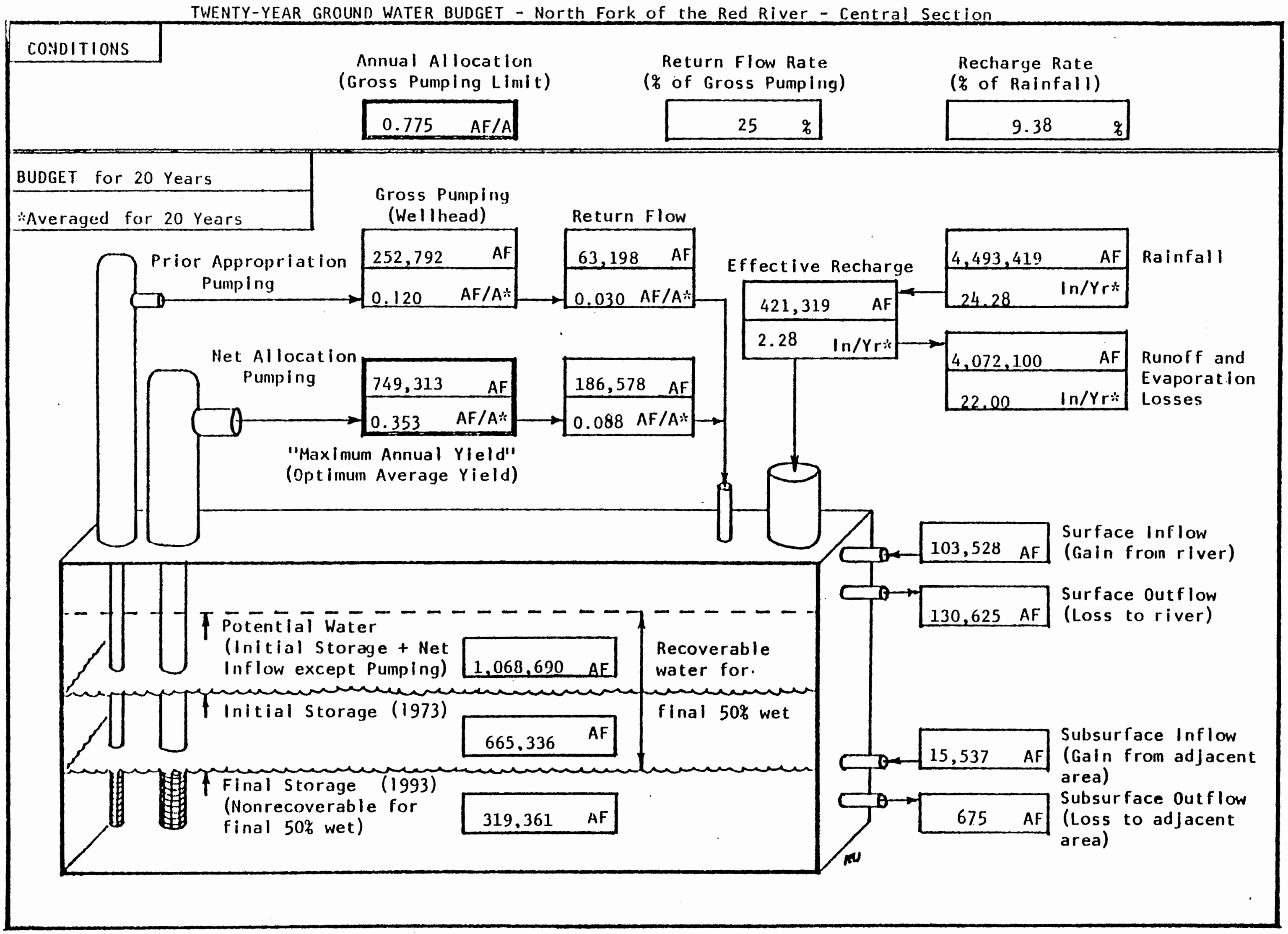


Figure 28. Twenty-Year Ground-Water Budget Central Section

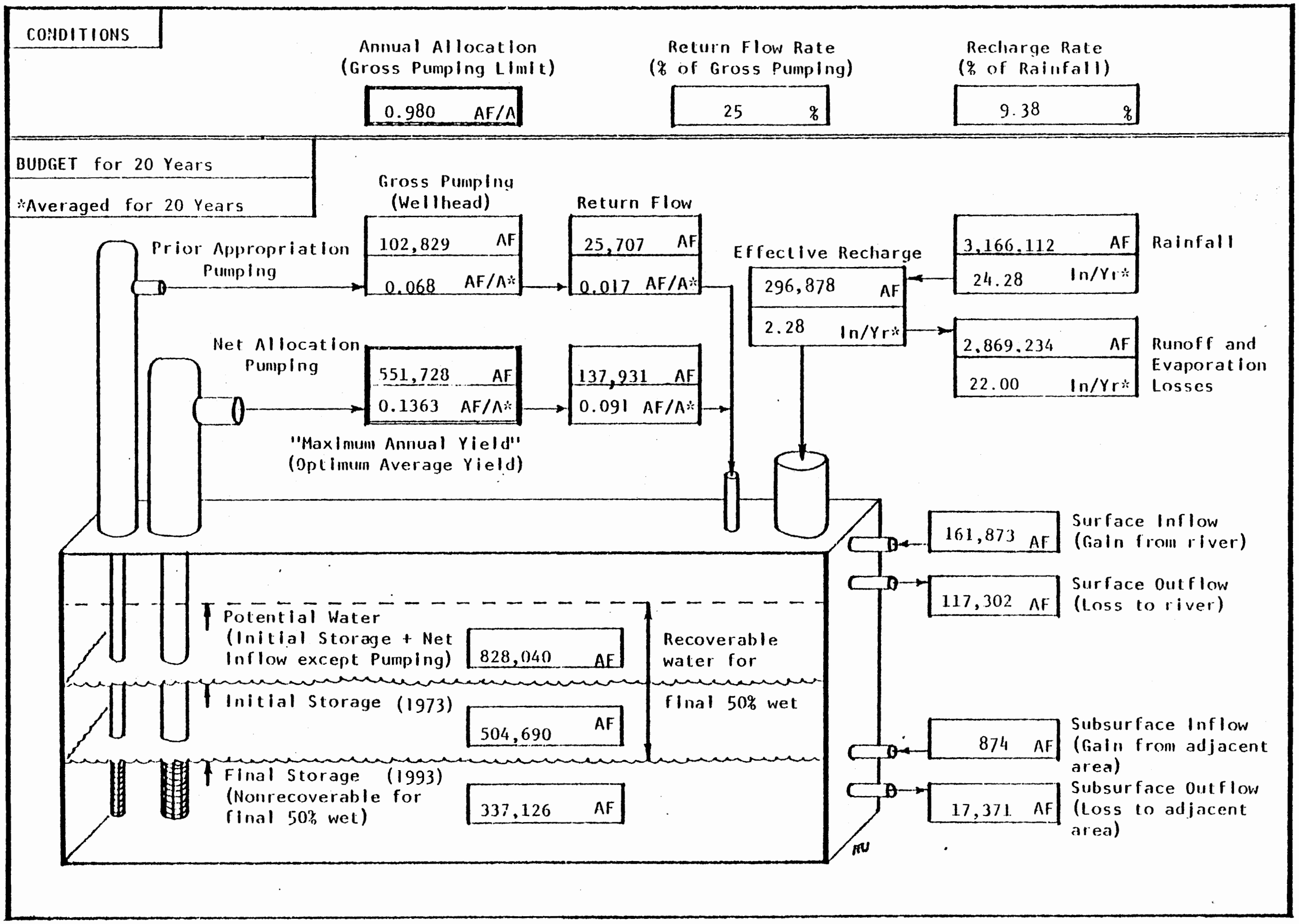

TWENTY-YEAR GROUND WATER BUDGET - North Fork of the Red River - Southern Section

Figure 29. Twenty-Year Ground-Water Budget Southern Area

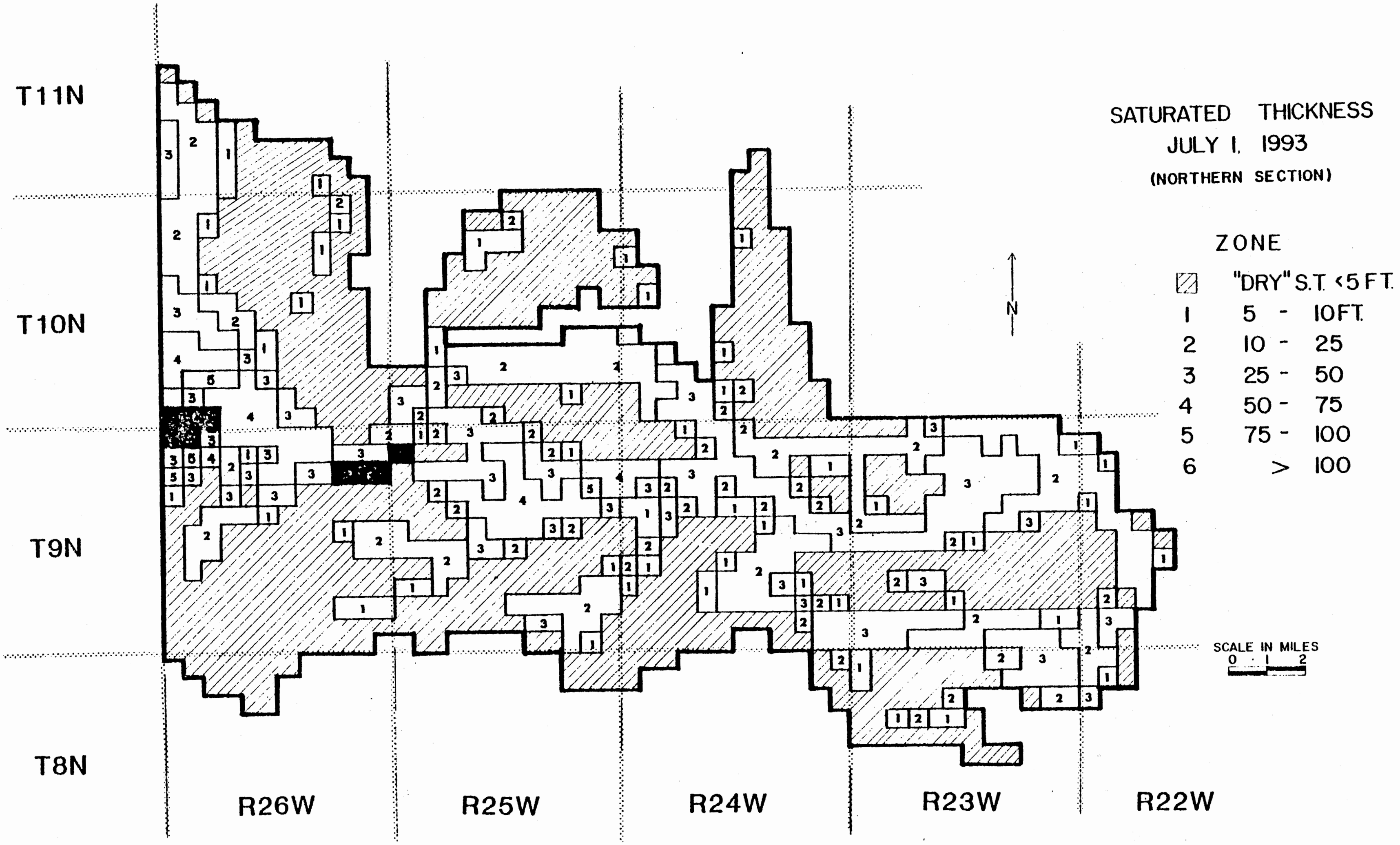


Figure 30. Saturated Thickness July 1, 1993 Northern Section

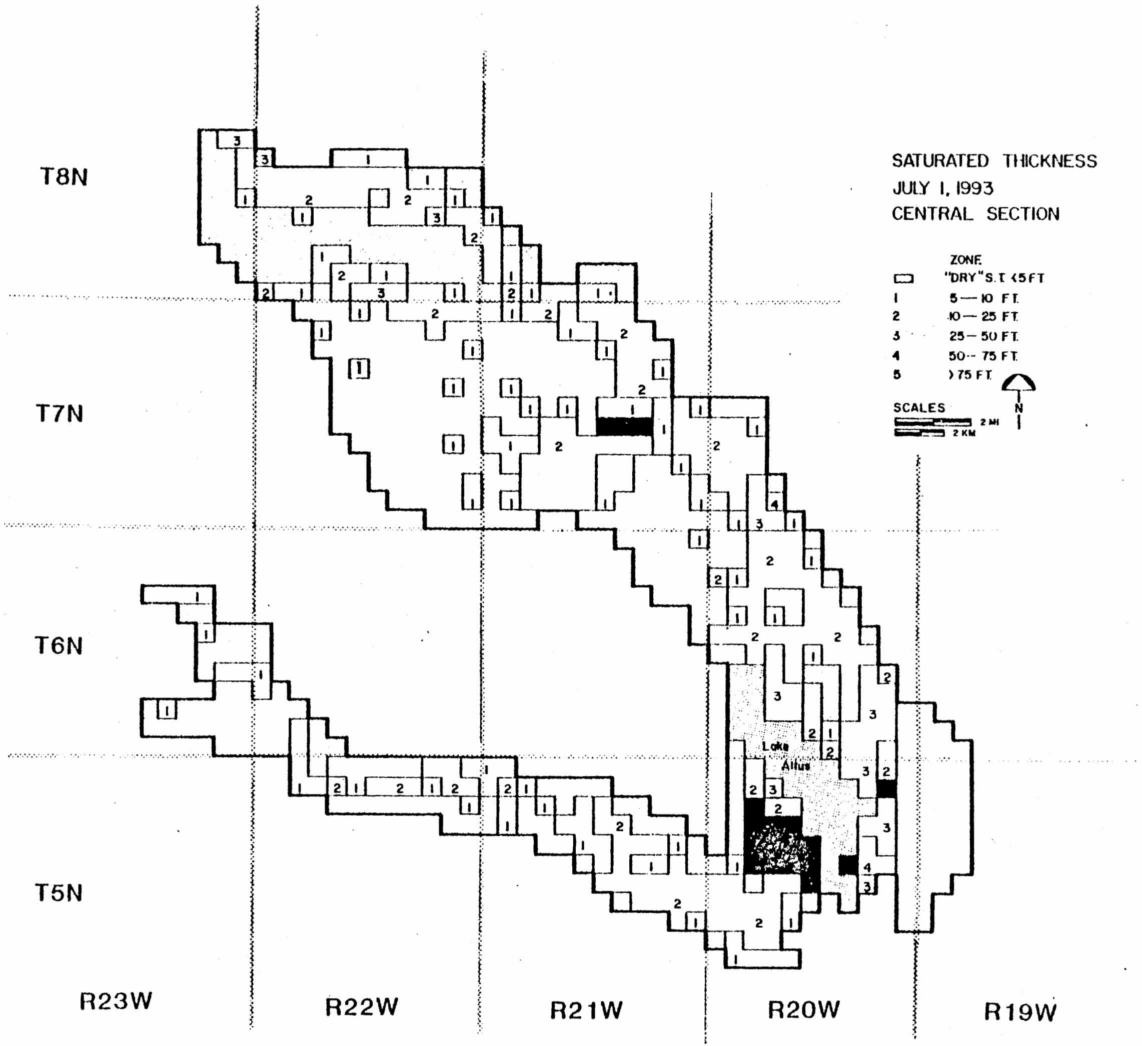


Figure 31. Saturated Thickness July 1, 1993 Central Section

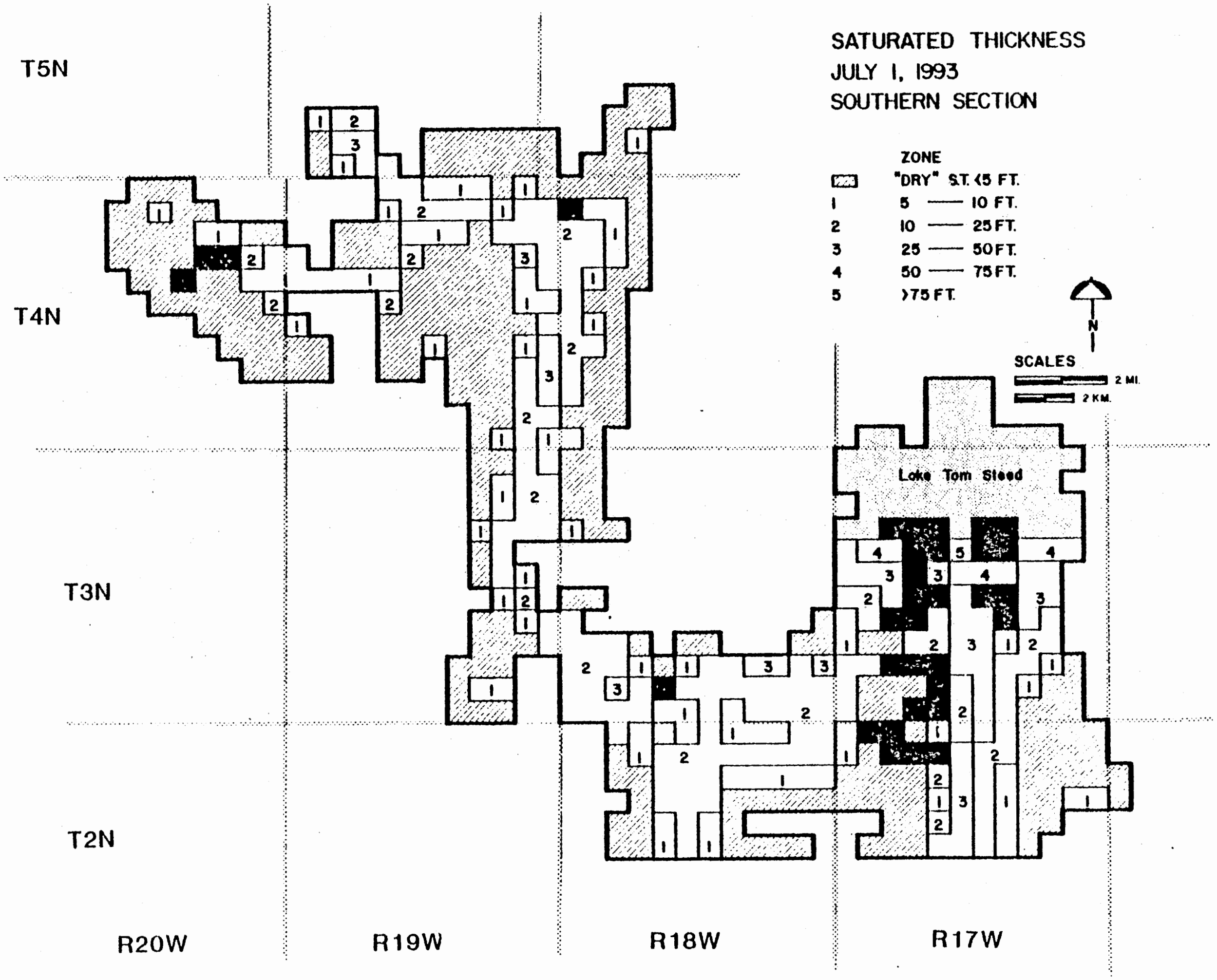


Figure 32. Saturated Thickness July 1, 1993 Southern Section

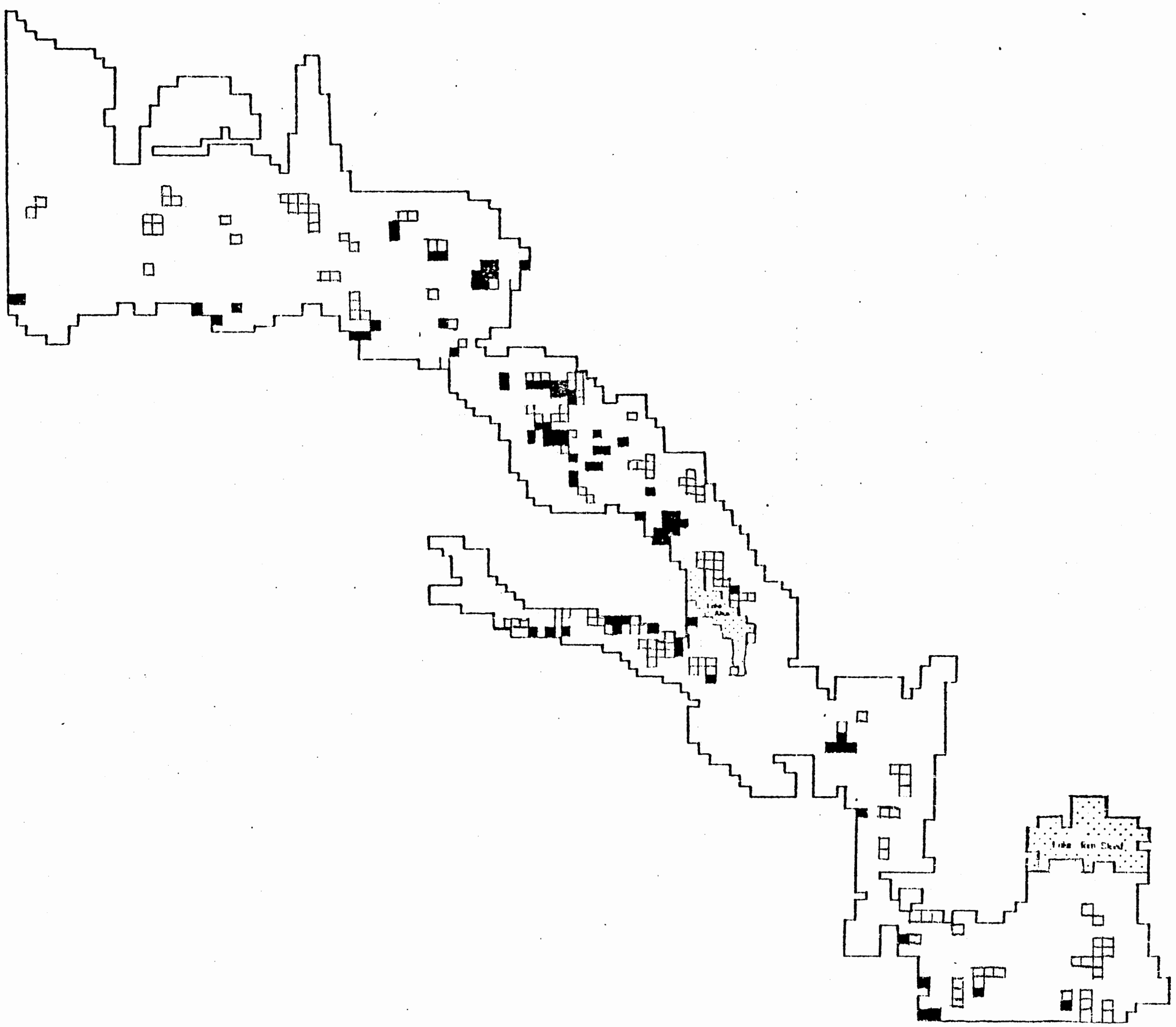


Figure 33. Affected Prior Right Owners-Prior Appropriative Pumping Plus Allocation

TABLE VII

AFFECTED (SATURATED THICKNESS < 5 FEET) PRIOR RIGHTS OWNERS DUE TO PUMPING AT ALLOCTED PUMPING RATE

	Annual Pumping Rate (ac-ft/ac)	Total Number Rights Owners	Affected Rights Owners				
			1973	1978	1983	1988	1993
Northern Section	0.995	58*	9%	19%	26%	18%	36%
Central Section	0.775	126*	1%	12%	31%	40%	44%
Southern Section	0.980	52*	0%	12%	17%	19%	19%
Total Area	0.92	236*	3%	14%	27%	35%	36%

*Number of Nodes (¼ Sections) with ground-water rights allocated before July 1, 1973.

percent of prior rights owners would go "dry" during the 20-year period based on prior appropriative pumping only (Figure 34).

