A GROUND-WATER MANAGEMENT MODEL FOR THE WASHITA RIVER ALLUVIAL AQUIFER IN ROGER MILLS AND CUSTER COUNTIES, OKLAHOMA

By

MARK RAYMOND SCHIPPER

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Ohio State University

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Thesis Approved:

Douglas C. Kent
Thesis Adviser

Wayne A Pettyjohn

A. Hounslow

Norman N. Durham
Dean of the Graduate College

PREFACE

This study concerns the hydrologic properties of the alluvial aquifer associated with the Washita River in Roger Mills and Custer Counties, Oklahoma. The primary objective of this study was to determine the maximum annual yield and corresponding annual pumping allocation for the Washita River alluvial aquifer in accordance with Oklahoma ground-water law. The computer model was used to determine the maximum annual yield based on predicted changes in the potentiometric surface (water table) caused by pumpage prior to July 1, 1973, and subsequent allocated pumpage until July 1, 1993.

The author wishes to thank Dr. Douglas C. Kent, his thesis adviser, for his valuable assistance and guidance during this study. Special appreciation is extended to Dr. Fred E. Witz, computer systems specialist, whose unbiased approach to problem solving proved illuminating. Gratitude is also extended to Dr. Wayne Pettyjohn and Dr. Arthur Hounslow, members of the advisory committee, for their critique of this thesis. Gratitude is extended to the Oklahoma Water Resources Board (OWRB) for providing pertinent data and funds for the project which was arranged through a contract with the Oklahoma State University and Dr. Kent, who was the principal investigator for this project. Special thanks is given to Mr. James Barnett, OWRB Director, and P. R. Wilson for their support.

Finally, special gratitude is extended to my family, whose moral support and encouragement are greatly appreciated.

TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

LIST OF FIGURES

Figure | Page

Figure		Page

Figure		Page

Figure | Page

CHAPTER I

ABSTRACT

The Washita River alluvium supplies water for irrigation, domestic and municipal use in Roger Mills and Custer Counties in west-central Oklahoma. It is a water-table aquifer composed of mostly fine to medium grained sand with some gravel and interbedded clays occupying a valley cut into Permian redbeds. It averages one mile wide, and the mean saturated thickness (1973) is about 118 feet. Well yields range from less than 200 gallons per minute (gpm) up to 1400 gpm, and the average well produces around 600 gpm. Dissolved solids are relatively high, averaging about 3000 parts per million (ppm), with bicarbonate hardness (Ca + Mg) and sulfate (SO_4) being the main constituents.

The purpose of the study was to determine the maximum ground-water pumping allocation for the Washita River alluvium as stated under Oklahoma law. Water-level data were obtained from drillers' logs supplied by the Oklahoma Water Resources Board. Water-quality and stream-flow data came from United States Geological Survey records. The data enabled definition of the relationships within the aquifer.

The Trescott-Pinder finite difference model was used to predict water level changes through time produced by various pumping rates. A five-year period was used for model calibration. Parameters including recharge, river base flow and aquifer gradient were adjusted within reasonable limits until a steady-state recharge-discharge relationship

was simulated.

Full prior appropriative rights in the Washita River alluvium in Roger Mills and Custer Counties total 17,115 acre feet/year. This is equivalent to an annual pumping rate of 0.3 acre feet/acre/year distributed evenly over the entire aquifer area (94 square miles).

Twenty-year simulation runs were made to determine the legal annual pumping allocation for the aquifer. An annual allocation of 2.18 acre foot/acre was established for the Washita River alluvium in Roger Mills and Custer Counties.

CHAPTER II

INTRODUCTION

General

The objective of this study was to determine the maximum annual yield of fresh water that can be produced from the Washita River alluvium in Roger Mills and Custer Counties. Under 82 Oklahoma Statute Sections 1020.44 and 1020.5 enacted by the Oklahoma Legislature, the Oklahoma Water Resources Board is responsible for completing hydrologic surveys of each fresh ground-water basin or sub-basin 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 sub-basin.