Another potential effect of pumping on the North Fork ground-water system is natural pollution. Natural pollution by induced infiltration of poor quality surface water could potentially threaten the North Fork aquifer if overpumping was to occur. Water quality data summarized by Carr and Bergman (1976) and Havens (1977) indicate that ground water within the project area is generally of better quality than surface water (see Table II, Chapter III). Overpumping of the alluvial aquifer could cause influent conditions to become established causing poor quality water from the rivers and lakes to enter the ground-water system. Assessment of 1993 simulated water-table elevation maps (Figures 35 through 37) indicates that pumping at the allocated rate apparently will not induce influent conditions over a large regional extent. Influent conditions may, however, occur locally (primarily near Lake Altus and Lake Tom Steed), and during high flows along the river. Under these circumstances, natural pollution events will be temporary and localized. Widespread natural pollution is not expected to be induced by regional pumping at the determined annual allocation rate.

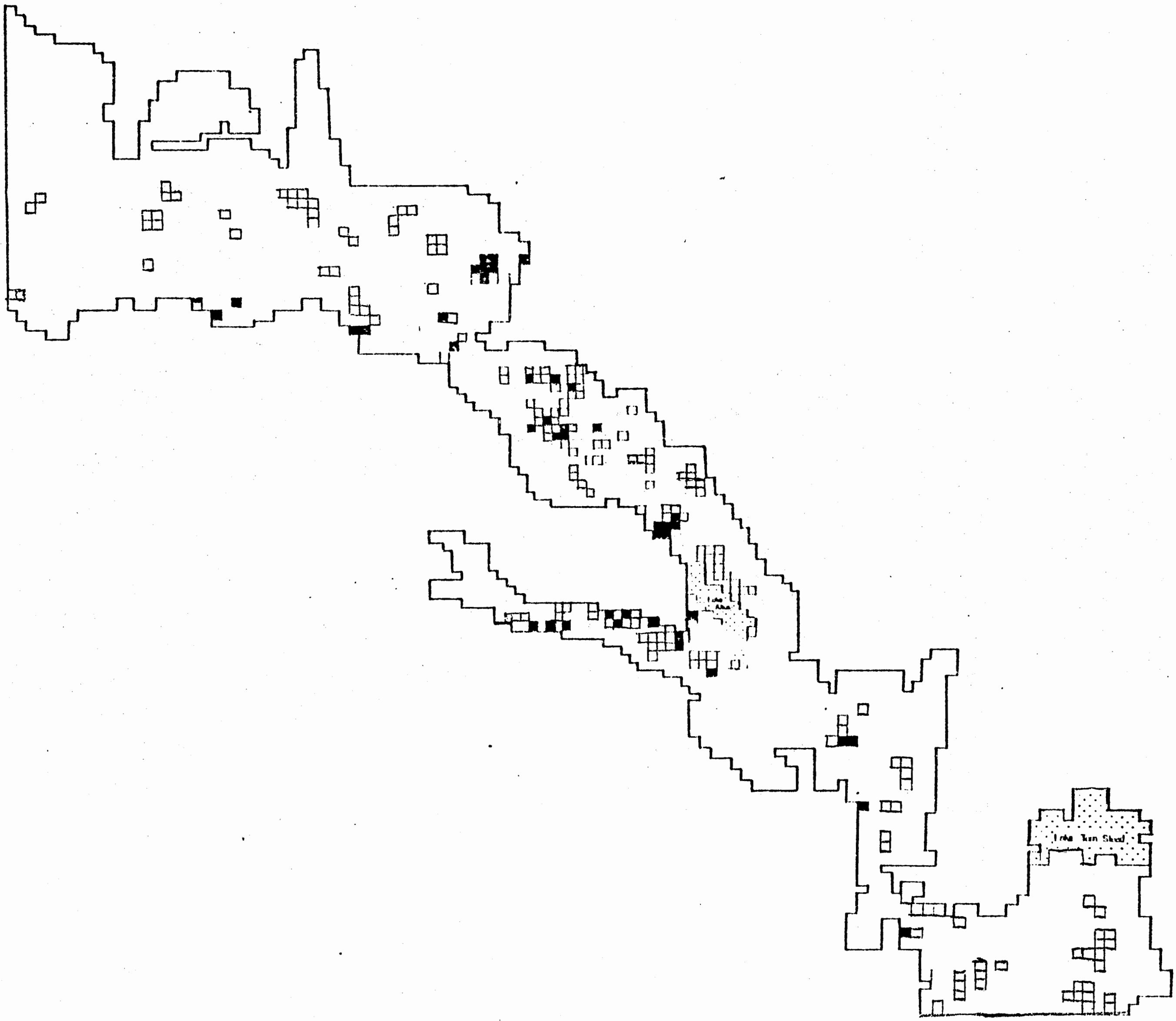


Figure 34. Affected Prior Right Owners-Prior Appropriative Pumping Only

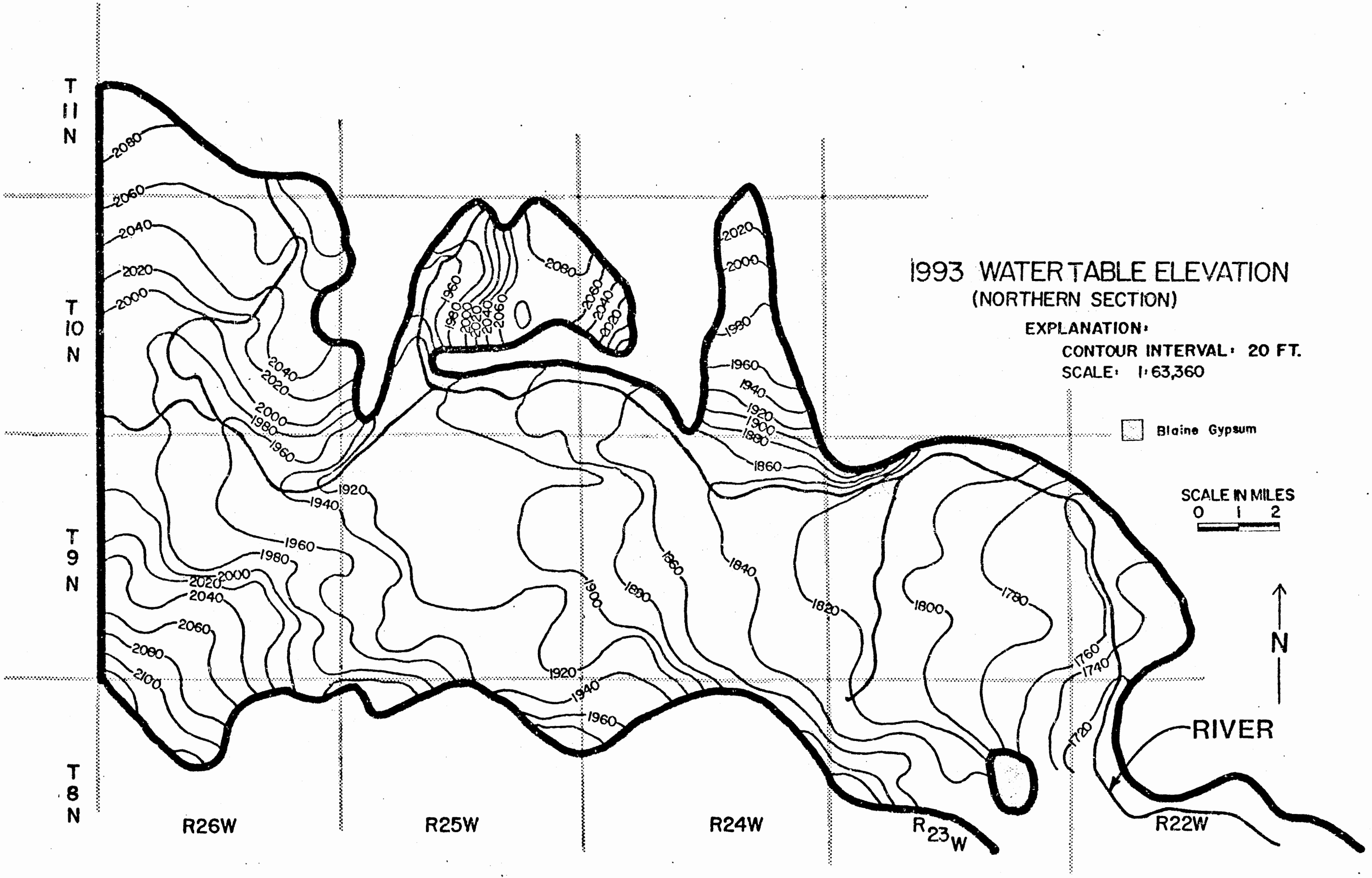


Figure 35. 1993 Water Table Elevation Northern Section

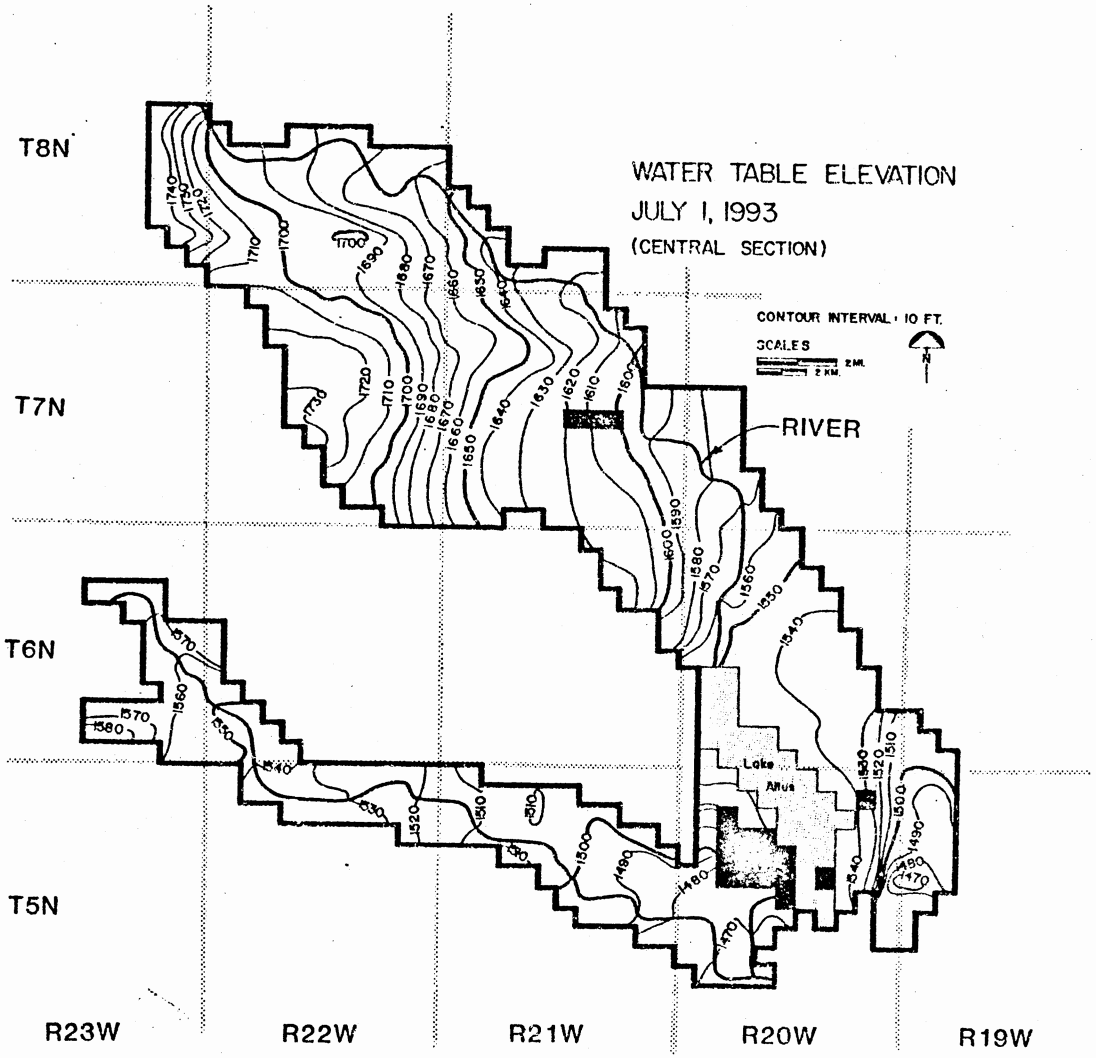


Figure 36. Water Table Elevation July 1, 1993 Central Section

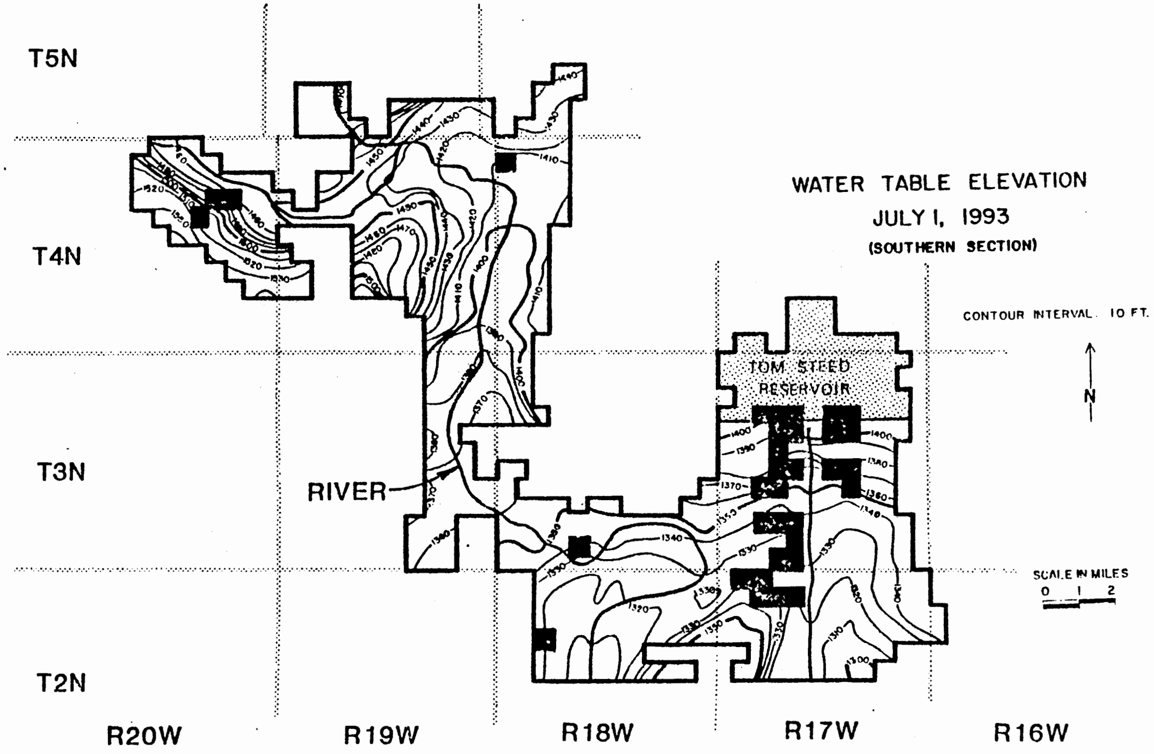


Figure 37. Water Table Elevation July 1, 1993 Southern Section

Chapter VI

CONCLUSIONS

Computer modeling has been shown to be an efficient method for handling large quantitites of hydrogeologic data to simulate changes in the ground-water regime over a large area. Model Calibration has provided a better understanding of hydrologic system of the North Fork aquifer. Ground-water modeling was used to determine the maximum annual yield and annual allocation which will guarantee a minimum 20-year life for the North Fork ground-water basin.

The maximum annual yield determined for the North Fork basin between the Texas border and Tillman County is the sum of the yields of the individual subbasins. The ground-water budget for the entire project area is illustrated in the conceptual mass balance shown in Figure 35. This figure summarizes the total ground-water inflow and outflow in the basin during the twenty year period July 1973, to July 1993, as well as initial and final ground-water storage.

Determination of the maximum annual yield of the North Fork subbasin is based on the following parameters in accordance with Oklahoma ground-water law:

1. The total land area of the sub-basin is 367,520 acres.
2. The volume of ground-water storage in the aquifer as of July 1, 1973 was calculated to be 2,659,000 acre-feet; the cumulative volume of ground-water storage over the 20-year period is 4,137,000 acre-feet.
3. The estimated rate of natural recharge is 9.38 percent of precipitation or 2.3 inches per year.

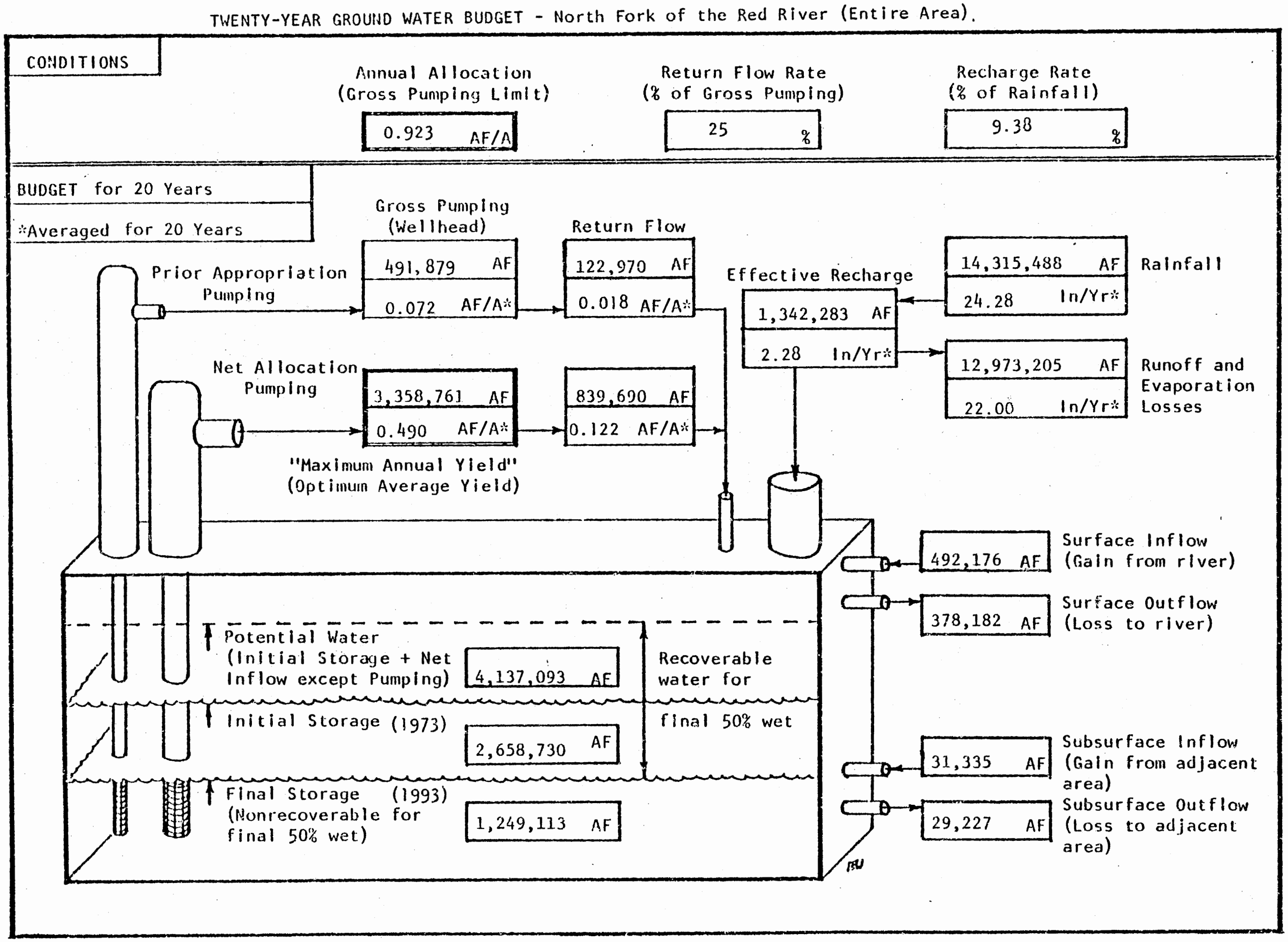


Figure 38. Twenty-Year Ground-Water Budget Entire Area

4. The average specific yield for the basin is 25 percent.
5. The average transmissivity in 1973 was 19,400 gpd/ft.

A recommended annual pumping allocation of 0.92 AF/A/yr was determined for the entire basin by averaging the allocations established for each subbasin using a weighting factor based on percentage of total aquifer area occupied by each subbasin (Table VIII).

The threat of natural pollution of the North Fork ground-water system due to pumping at the allocated rate was determined to be minimal. Although some induced infiltration could occur along the river, the effects are not of regional extent.

Recommendations for future, similar investigations include an exploratory drilling and/or other hydrogeologic data gathering program to follow the modeling effort. A computer model can only be as good as the data used to build it. Good data coverage over the entire project area is needed to obtain a thorough understanding of the hydrogeologic setting prior to refinement of modeling. Additional or more uniform distribution of data points, in the form of past and present water levels, drillers logs, and aquifer test results, would eliminate the need for interpolation of data over large areas and greatly refine model results.

TABLE VIII

WEIGHTED AVERAGE ALLOCATION FOR NORTH FORK OF THE RED RIVER (ENTIRE SUB-BASIN)

Sub-Basin	Area (acres)	% Total Area	Allocation (ac. ft/ac)
Northern	161,280	47	.995
Central	105,600	31	.775
Southern	76,160	22	.980
Total	343,040	100	.92 *

*Weighted Average:

$$\frac{161{,}280 \text{ Acres}}{343{,}040 \text{ Acres}} (47\%) \text{ X } .995 \frac{\text{Acre-feet}}{\text{Acre}} = 160{,}474 \text{ ac-ft}$$

plus

$$\frac{105{,}600 \text{ Acres}}{343{,}040 \text{ Acres}} (31\%) \text{ X } .775 \frac{\text{Acre-feet}}{\text{Acre}} = 81{,}840 \text{ ac-ft}$$

plus

$$\frac{76{,}160 \text{ Acres}}{343{,}040 \text{ Acres}} (22\%) \text{ X } .980 \frac{\text{Acre-feet}}{\text{Acre}} = 74{,}637 \text{ ac-ft}$$

	Maximum Annual Yield:	<u>316,915 ac-ft</u>
÷	Total Area (Entire Sub-Basin):	343,040 Acres
	Weighted Average Allocation: (Entire Sub-Basin)	.92 ac-ft/ac/yr

REFERENCES CITED

Al-Sumait, Abdulaziz Jasem, 1978, A Computer Ground-Water Model for the Tillman Alluvium, Tillman County, Oklahoma: Unpublished Master's Thesis, Oklahoma State University.

Burton, L.C., 1965, Ground water in the Terrace Deposits of Central Beckham County, Oklahoma: Oklahoma Water Resources Board, Bull. 25.

Carr, J.E., and Bergman, D.L., 1976, Clinton Quadrangle, Oklahoma: Oklahoma Geological Survey, Hydrologic Atlas No. 5.

Clifton, R.L., 1928, Oil and Gas in Oklahoma; Geology of Harmon, Greer, Jackson, and Tillman Counties: Oklahoma Geological Survey Bull. 40-Y.

Cooper, H.H., Jr and Jacob, C.E., 1946, A generalized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History Trans. Am Geophysical Union, Vol. 27, pp. 524-526, Washington.

DeVries, R.M. and Kent, D.C., 1973, Sensitivity of Ground-Water Flow Model to Vertical Variability of Aquifer Constants: Water Resources Research, Vol. 9, No. 6, p. 38-41.

Dobrin, Milton B., 1976, Introduction to Geophysical Prospecting: New York, McGraw Hill Book Company.

Gould, Charles N., 1926, The Geology and Water Resources of Oklahoma: U.S. Geological Survey, Water Supply Paper 148.

Gould, Charles N. and Lewis, Frank E., 1926, The Permian of Western Oklahoma and the Panhandle of Texas: Oklahoma Geolgical Survey Circular No. 13.

Griffen, W.E., 1949, Residual Gravity in Theory and Practice: Geophysics, Vol. 14, p. 39-56.

Havens, John S., 1977, Lawton Quadrangle, Oklahoma: Oklahoma Geological Survey, Hydrologic Atlas No. 6.

Hjelmfelt, Allen T. and Cassidy, John J., 1976, Hydrology for Engineers and Planners: Ames, Iowa, Iowa State University Press, pp. 71-76.

Hollowell, J.R., 1965, Ground-Water in the Alluvium of Otter Creek Basin, Oklahoma: Oklahoma Water Resources Board, Bull. 27.

Johnson, A.T., 1967, Specific Yield - Compilation of Specific Yields for Various Materials: U.S. Geological Survey, Water Supply Paper 1662-D.

Johnson, K.S., 1963, Brine Well Production of Permian Salt at Sayre, Beckham County, Oklahoma: Oklahoma Geological Survey, Geology Notes: Vol. 23, No. 4.

Johnson, K.S., 1969, Geology and Mineral Resources of the Permian Blaine Formation and Associated Strata of Southwestern Oklahoma: Oklahoma Geological Survey.

Kent, D.C., Naney, J.W. and Barnes, B., 1973, An Approach to Hydrogeologic Investigations of River Alluvium: Groundwater, Vol. II, No. 4, pp. 30-42.

Kent, D.C. and Naney, J.W., 1978, Results of Computer Modelling of Alluvium and Terrace Deposits in Western Tillman County and Along the Washita River, Southwestern Oklahoma for Water Supply Capability: Report to Oklahoma Water Resources Board, Oklahoma State University.

Loo, Walter., 1972, The Influence of Vertical Variations in Lithology on a Mathematical Management Model for the Ogallala Aquifer, Texas County, Oklahoma: Unpublished Master's Thesis, Oklahoma State University.

Maderak, M.L., 1973, Ground-Water Resources of Wheeler and Eastern Gray Counties, Texas: Texas Water Development Board Report No. 170.

Meinert, J.G., 1961, Areal Geology of the Starvation Creek Area, Roger Mills and Beckham Counties, Oklahoma: Unpublished Master's Thesis, University of Oklahoma.

Merritt, C.A., 1958, Igneous Geology of the Lake Altus Area: Oklahoma Geological Survey Bulletin 76.

Murphy, C.W., 1958, Areal Geology of the Erick Area, Beckham and Greer Counties, Oklahoma: Unpublished Master's Thesis, University of Oklahoma.

Naney, James W., Barnes, Bill B., and Kent, Douglas C., 1976, A User's Manual for Computerization of Hydrogeologic Data for a River Alluvium: U.S. Department of Agriculture ARS-S-138.

Naney, James W. and Kent, D.C., 1980, Establishing ground water rights using a model: Symposium on watershed management, ASCE, Boise, Idaho.

Oklahoma Highway Department, 1969, Engineering Classification of Geologic Materials: Oklahoma Highway Department, Division 5.

Oklahoma Legislature, "Oklahoma Ground Water Law," Chapter 11, 1973, pp. 51-53.

Oklahoma Water Resources Board, 1968, Appraisal of the Water and Related Land Resources of Oklahoma, Region 1: Oklahoma Water Resources Board, publication 17.

Pinder, G.F., 1969, An Interactive Digital Model for Aquifer Evaluations: U.S. Geological Survey Open-File Report.

Pinder, G.F., 1970, An Interactive Digital Model for Aquifer Evaluation: U.S. Geological Survey Open-File Report.

Prickett, T.A., 1965, Type Curve Solution to Aquifer Test Under Water Table Conditions; Groundwater, Vol. 3, No. 3 pp. 5-14.

Scott, G.L., 1955, Areal Geology of Portions of Beckham, Greer, Kiowa, and Washita Counties, Oklahoma: Unpublished Master's Thesis, University of Oklahoma.

Scott, G.L., and Ham, W.E., 1957, Geology and Gypsum Resources of the Carter Area, Oklahoma: Oklahoma Geological Survey Circular 42.

Sawyer, Roger W., 1924, Areal Geology of a Part of Southwestern Oklahoma: Bulletin of the American Association of Petroleum Geologists, Vol. 8, No. 3 pp.

Smith, A.W., 1964, Areal Geology of Elk City Area, Beckham and Roger Mills Counties, Oklahoma: Unpublished Master's Thesis, University of Oklahoma.

Trescott, Peter A., and Pinder, George F., 1976, Finite-Difference Model for Aquifer Simulation in Two Dimensions with Results of Numerical Experiments: U.S. Geological Survey Open-File Report.

Trescott, Peter A., 1973, Interactive Digital Model for Aquifer Evaluation: U.S. Geological Survey Open-File Report.

U.S. Department of Agriculture, 1961, Soil Survey of Jackson County, Oklahoma: Soil Conservation Service, Stillwater, Oklahoma.

U.S. Department of Agriculture, 1967, Soil Survey of Greer County, Oklahoma: Soil Conservation Service, Stillwater, Oklahoma.

U.S. Department of Agriculture, 1969, Soil Survey of Kiowa County, Oklahoma: Soil Conservation Service, Stillwater, Oklahoma.

U.S. Department of Agriculture, 1979, Soil Survey of Beckham County, Oklahoma: Soil Conservation Service, Stillwater, Oklahoma (in press).

Walton, William C., 1970, Ground-Water Resource Evaluation: New York, McGraw-Hill Book Company.

Witz, Fred, 1978, Users Manual for Ground-Water Model: Unpublished Report, Oklahoma State University.

Witz, Fred, 1978, Users Manual for Print/Plot Package: Unpublished Report, Oklahoma State University.