The maximum annual yield of each fresh ground-water basin or sub-basin is based upon a minimum basin or sub-basin life of 20 years from the effective date of the ground-water law (July 1, 1973). An annual allocation, in terms of acre-feet, is determined based on the maximum annual yield and is restricted to the aquifer area. The annual allocation is the number of acre-feet per acre per year that can be produced by the aquifer that will cause one-half of the area of the aquifer to be depleted of water to five feet or less saturated thickness over a 20-year pumping period starting July 1, 1973.

Location

The area of study is in west-central Oklahoma in Roger Mills and

Custer Counties (Figure 1). The Washita River basin defines the area. It covers about 2000 square miles above Clinton, Oklahoma, including its headwaters in the High Plains of Texas. The basin area in Roger Mills and Custer Counties is about 1582 square miles. The river enters Roger Mills County at an elevation of 2250 feet, and leaves Custer County at 1460 feet. The river gradient is 10 feet per mile in Roger Mills, and about 6.5 feet per mile in Custer County. The average gradient is 8.5 feet per mile. The course of the river and its alluvium is strongly meandering.

The aquifer is defined as the alluvial flood plain and low terrace deposits of the Washita River (Figure 2). It averages about one mile wide throughout its 93-mile length through the study area. The surface area of the aquifer is approximately 94 square miles (60,160 acres). The modeled area was not extended very far up tributary valleys, therefore only the lower reaches of some of the larger tributaries were included. The alluvium in tributary streams is usually thin and fine grained. This results in lower transmissivity, and wells often yield no more than what is typical for a rural domestic water supply (Hart, 1978).

The aquifer was divided into three modeled reaches. Areas were selected on the basis of well density and distribution of prior rights (Figures 3 and 4). Allocations determined in the modeled reaches have been extended to adjacent areas where data are lacking.

Previous Work

Kitts (1959) studied the Cenozoic geology of Roger Mills County. Extent and thickness of the Ogallala is described, and a depositional