APPENDIX

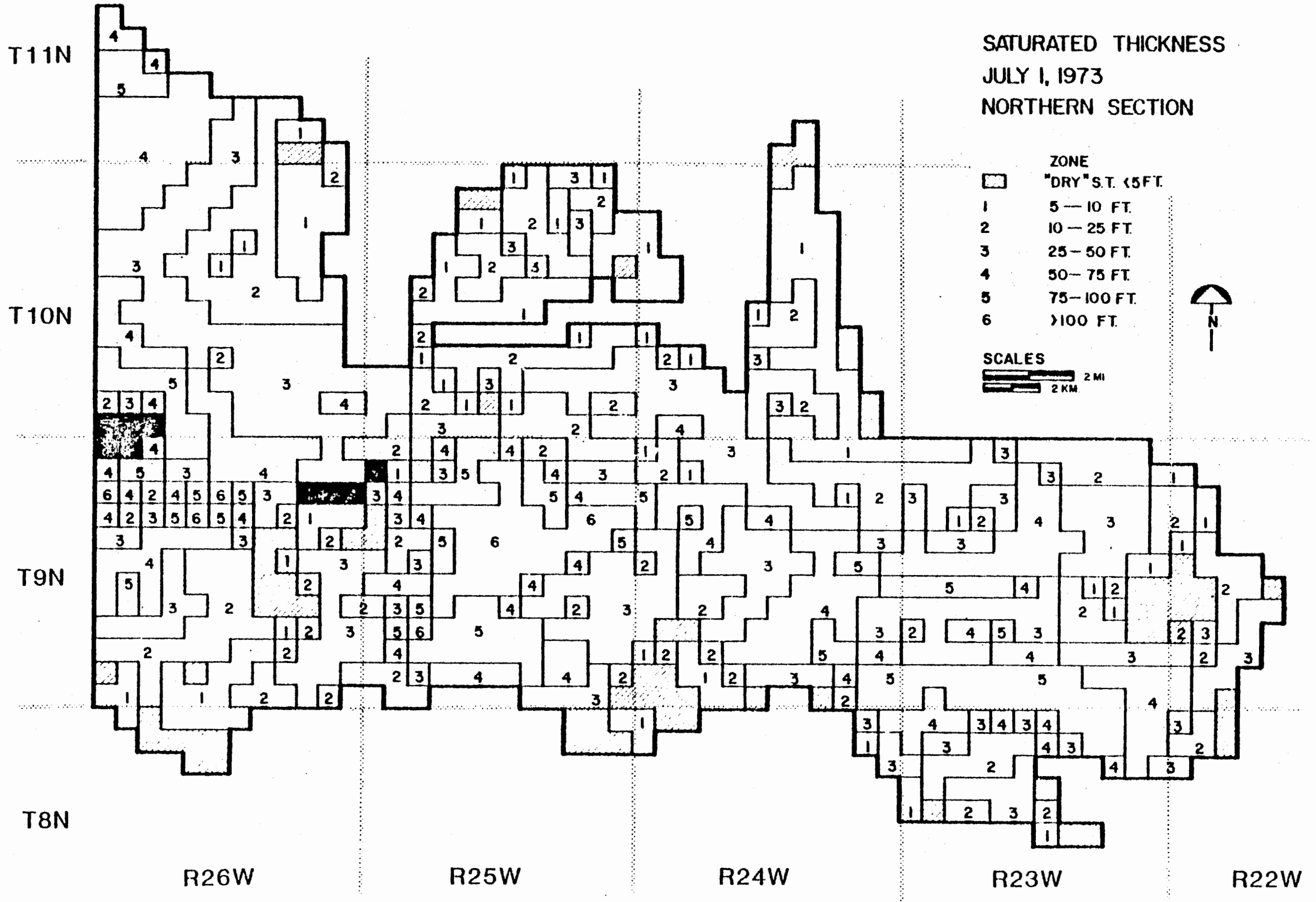


Figure 39. Saturated Thickness July 1, 1973 Northern Section

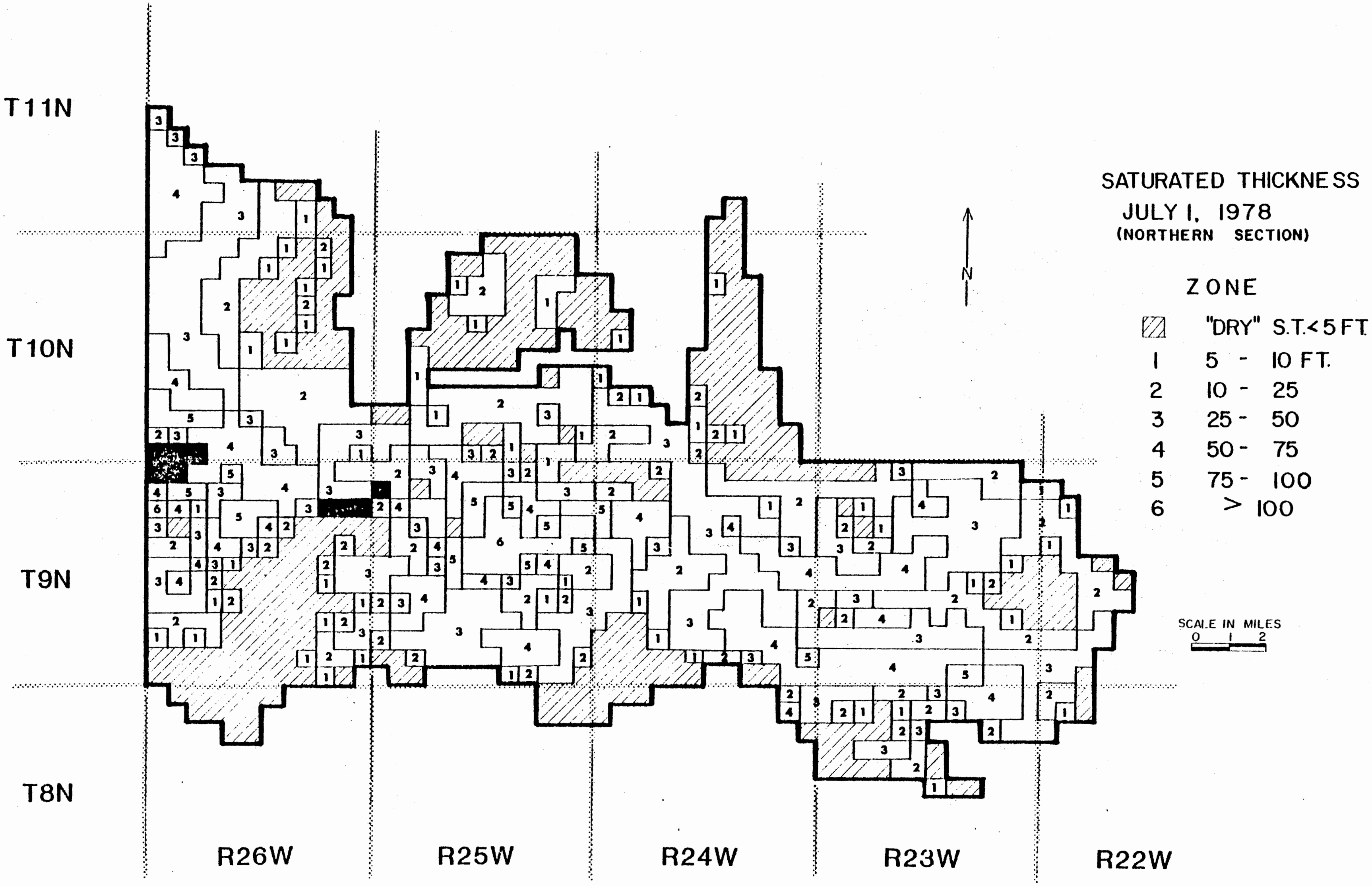


Figure 40. Saturated Thickness July 1, 1978 Northern Section

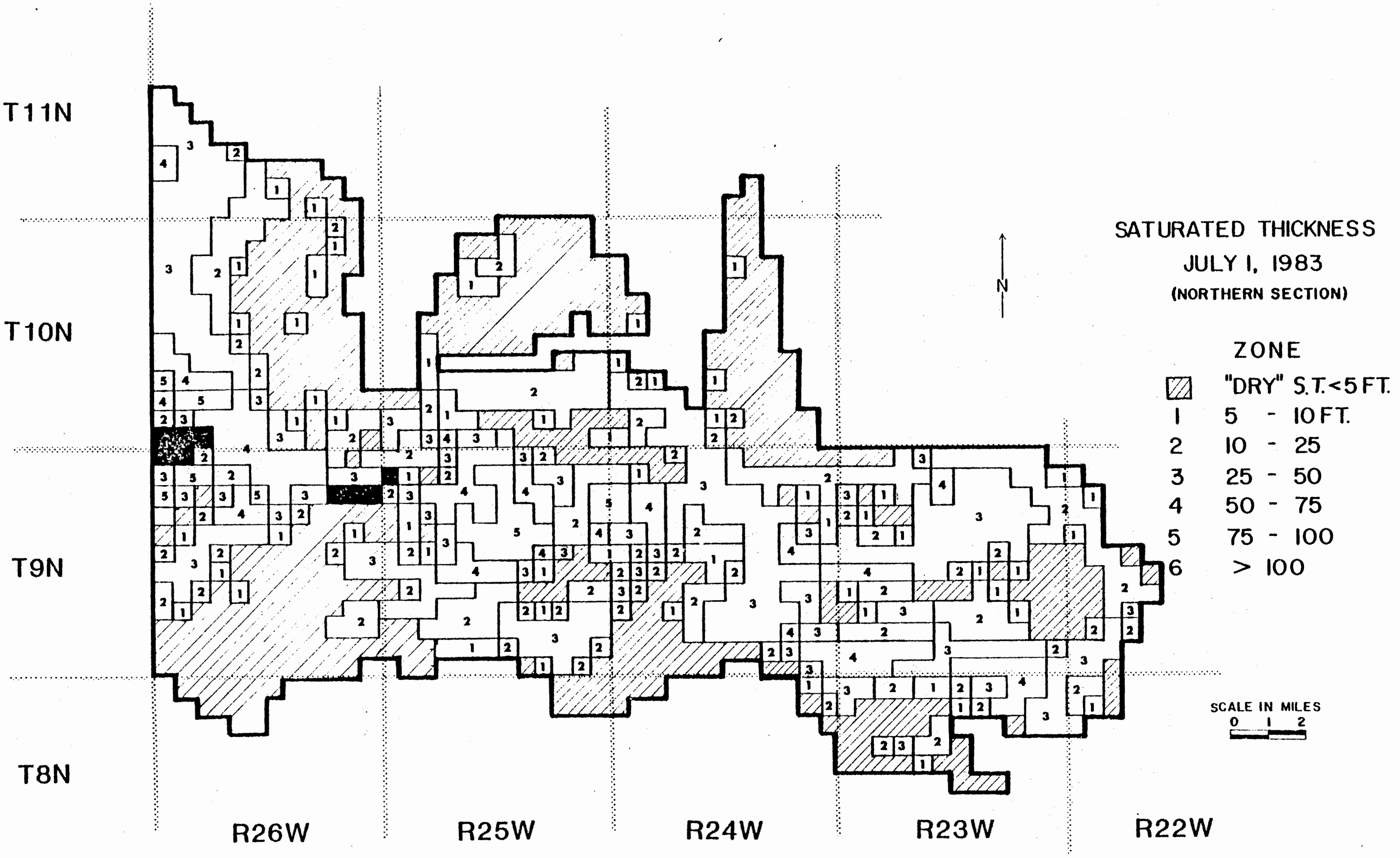


Figure 41. Saturated Thickness July 1, 1983 Northern Section

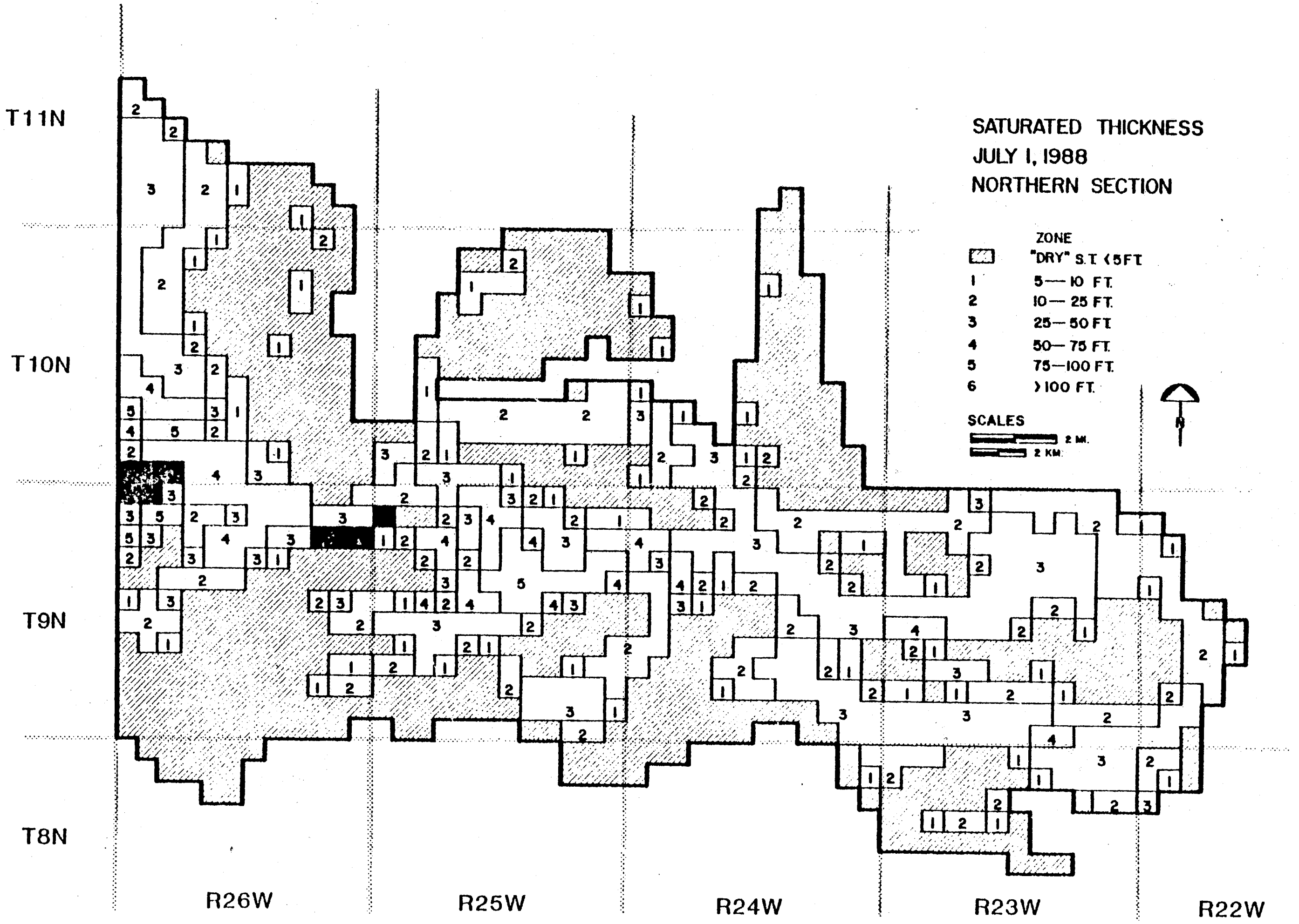


Figure 42. Saturated Thickness July 1, 1988 Northern Section

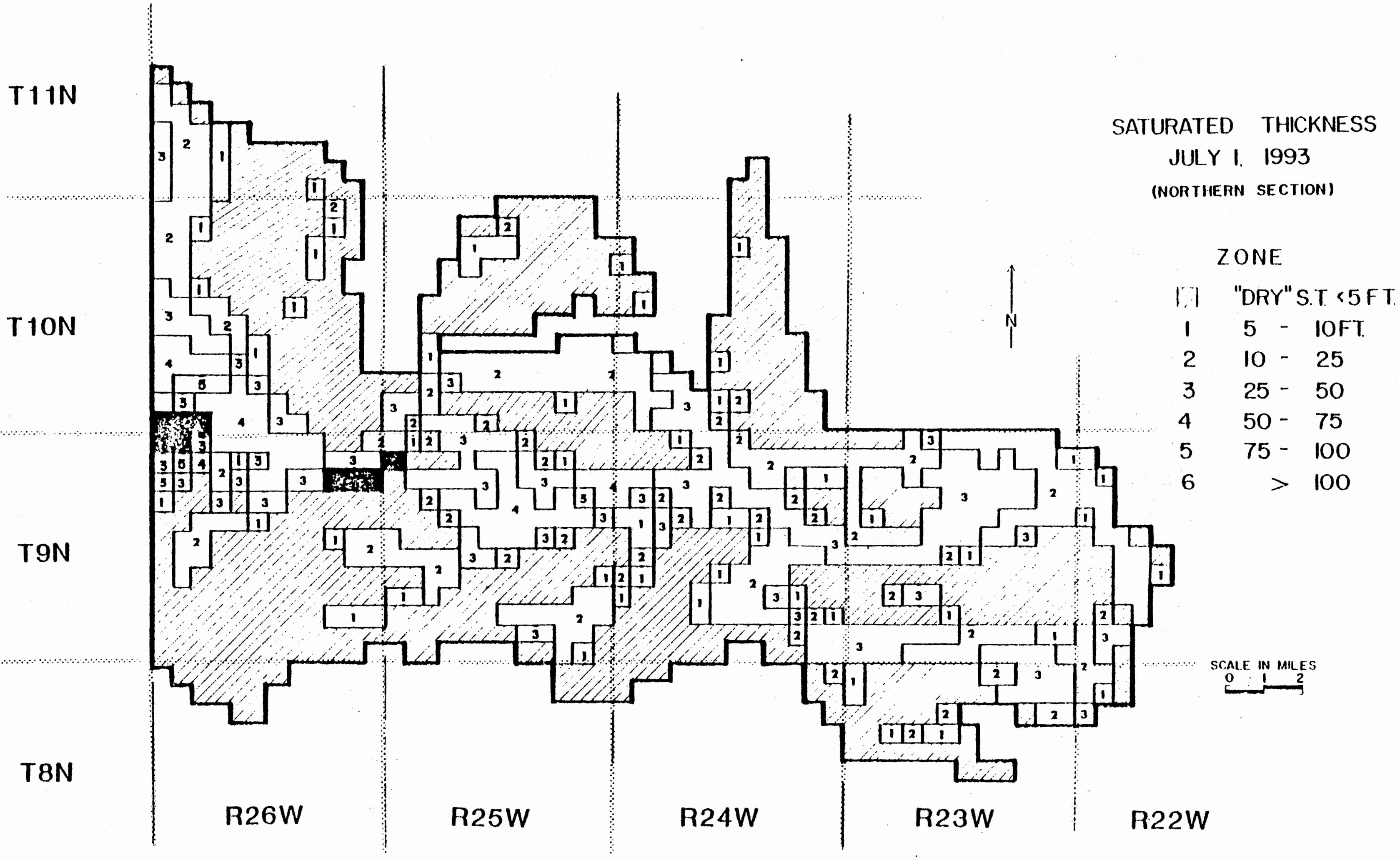


Figure 43. Saturated Thickness July 1, 1993 Northern Section

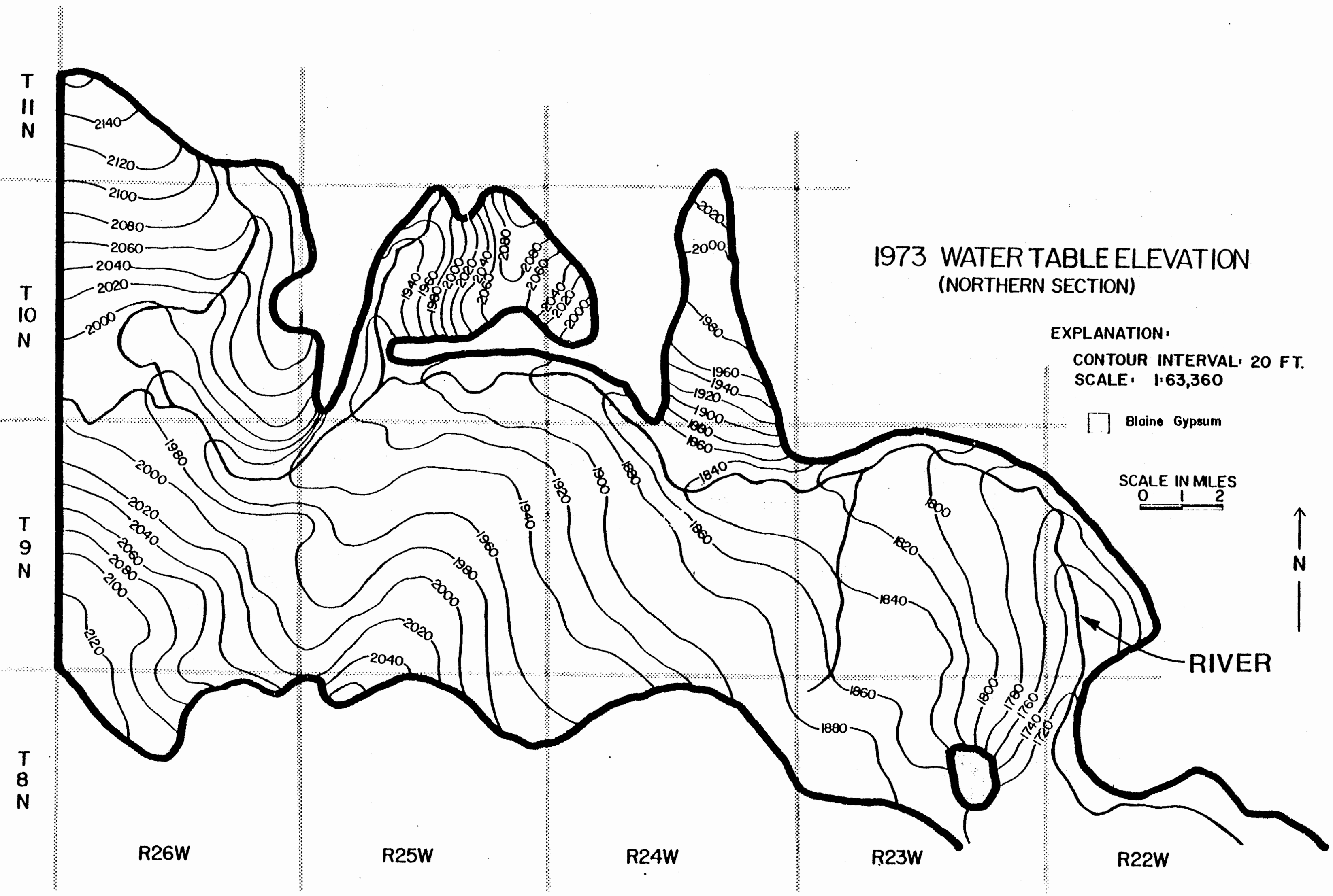


Figure 44. 1973 Water Table Elevation Northern Section

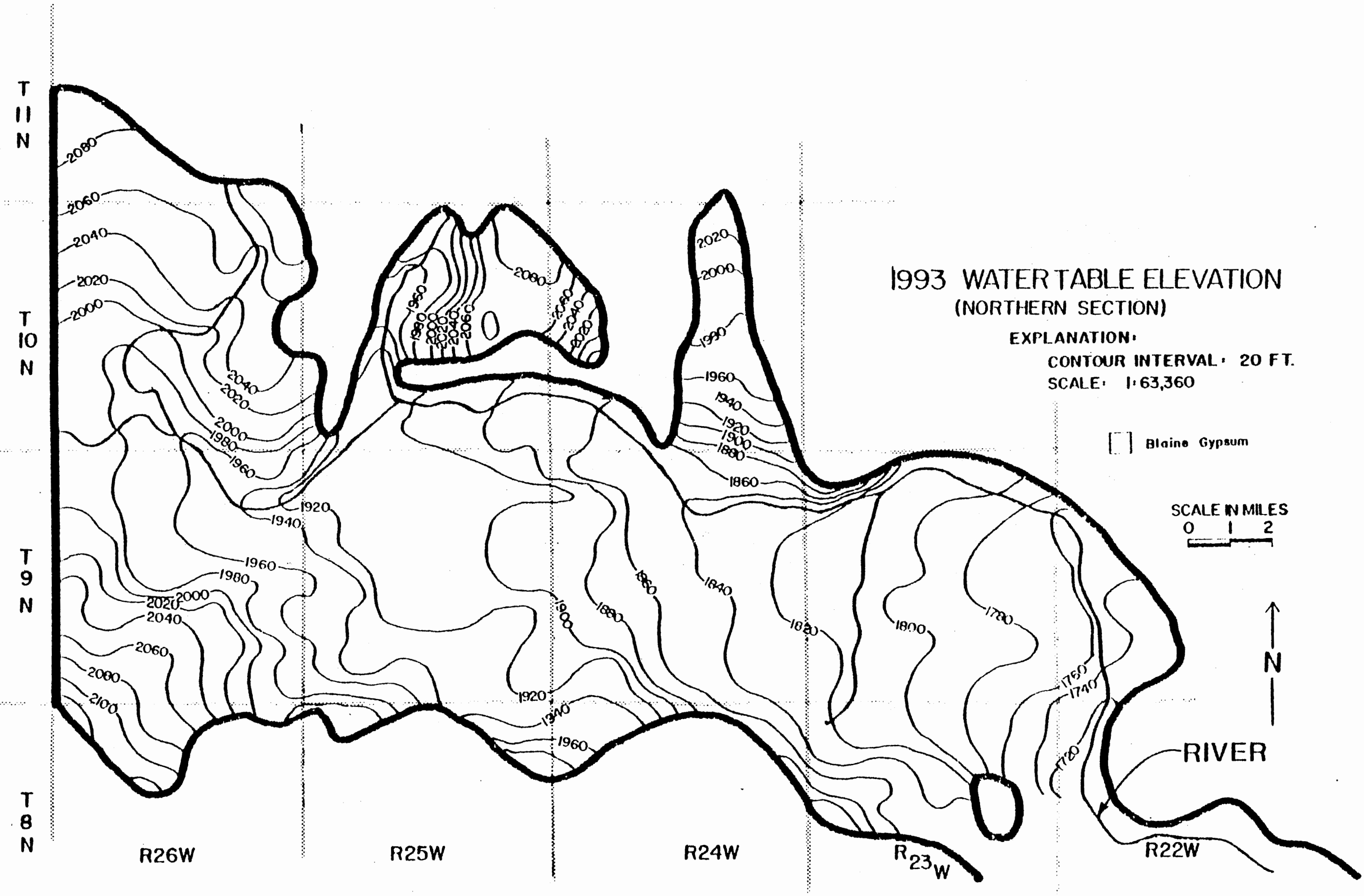


Figure 45. 1993 Water Table Elevation Northern Section

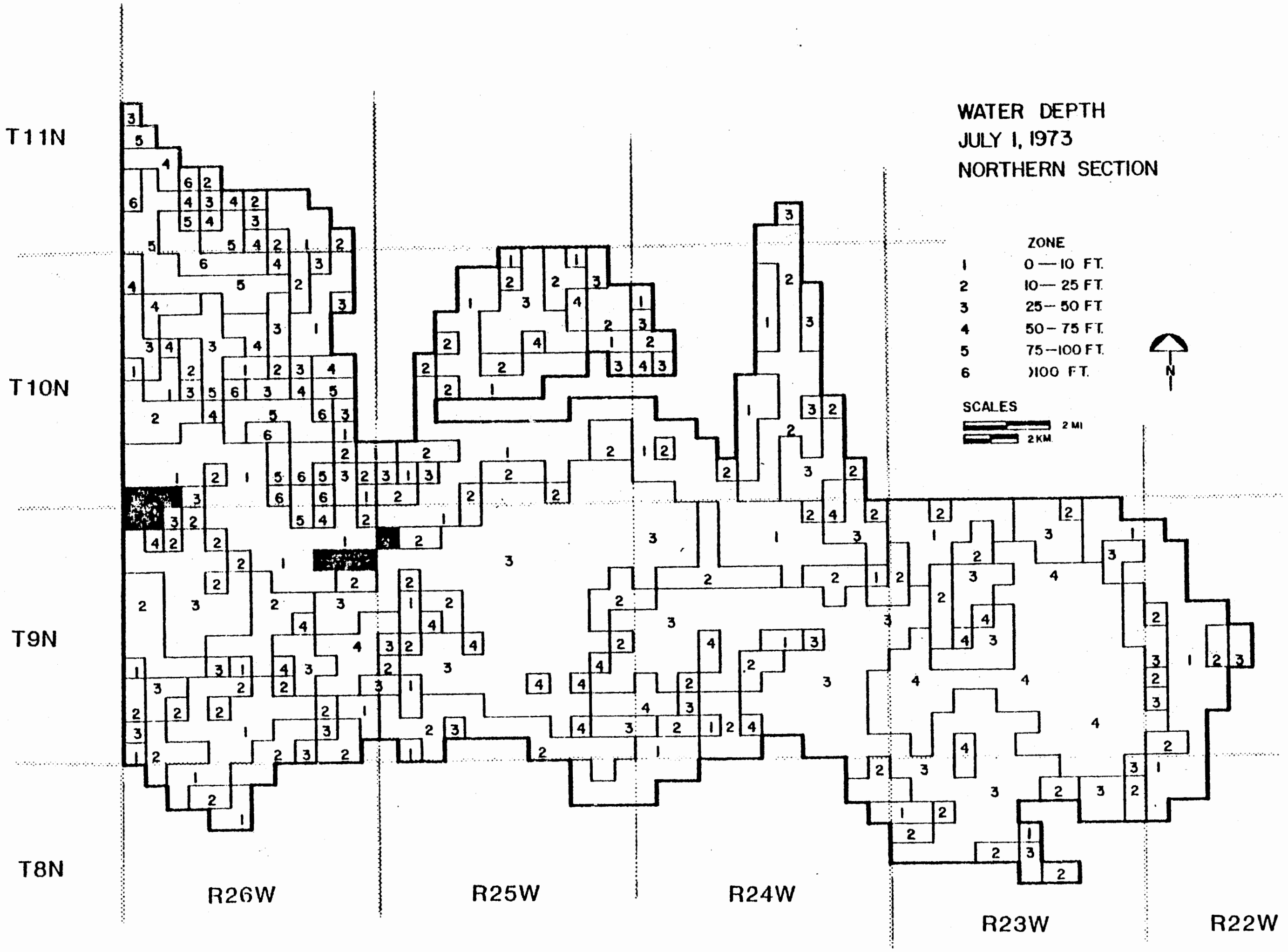


Figure 46. Water Depth July 1, 1973 Northern Section

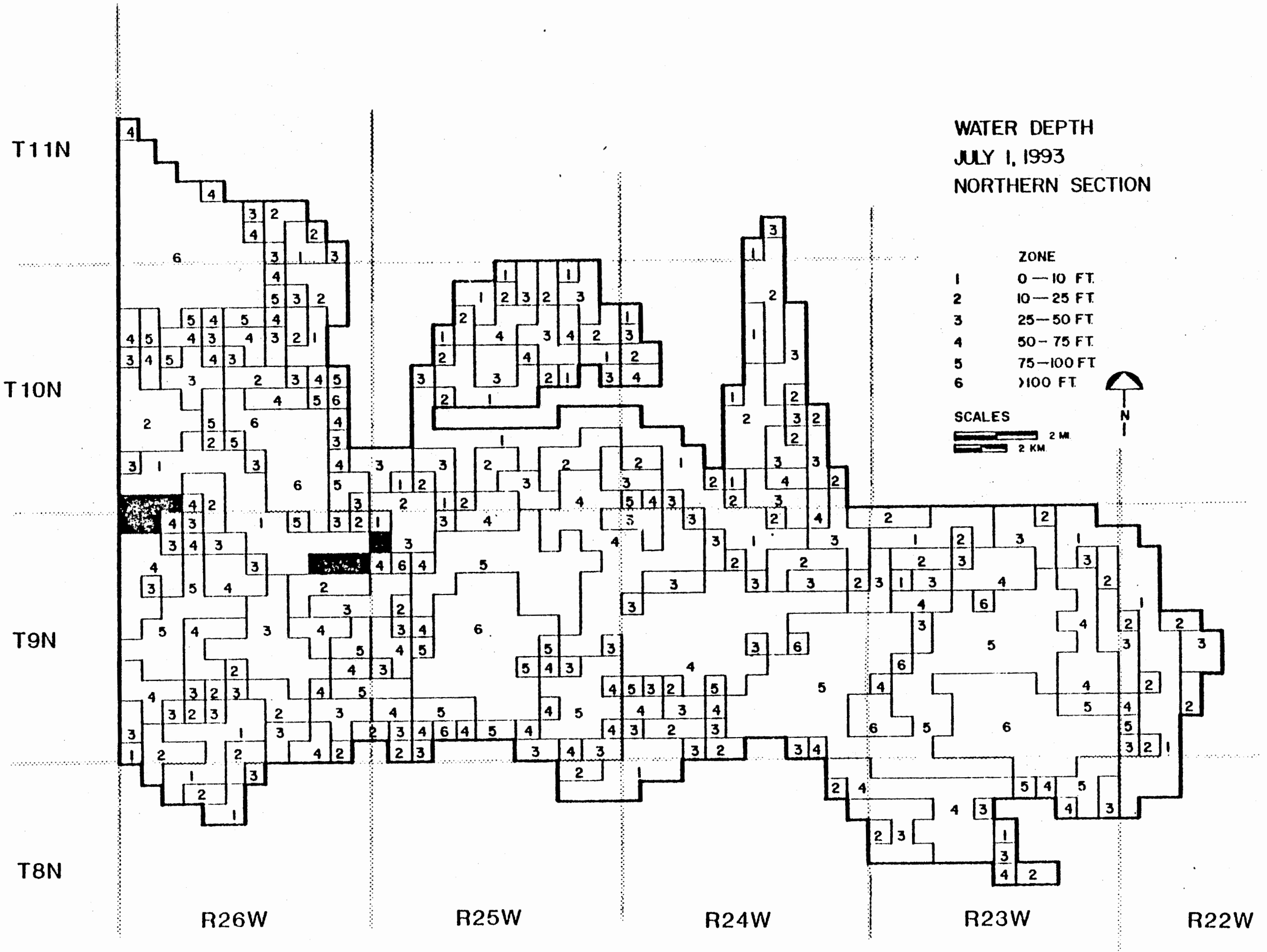


Figure 47. Water Depth July 1, 1993 Northern Section

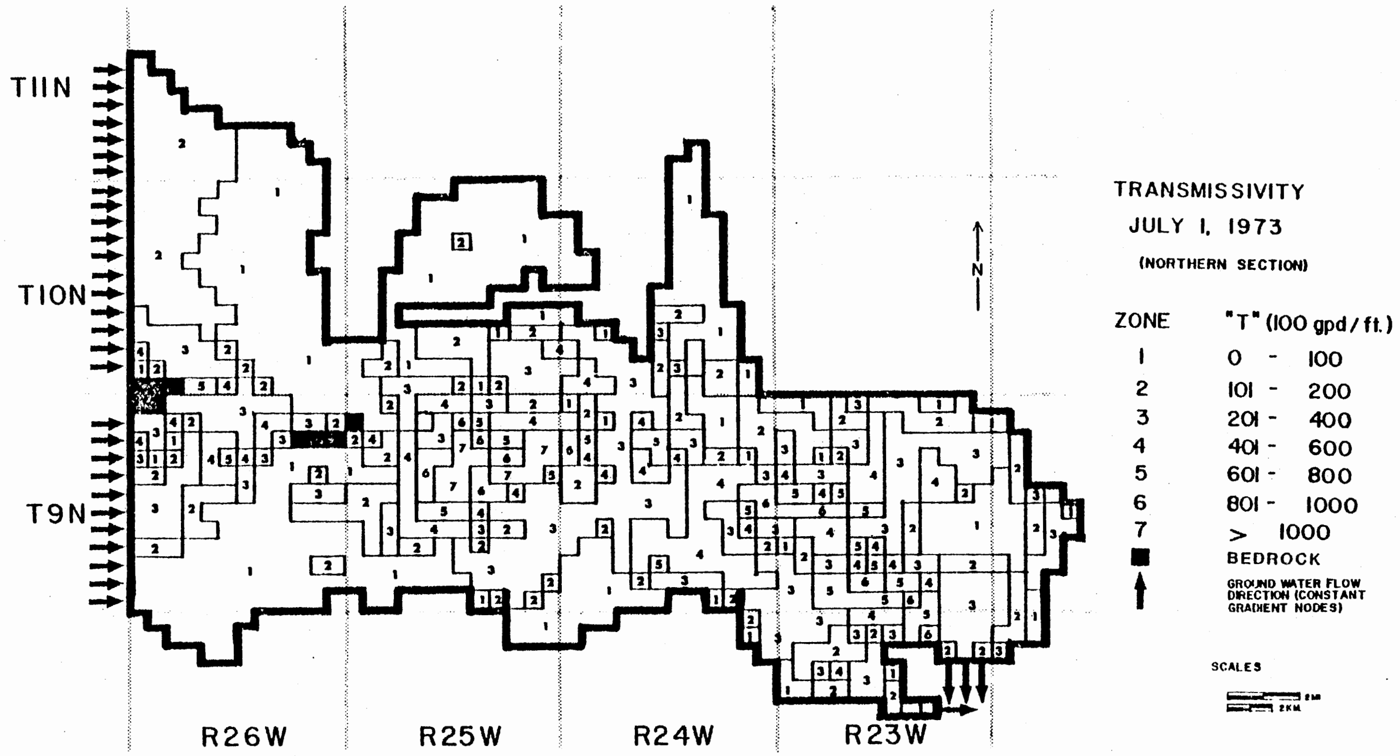


Figure 48. Transmissivity July 1, 1973 Northern Section

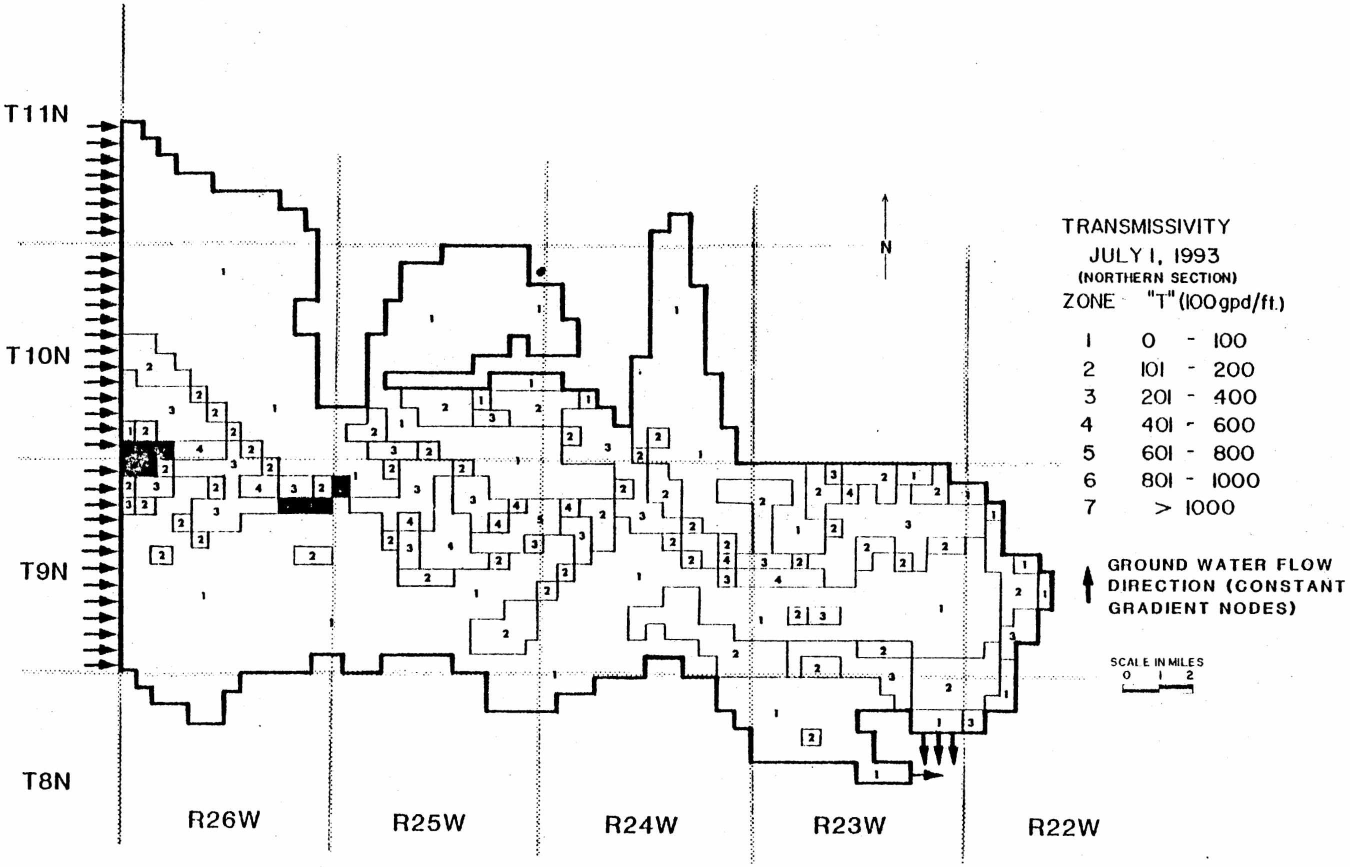


Figure 49. Transmissivity July 1, 1993 Northern Section

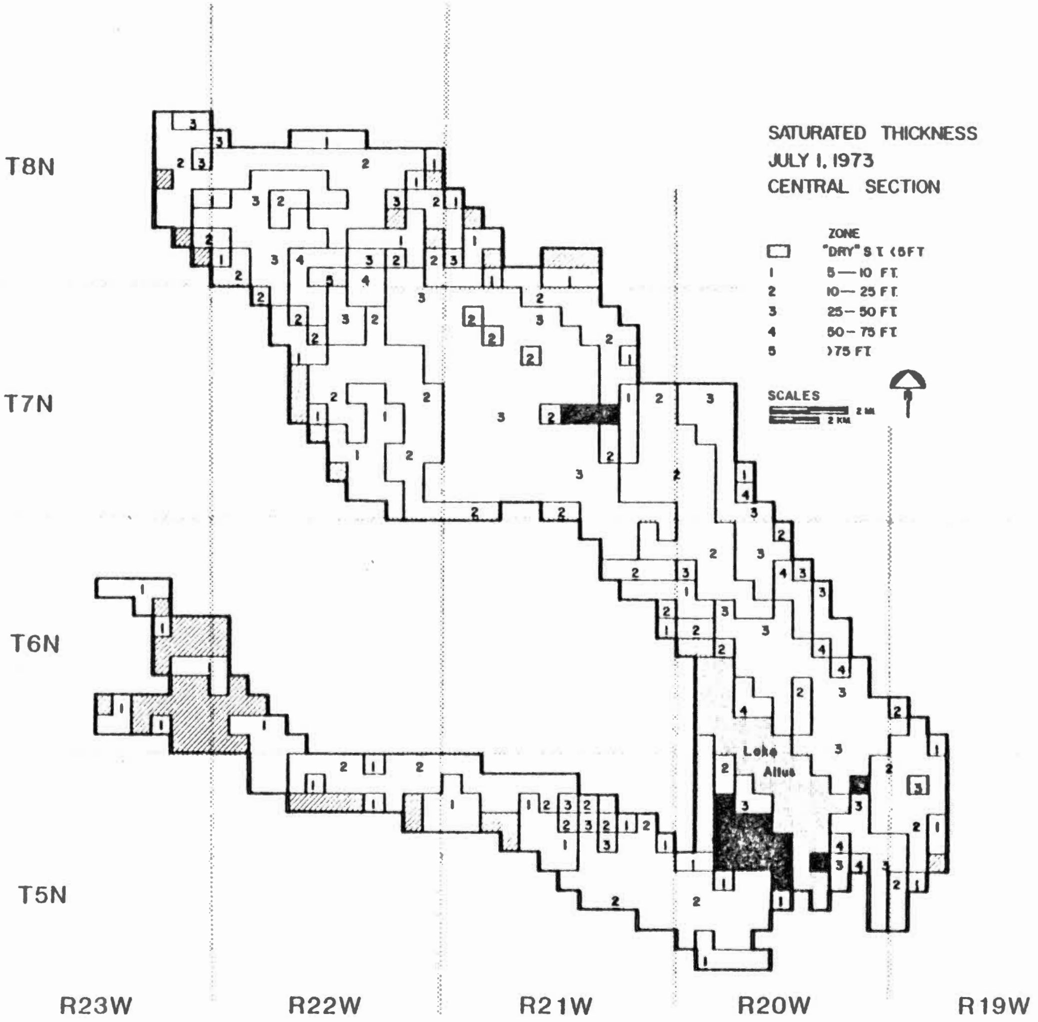


Figure 50. Saturated Thickness July 1,1973 Central Section

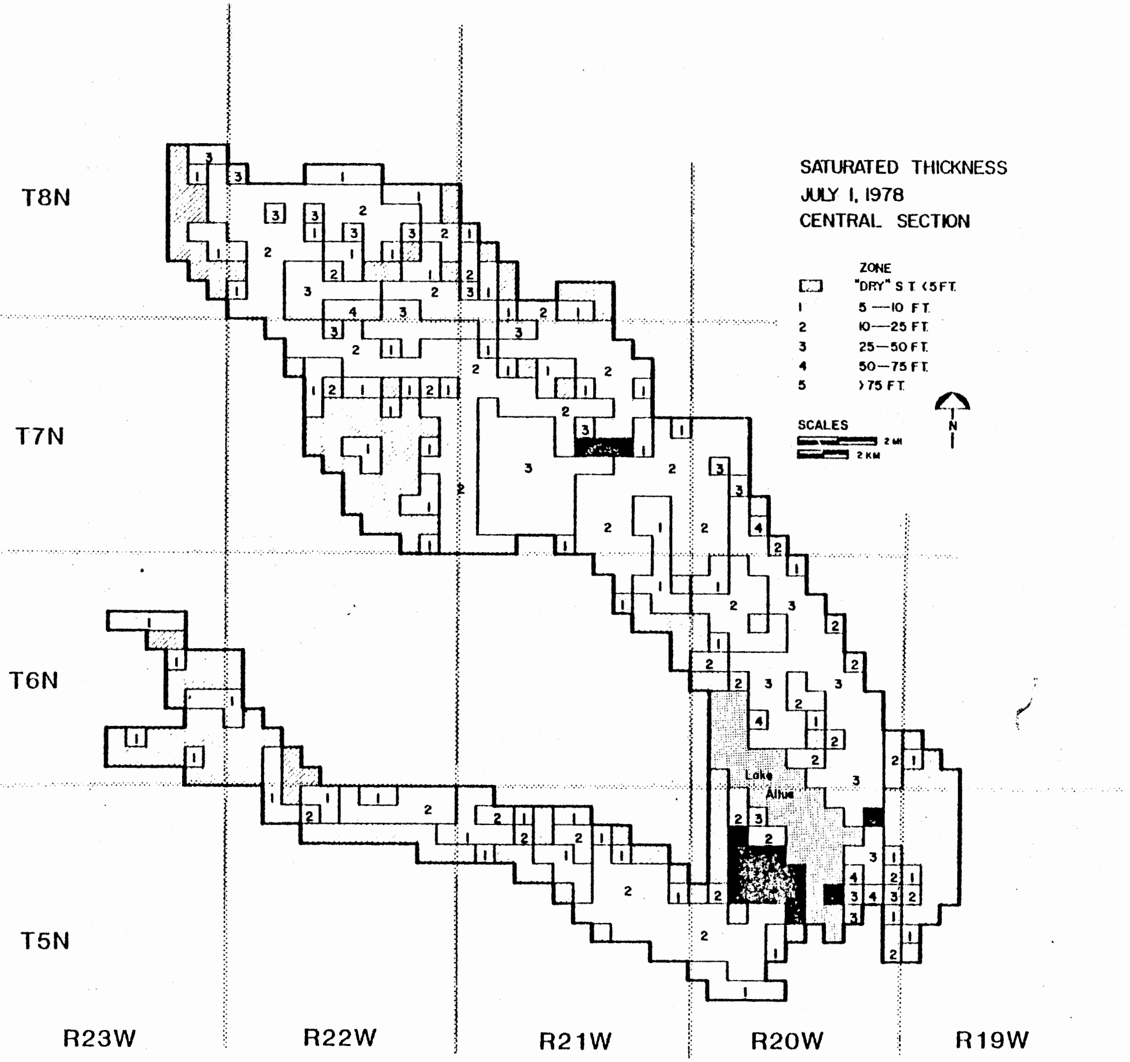


Figure 51. Saturated Thickness July 1, 1978 Central Section

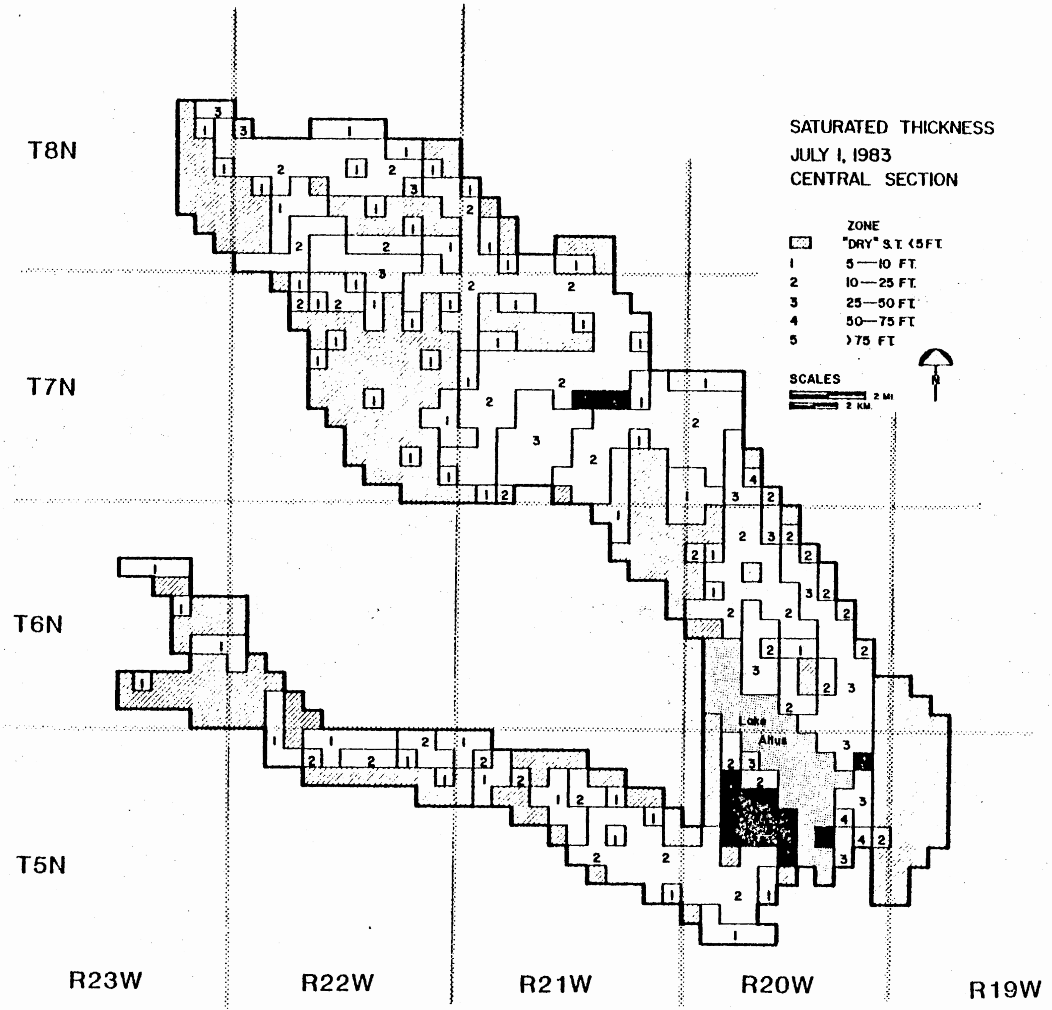


Figure 52. Saturated Thickness July 1, 1983 Central Section

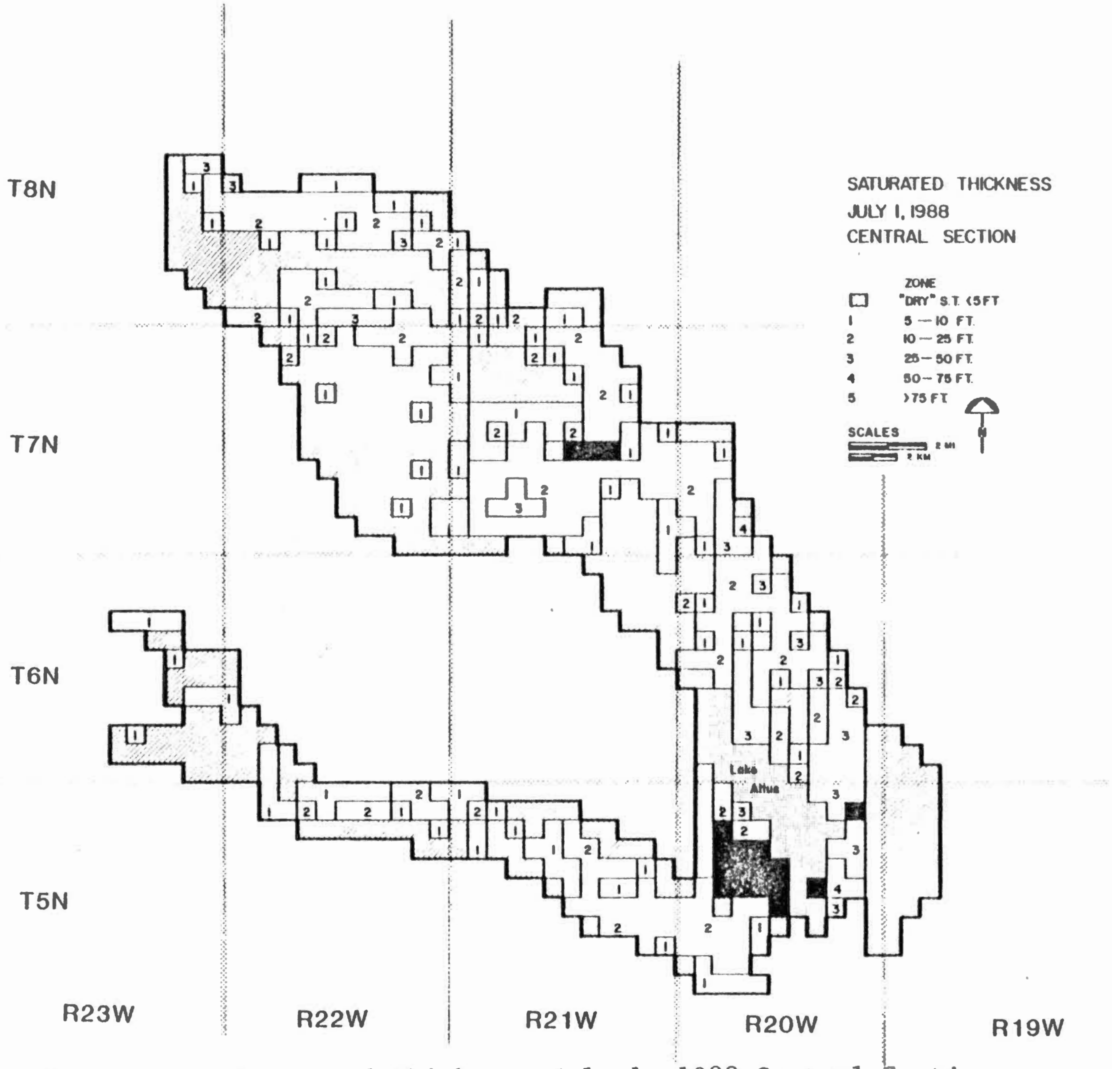


Figure 53. Saturated Thickness July 1, 1988 Central Section

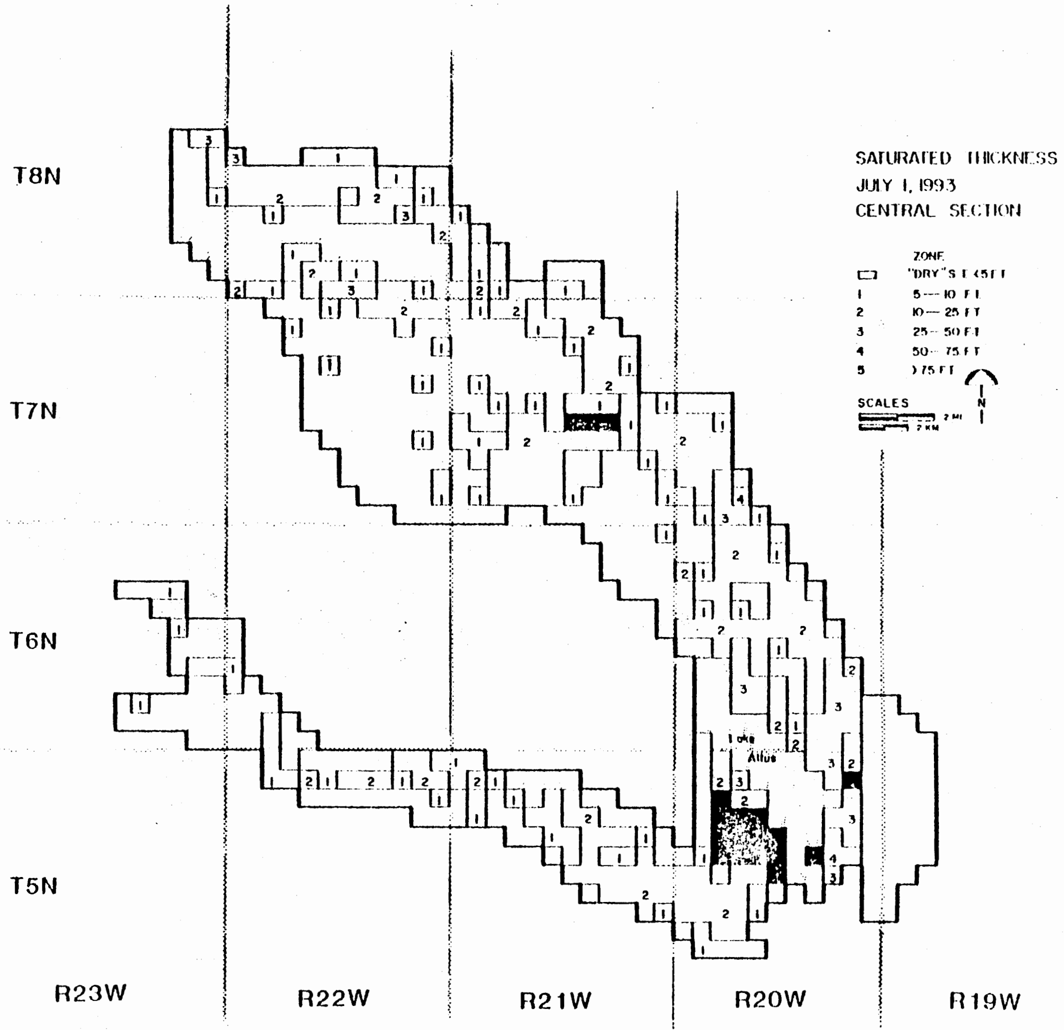


Figure 54. Saturated Thickness July 1, 1993 Central Section

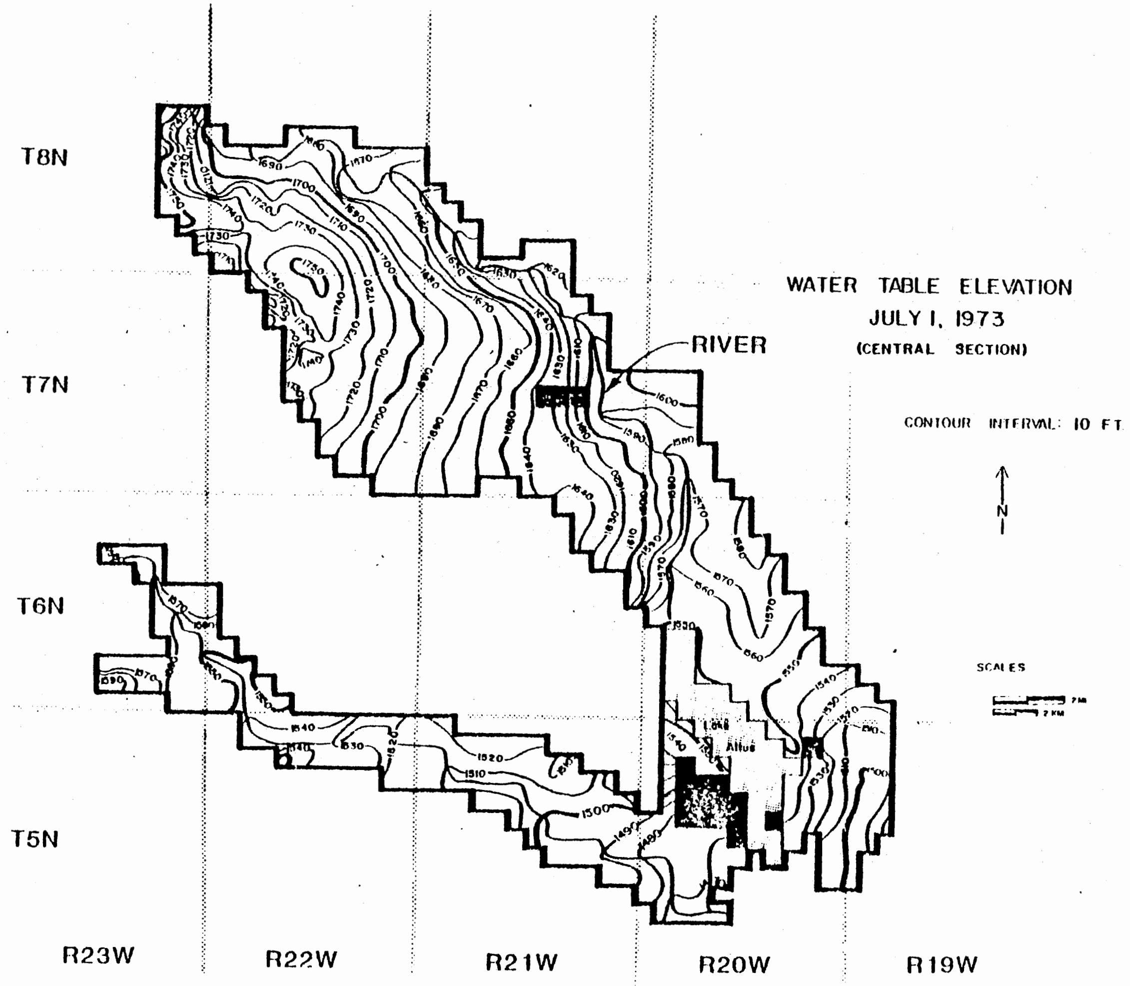


Figure 55. Water Table Elevation July 1, 1973 Central Section