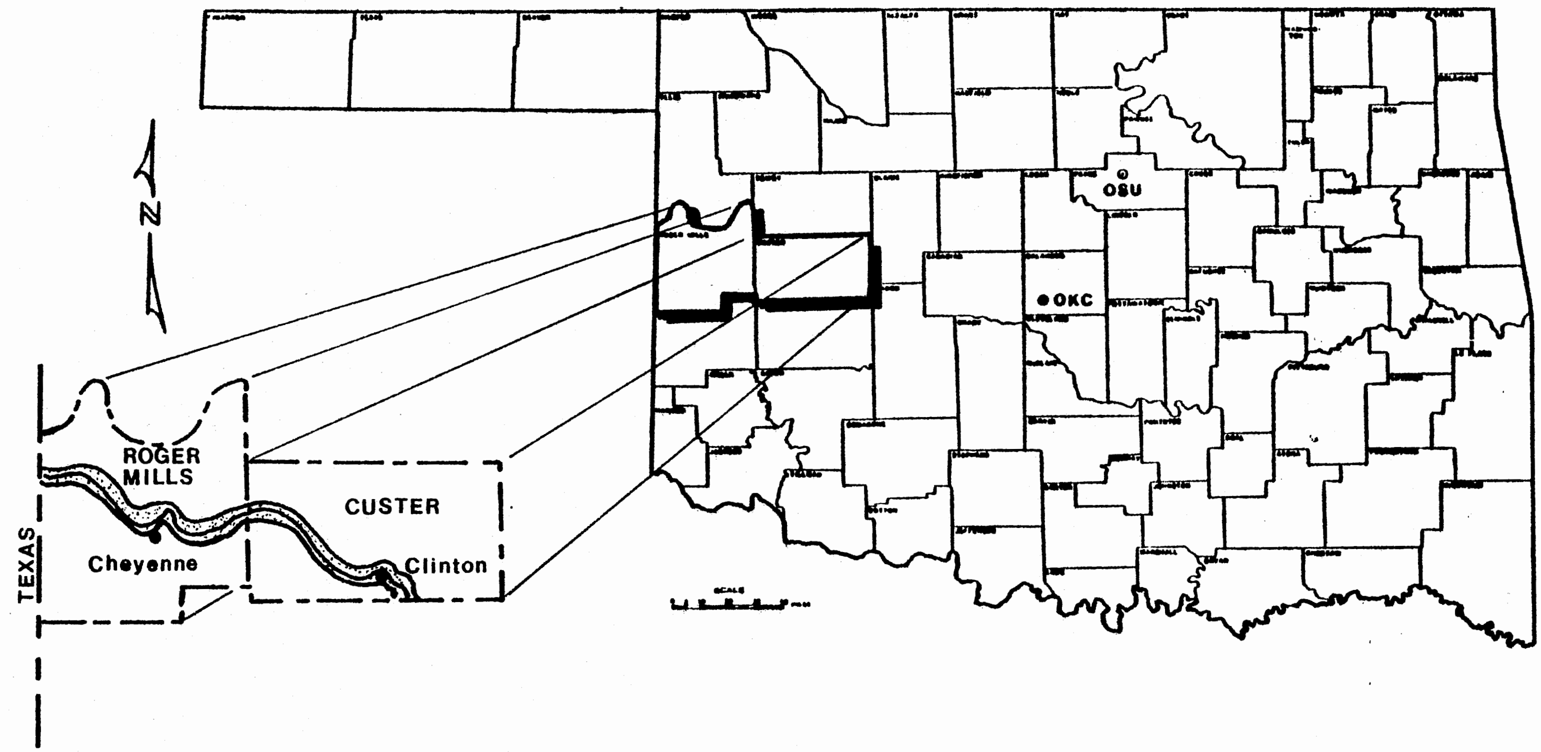


Figure 1. Location of Study Area

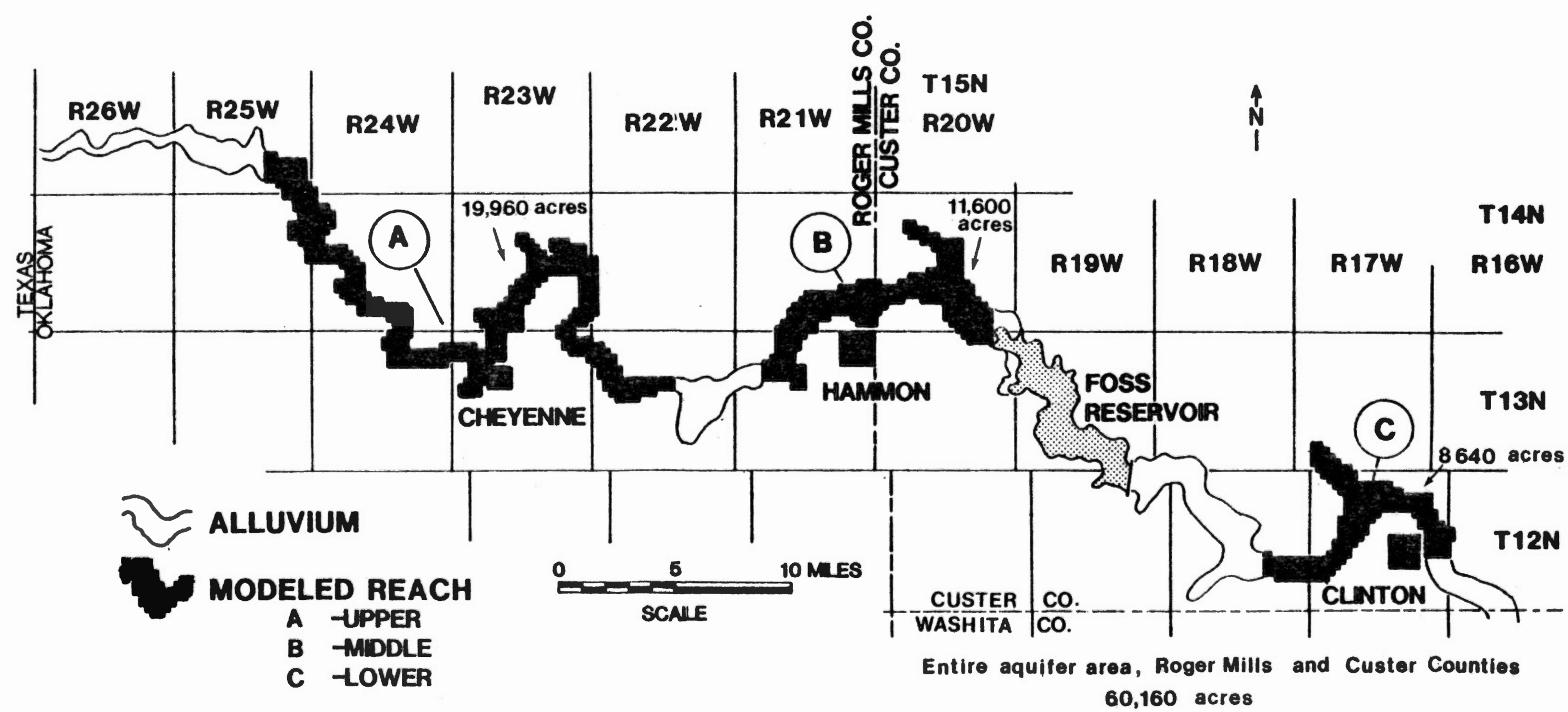


Figure 2. Regional Composite, Washita River Alluvium

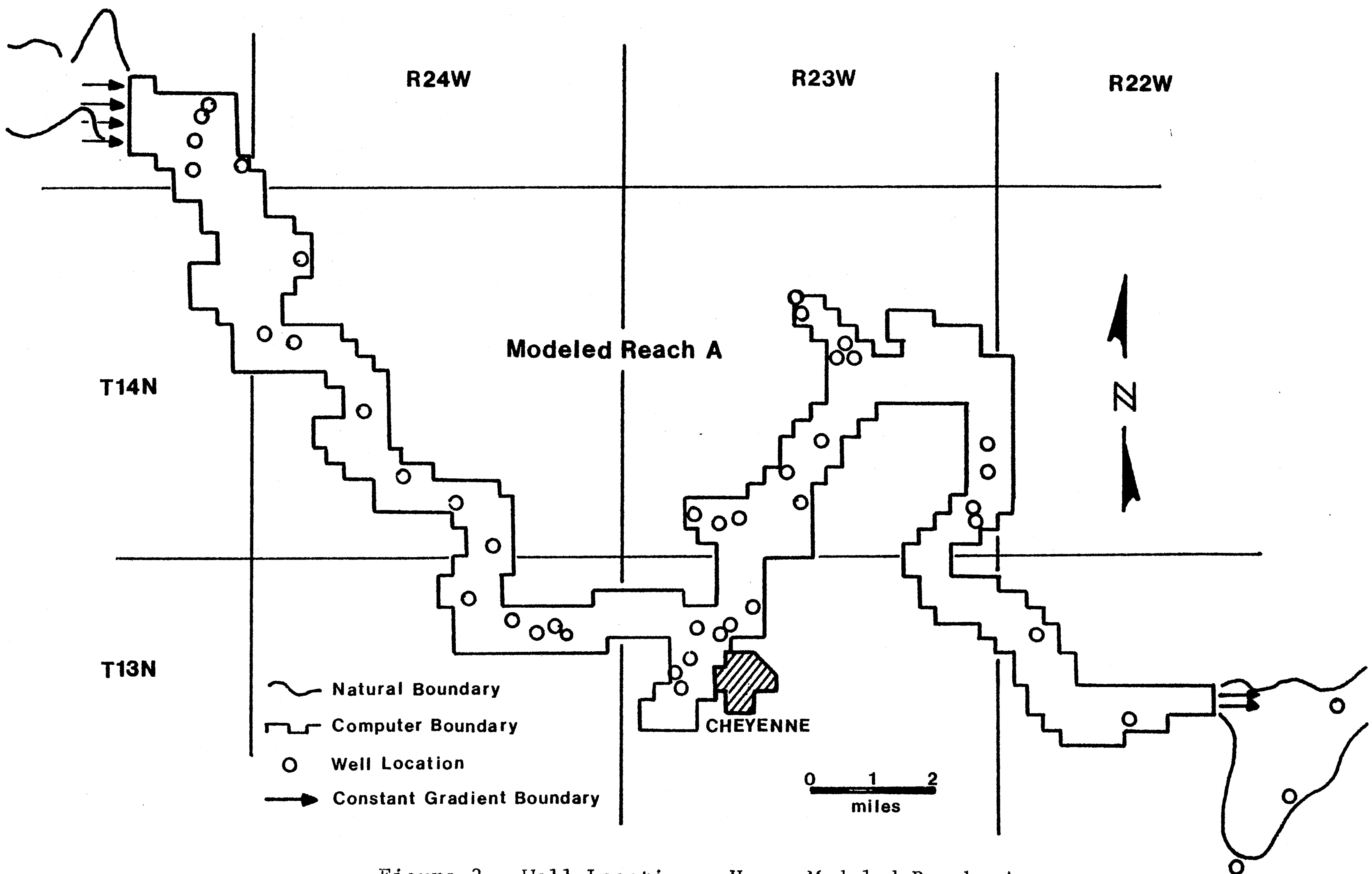


Figure 3. Well Locations, Upper Modeled Reach, A

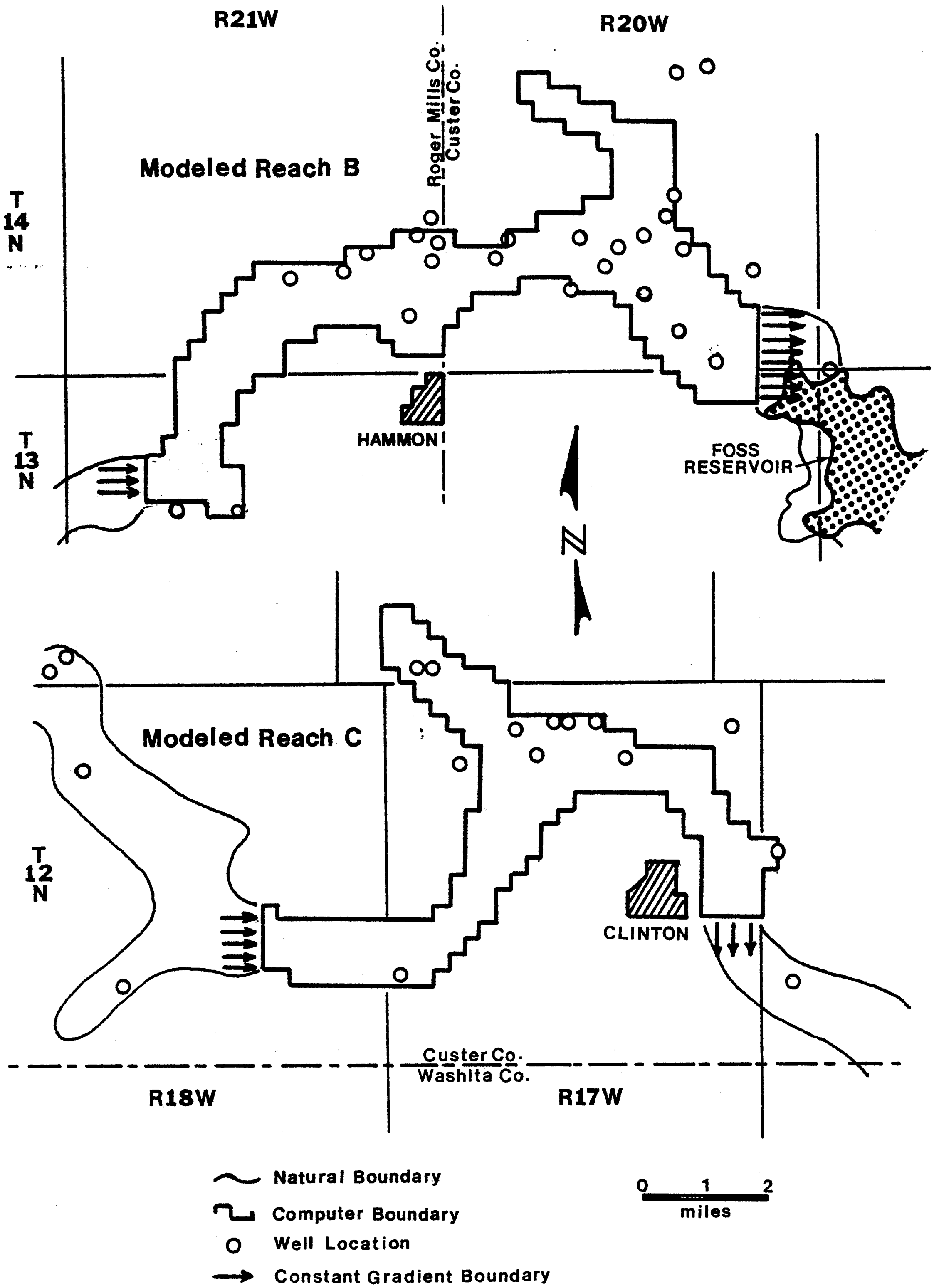


Figure 4. Well Locations, Middle and Lower Reaches, B and C

model for Pleistocene river terraces is suggested. The areal geology of eastern Roger Mills County and southeast Ellis County is described in detail by Lovett (1960). His study outlines the stratigraphy and structure and includes several measured sections and a geologic map. Bowers (1967) did a similar study in central Roger Mills County. His study also focuses on stratigraphy. It contains measured sections from throughout the area and also contains a geologic map.