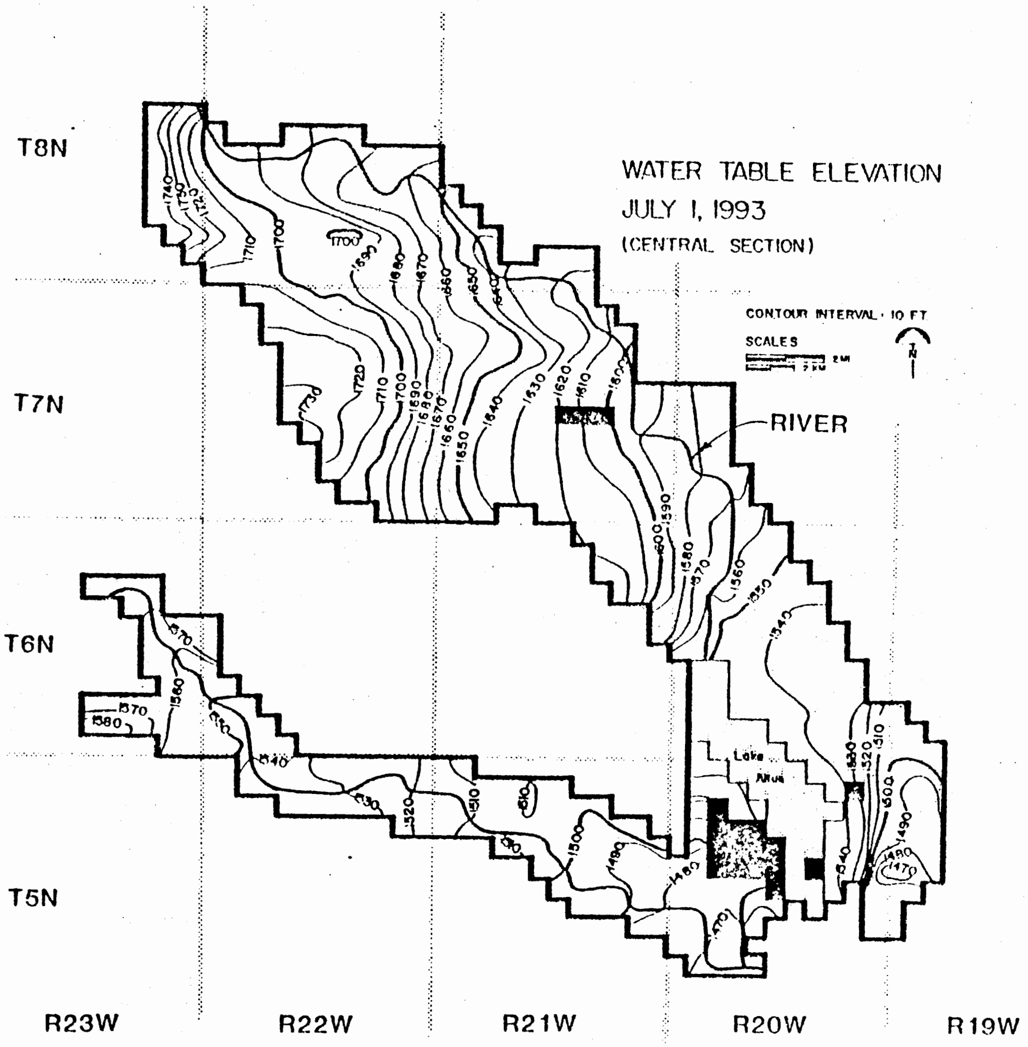


Figure 56. Water Table Elevation July 1, 1993 Central Section

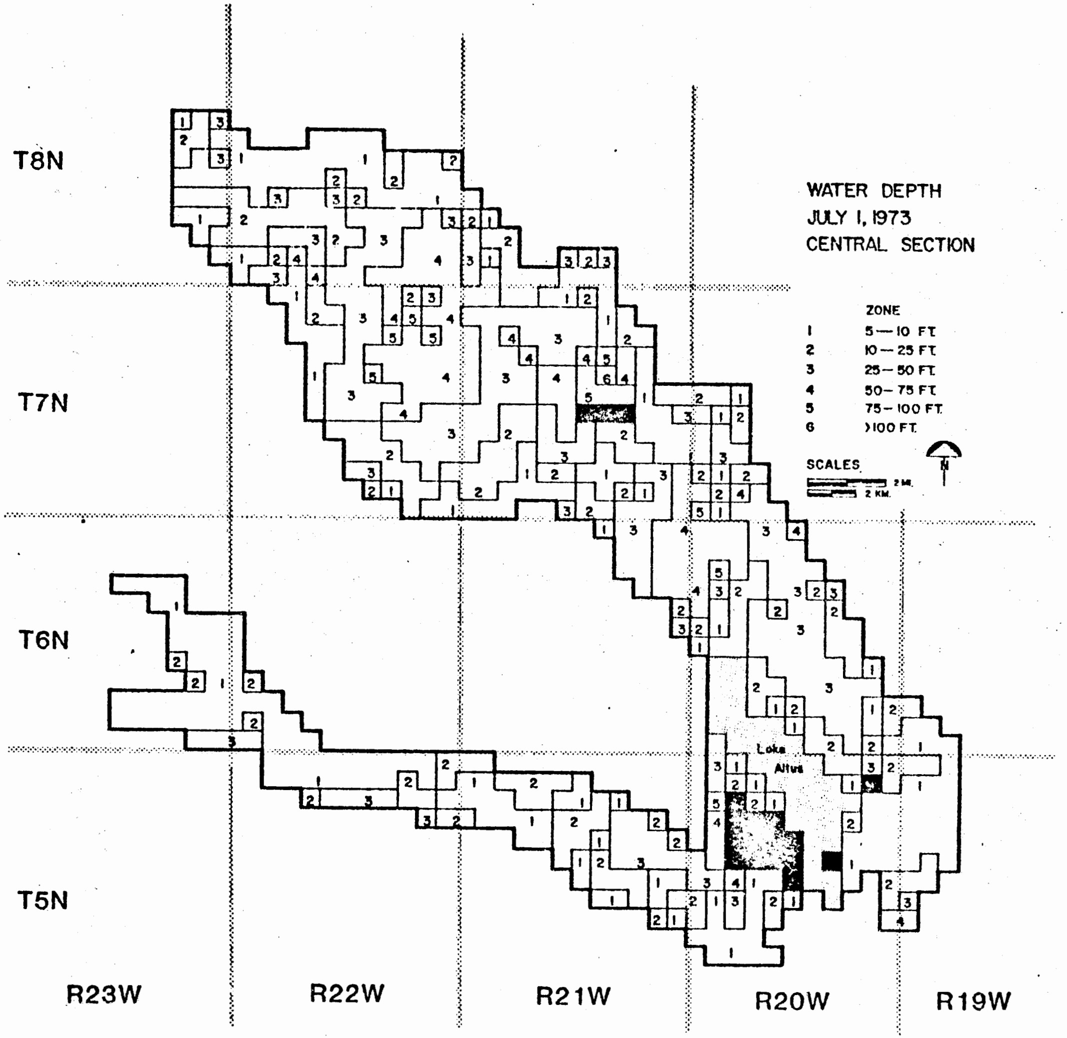


Figure 57. Water Depth July 1, 1973 Central Section

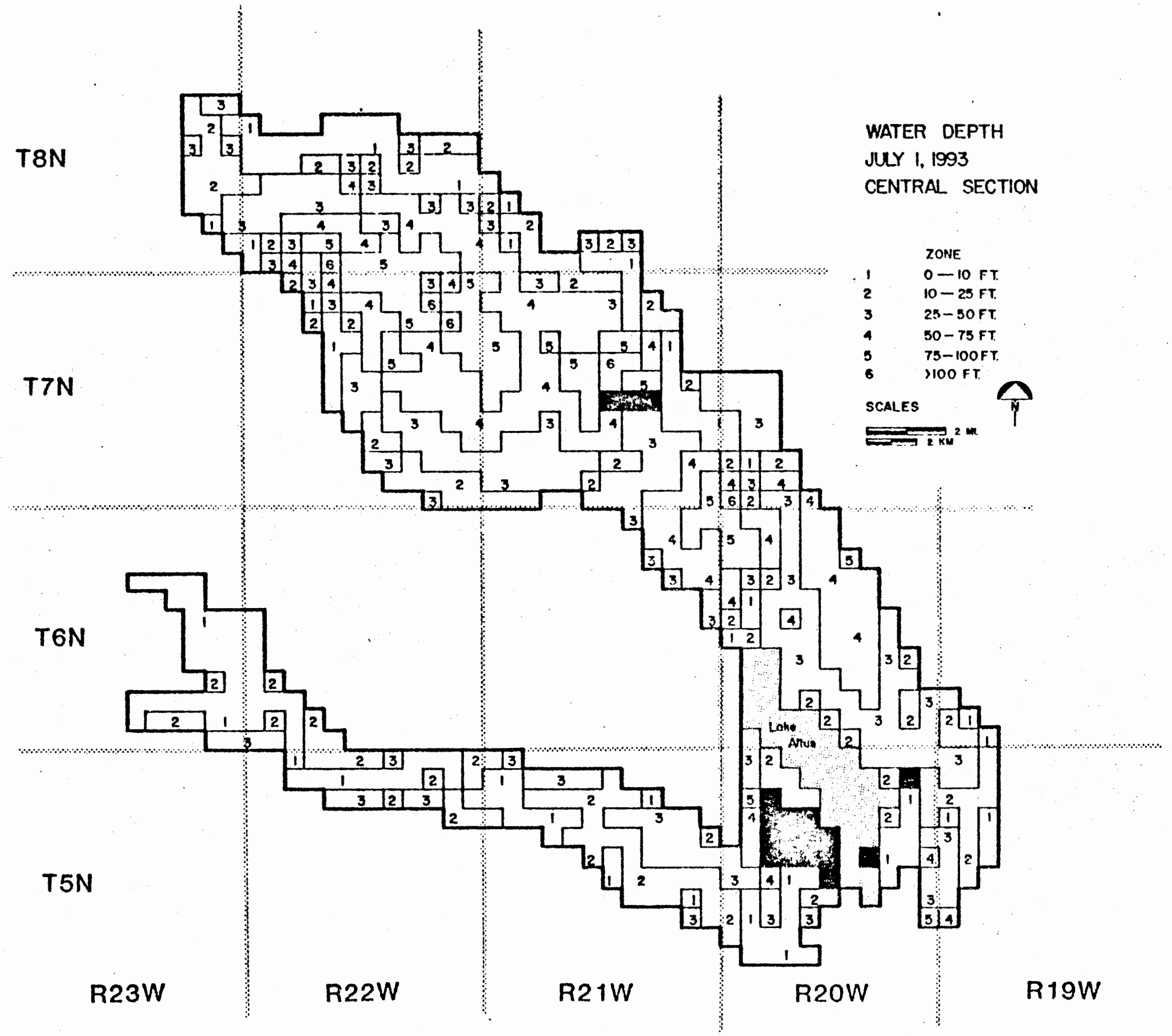


Figure 58. Water Depth July 1, 1993 Central Section

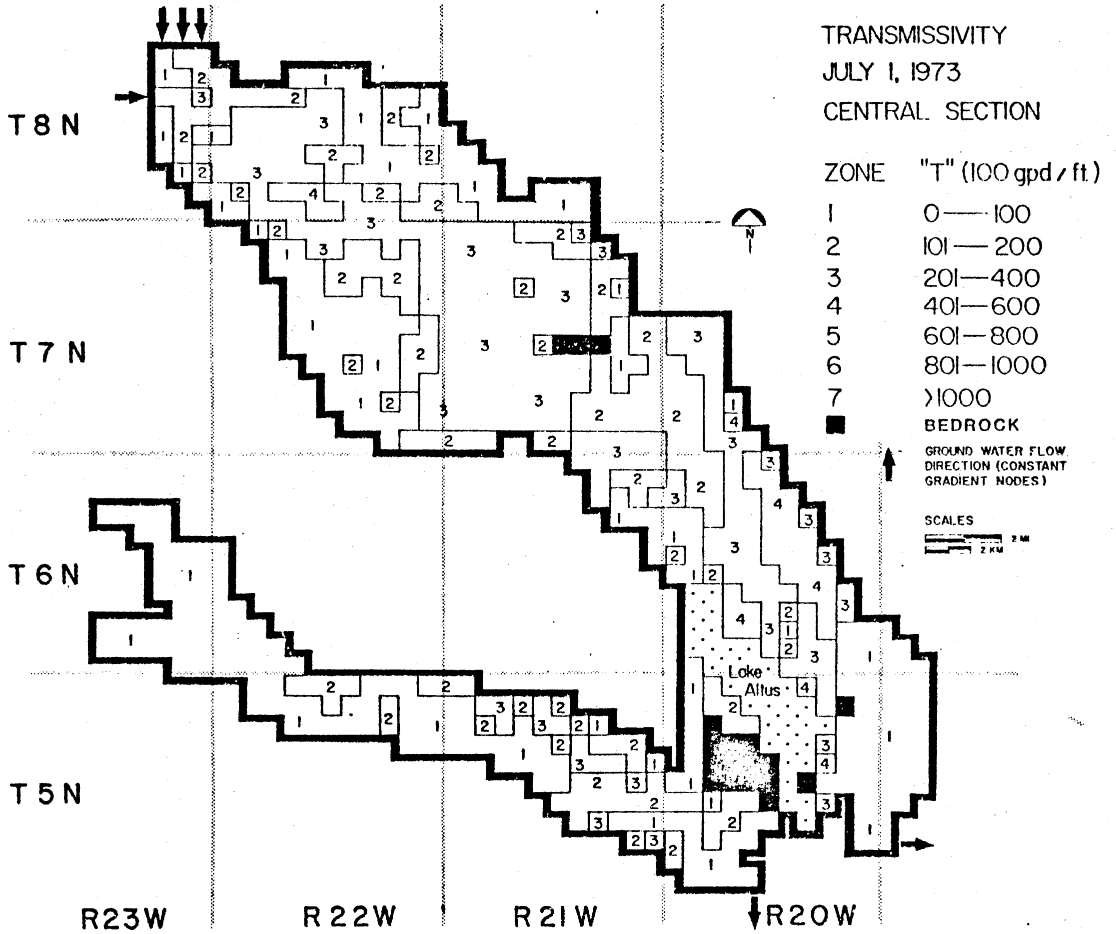


Figure 59. Transmissivity July 1, 1973 Central Section

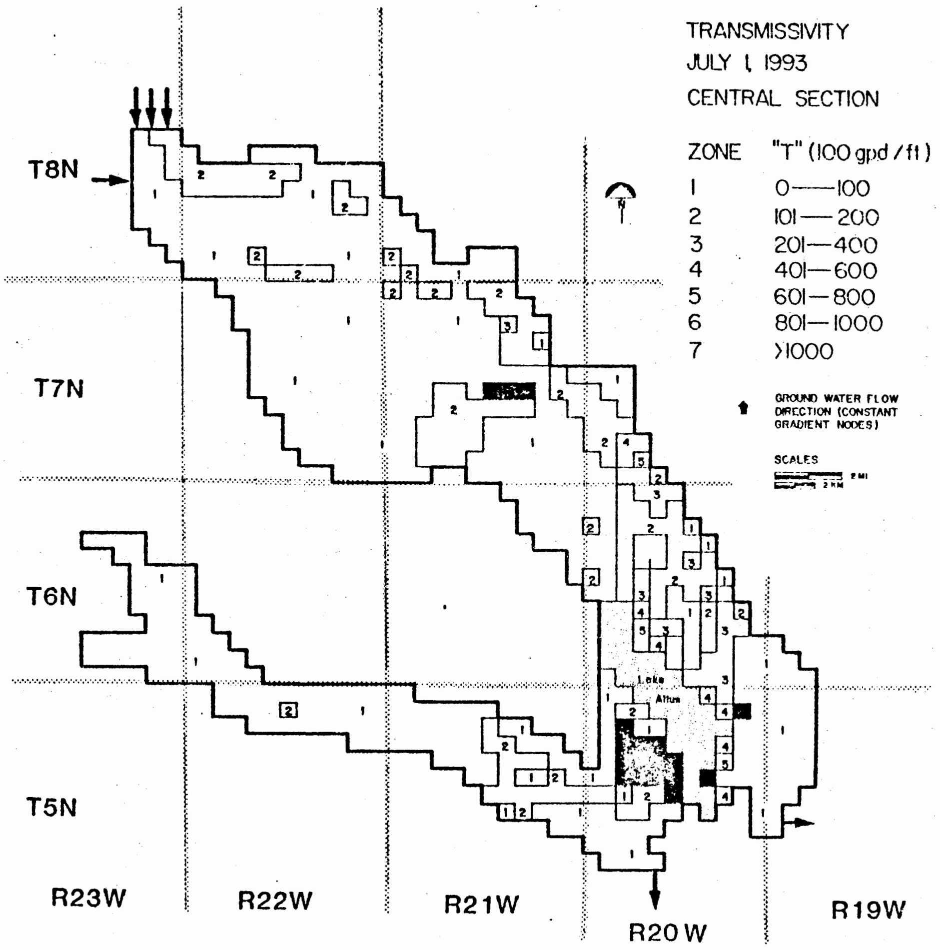


Figure 60. Transmissivity July 1, 1993 Central Section

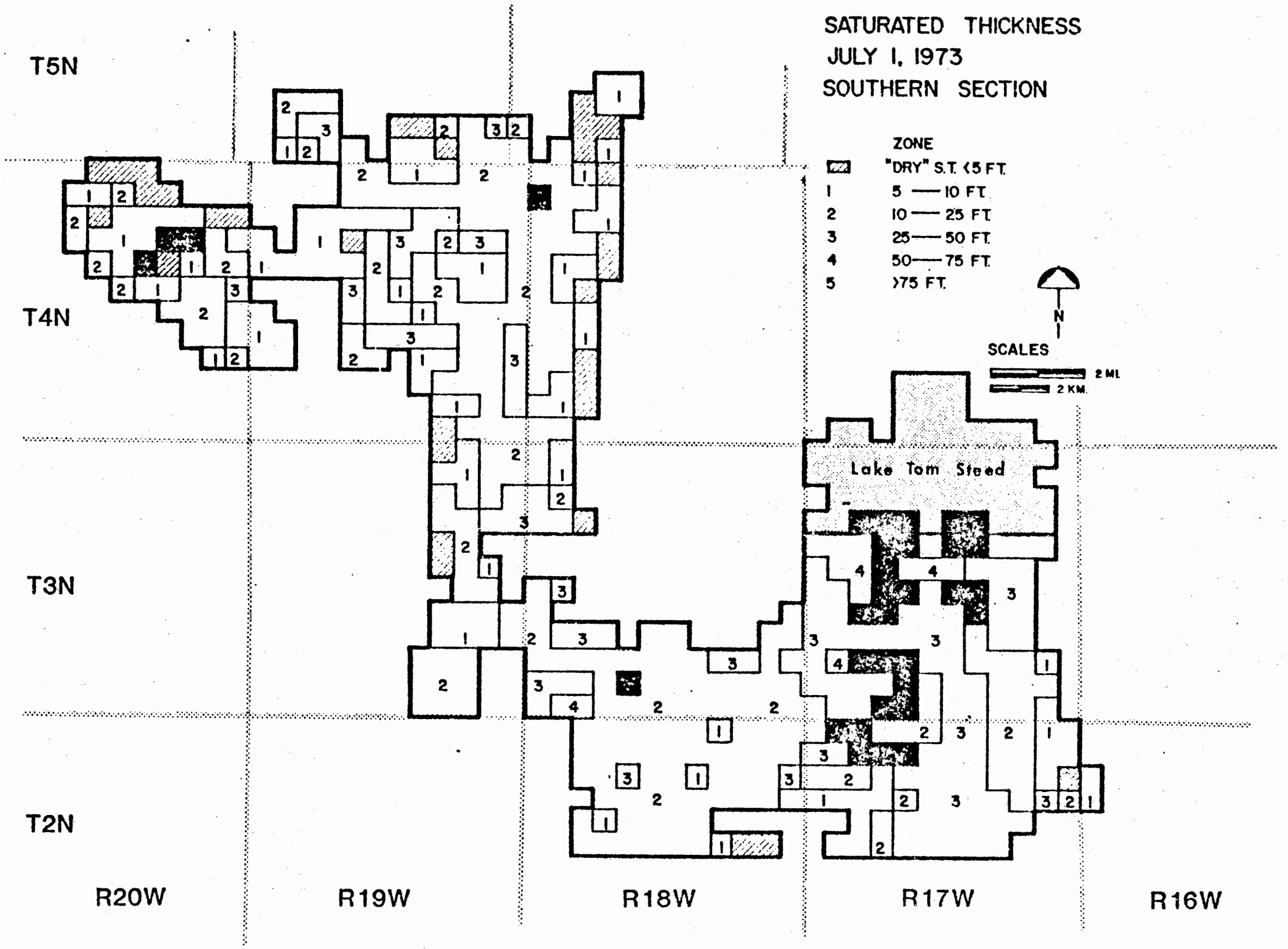


Figure 61. Saturated Thickness July 1, 1973 Southern Section

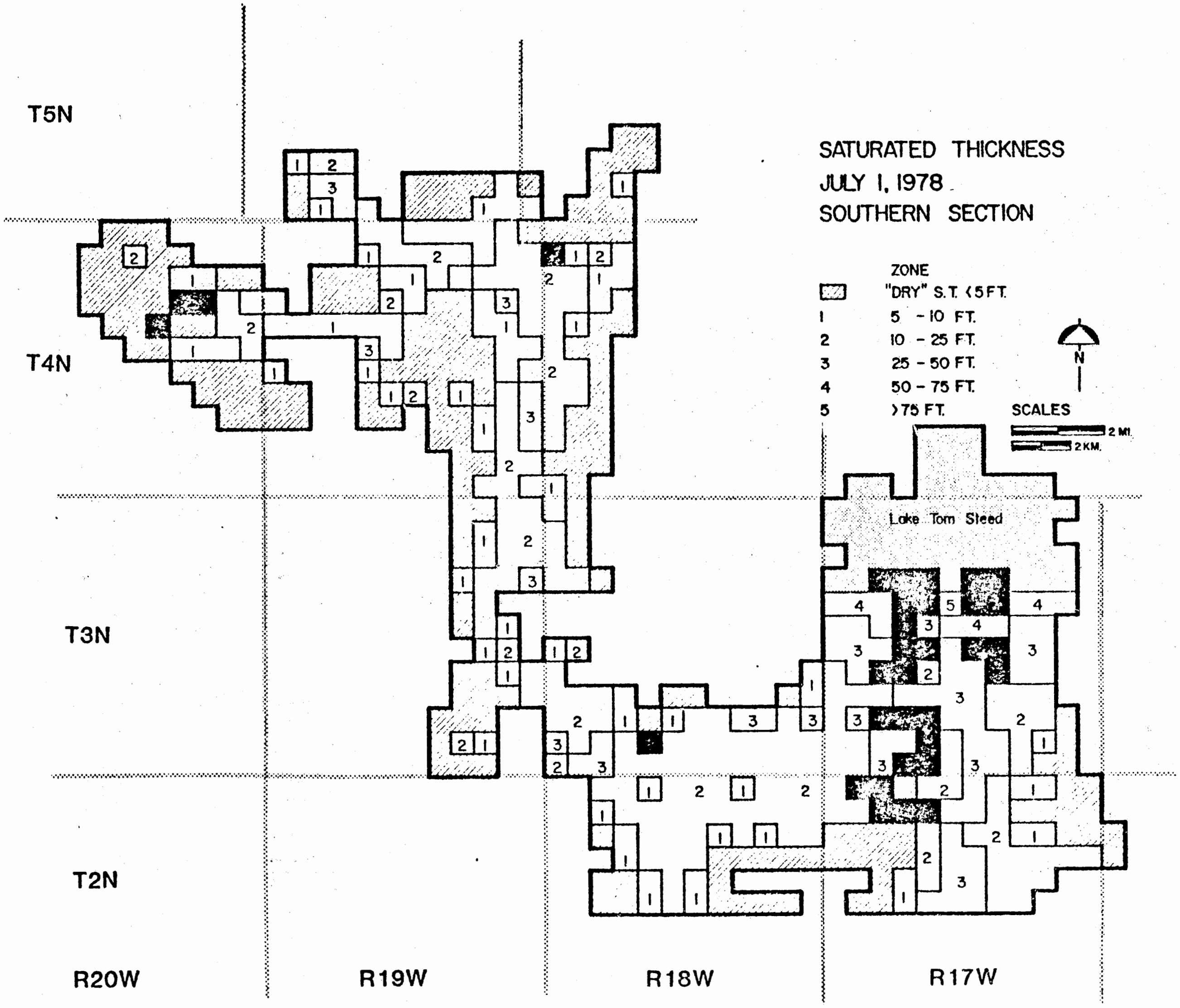


Figure 62. Saturated Thickness July 1, 1978 Southern Section

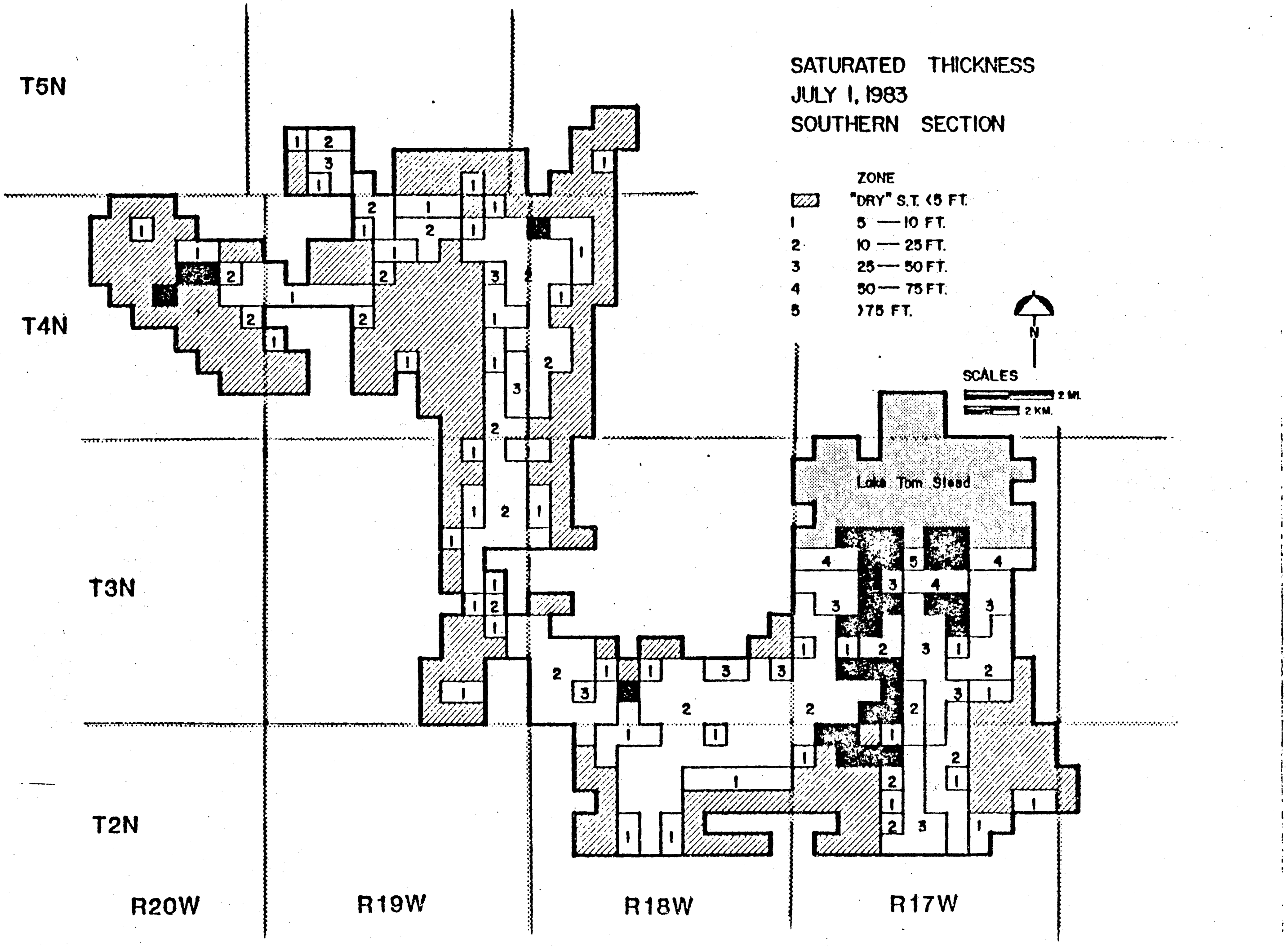


Figure 63. Saturated Thickness July 1, 1983 Southern Section

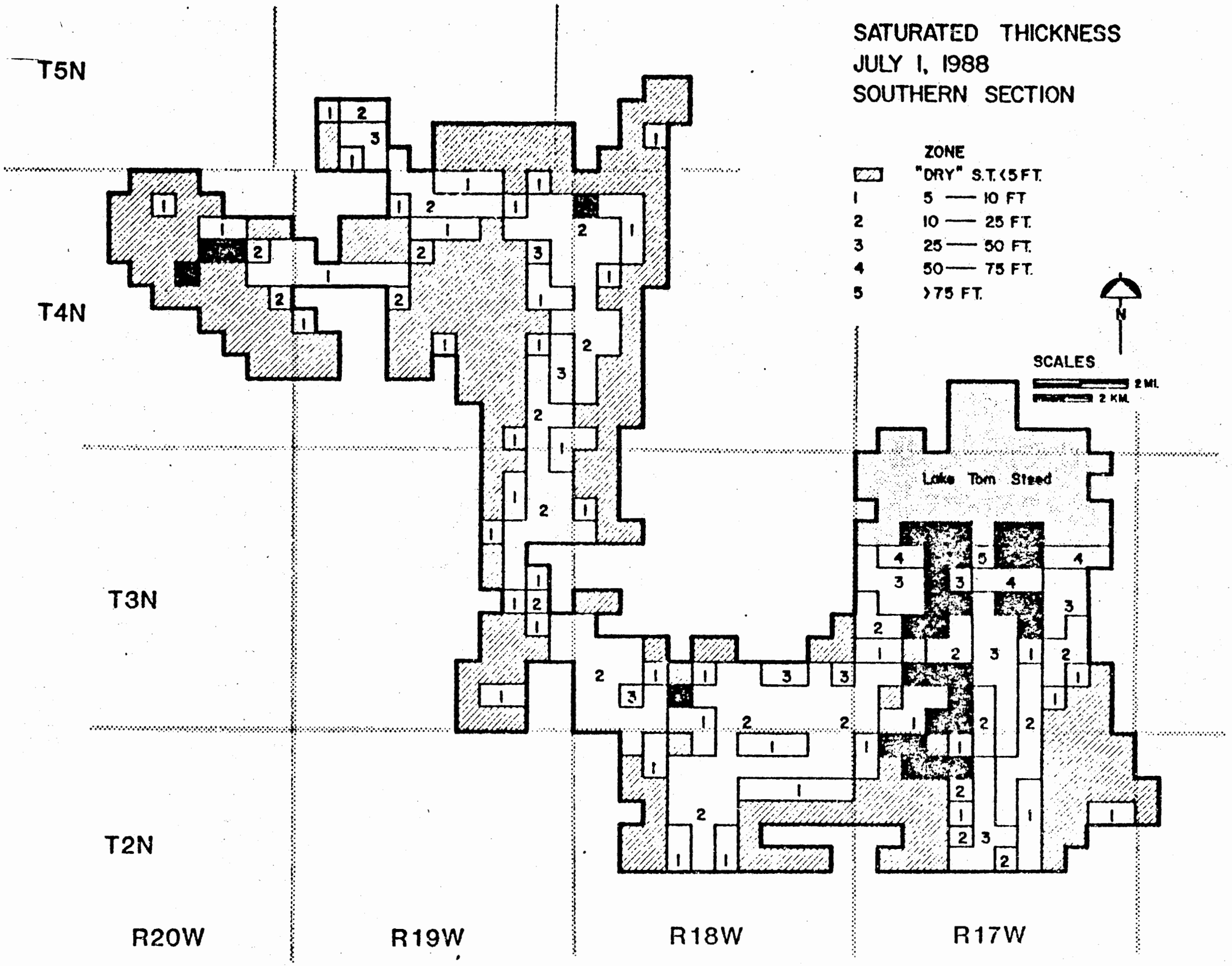


Figure 64. Saturated Thickness July 1, 1988 Southern Section

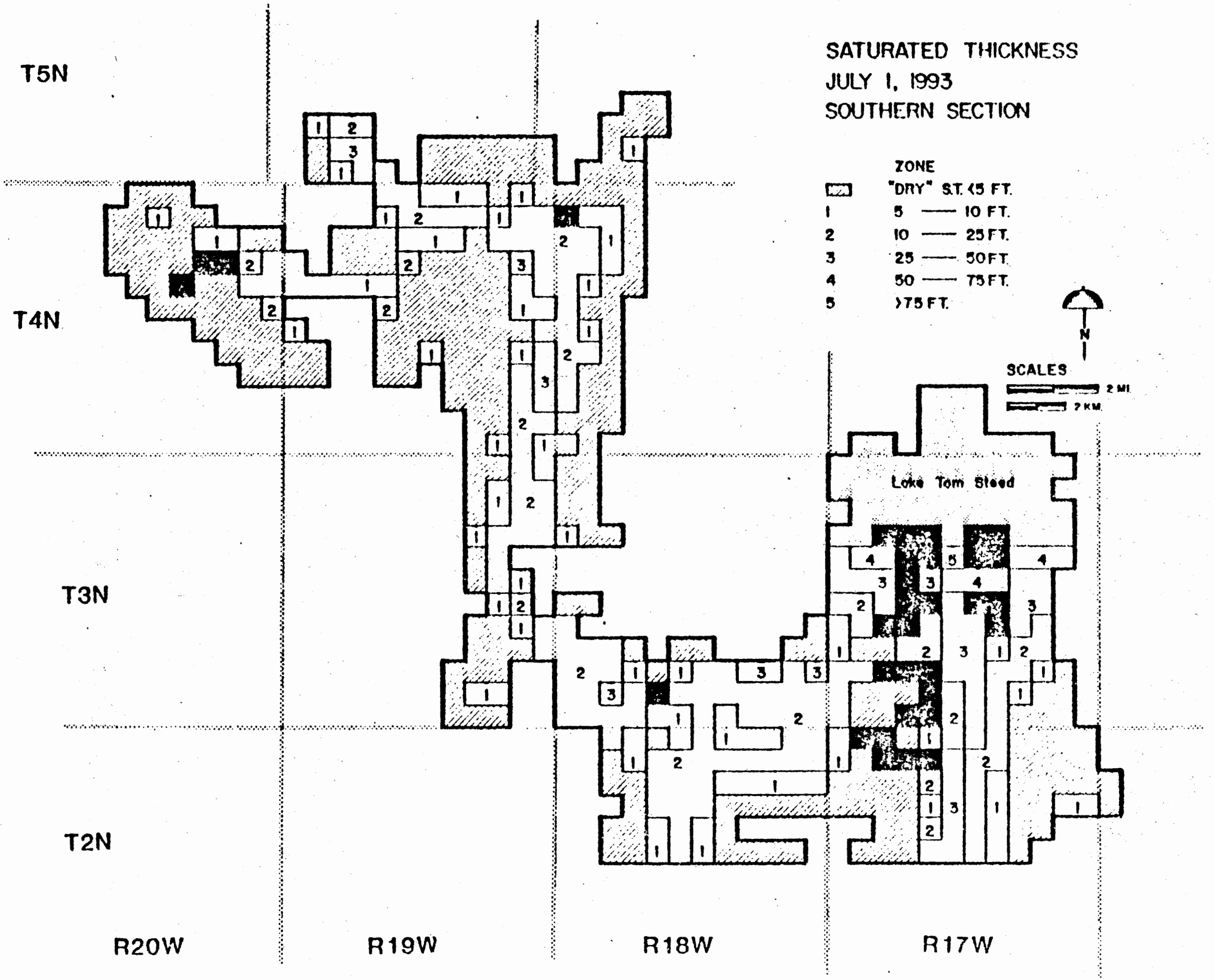


Figure 65. Saturated Thickness July 1, 1993 Southern Section

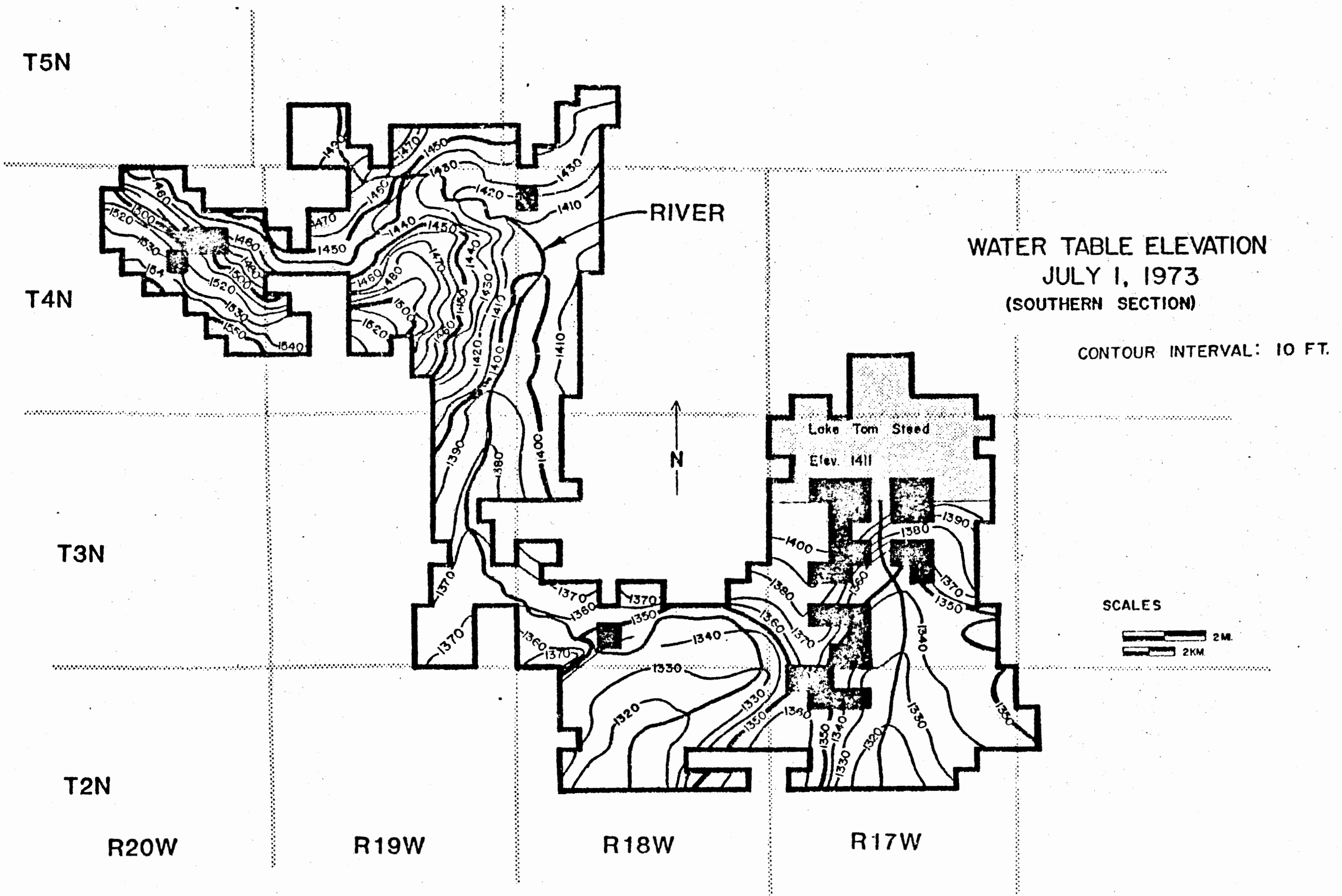


Figure 66. Water Table Elevation July 1, 1973 Southern Section

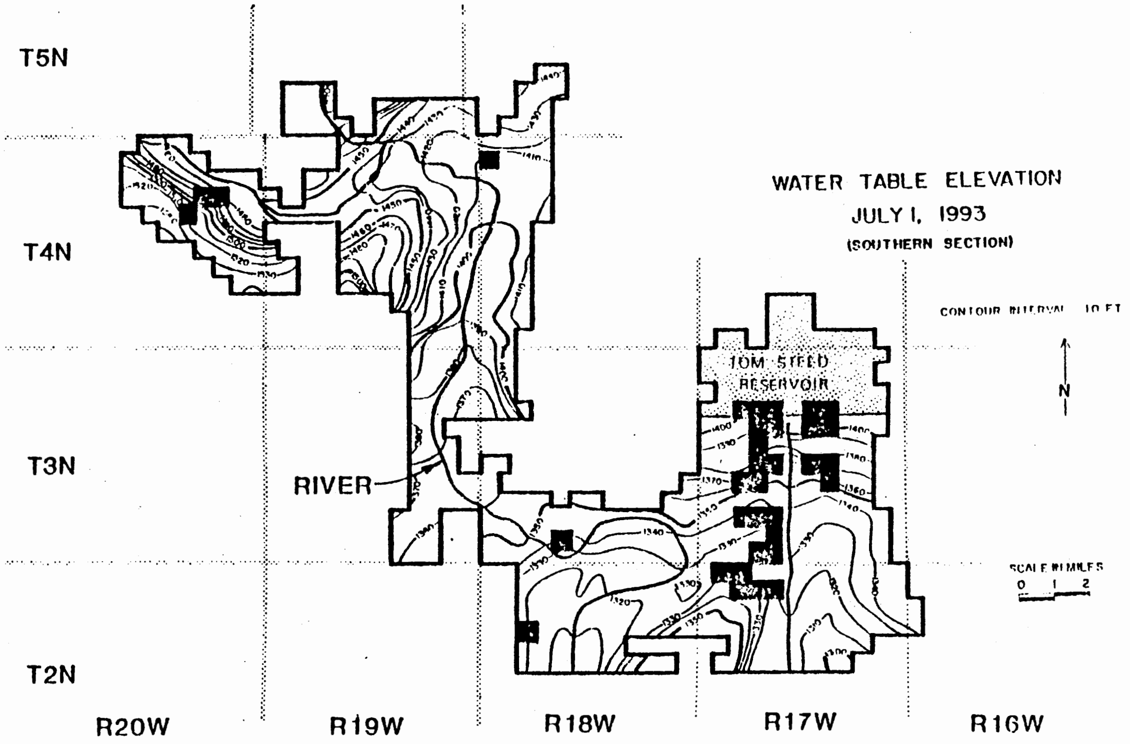


Figure 67. Water Table Elevation July 1, 1993 Southern Section

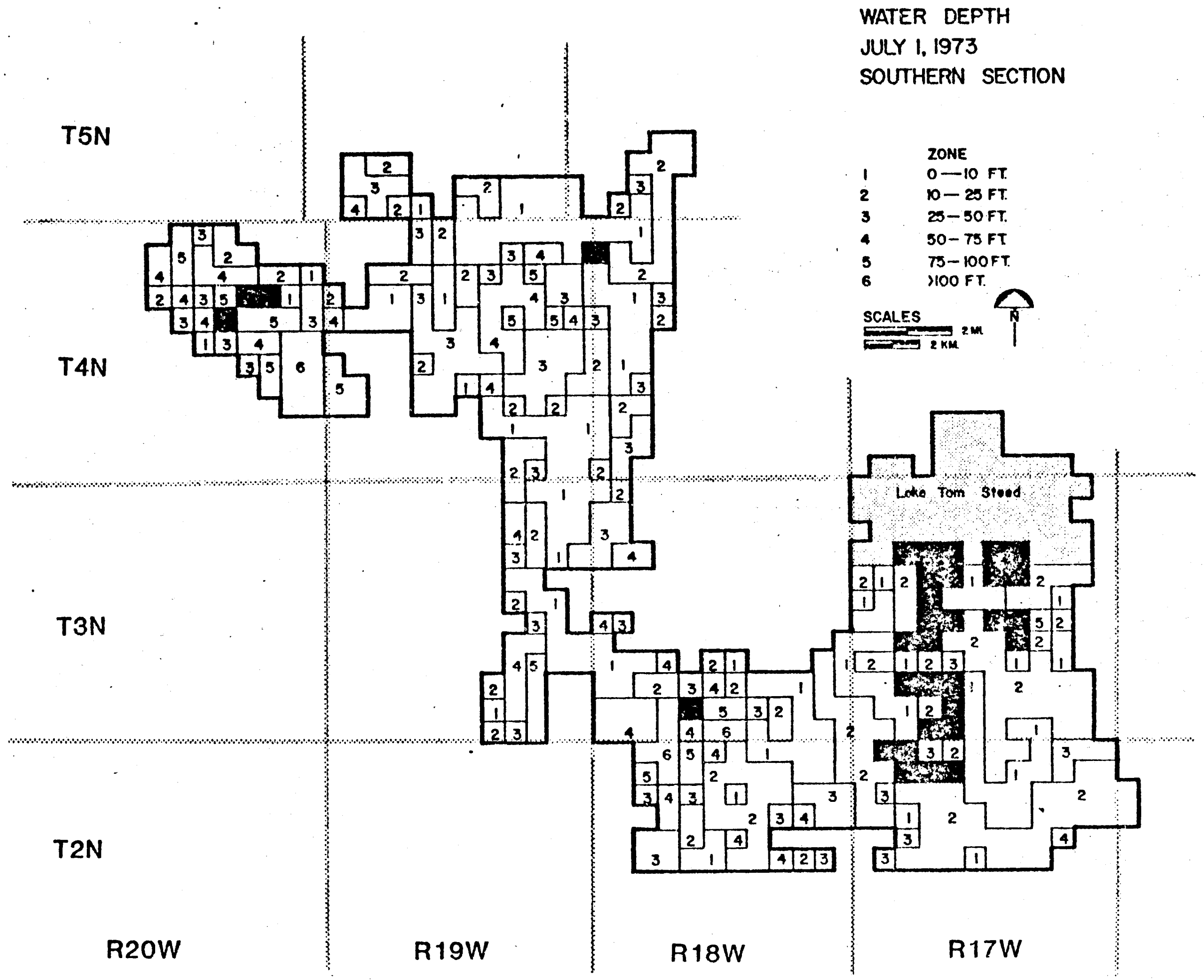


Figure 68. Water Depth July 1, 1973 Southern Section

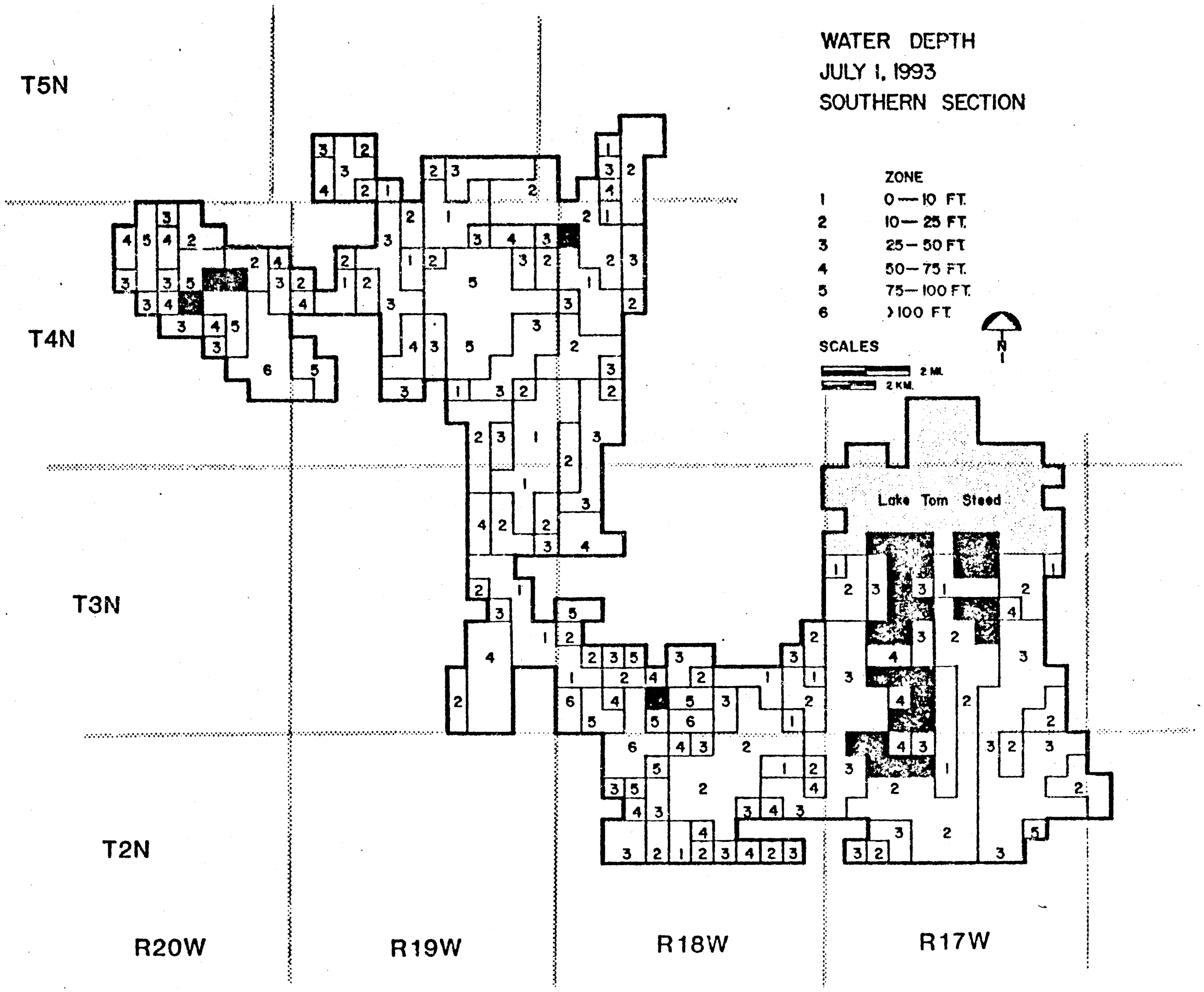


Figure 69. Water Depth July 1, 1993 Southern Area

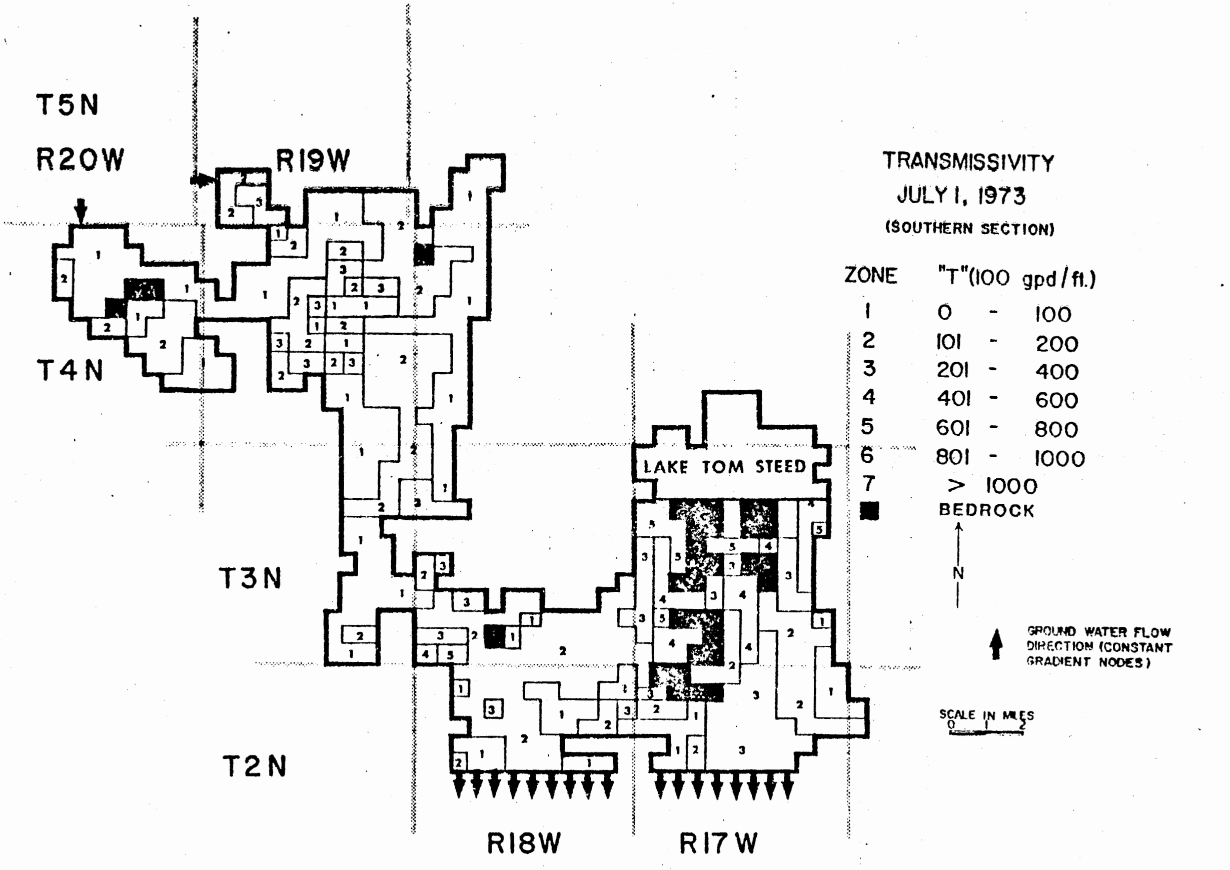


Figure 70. Transmissivity July 1, 1973 Southern Section

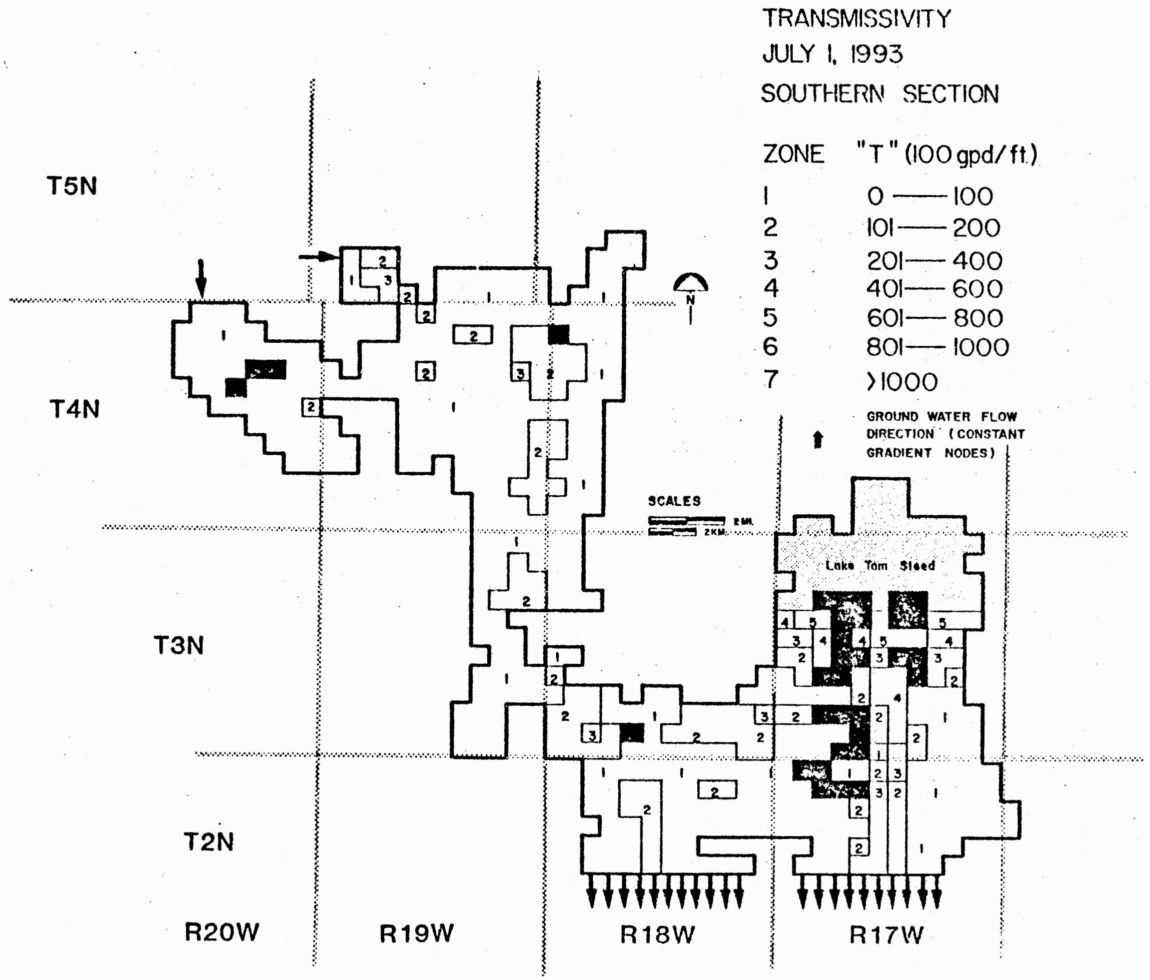


Figure 71. Transmissivity July 1, 1993 Southern Section

VITA

Eric John Paukstaitis

Candidate for the Degree of

Master of Science

Thesis: COMPUTER SIMULATION OF THE ALLUVIAL AQUIFER ALONG THE NORTH FORK OF THE RED RIVER IN SOUTHWESTERN OKLAHOMA

Major Field: Geology

Biographical:

Personal Data: Born in Passaic, New Jersey, January 13, 1950, the son of Mr. and Mrs. John Paukstaitis

Education: Graduated from Nutley High School, Nutley, New Jersey, in June, 1968; received Bachelor of Arts degree in Geology from Rutgers University in 1973; attended University of Massachusetts in 1976-1977; completed requirements for the Master of Science degree at Oklahoma State University in July, 1981.

Professional Experience: field engineer, Edwards and Kelcey, Inc., 1973-1974; staff geologist, James P. Collins, P.E., 1974-1975; graduate teaching assistant, Oklahoma State University, 1977-1978; research assistant, Oklahoma State University, 1978-1979; staff hydrogeologist, Espey, Huston and Associates, Inc., 1979-1981.