The geology of Custer County was thoroughly described by Fay (1978). His report covers general geology and stratigraphy. Several measured sections and core descriptions are included. A detailed geologic map of Custer County with cross sections is available in his report.

The hydrology of the Washita River and its alluvium was investigated by Leonard, Davis, and Stacy (1958). Their report gives a general description of the physiography, hydrogeology, water quality, and well yields along the entire river length in Oklahoma. It includes plates with locations and owners of water wells.

Hart (1965) looked at ground water in the alluvial deposits of the Washita basin in the reach from Clinton to Anadarko, Oklahoma. Ten valley transects of three to eight test holes each were completed in the alluvium at points along the study reach. Detailed geologic logs of the test holes were made and are contained in his report. Five test holes were finished as water wells. Specific capacity data are provided for those wells.

A reconnaissance study of the water resources of the Clinton one-by-two degree quadrangle was carried out by Carr and Bergman (1976). The report is formatted as a hydrologic atlas and includes maps showing geology, availability of ground water, water quality, and selected well hydrographs. There is complete coverage of the Washita River alluvium in Roger Mills, Custer, Washita, and Caddo Counties.

The ground water availablility in Custer County was studied by Hart (1978). He described briefly the water quality and quantity characteristics of the geologic units in the county, including alluvium and terrace deposits. Kent, Naney, and Barnes (1973) applied computerized data processing techniques to the Washita River alluvium between Anadarko and Alex in Caddo and Grady Counties, Oklahoma.

Pinder (1970) developed a finite difference model to stimulate two dimensional aquifer flow. This model has been modified several times, and is described by Trescott and Larson (Trescott, Pinder, and Larson, 1976). New input-output options for use with the IBM 370-158 computer have been used for this study. The options were designed by Witz (1978) under the direction of D. C. Kent. The same model was used by Kent (1980) and Paukstaitis (1981) to model the alluvium and terrace deposits of the North Fork of the Red River. Lyons (1981) and Beausoleil (1981) under the direction of D. C. Kent applied it to ground-water management studies of the Elk City sandstone in west-central Oklahoma and the Enid isolated terrace deposits in north central Oklahoma, respectively. These latter studies have recently been published as final reports to the Oklahoma Water Resources Board (OWRB) by Kent, Lyons, and Witz (1982), and by Kent, Beausoleil, and Witz (1982).

CHAPTER III

GEOLOGY

The rocks exposed within the study area range in age from Permian to Quaternary (Figures 5 and 6). Nearly horizontal Permian strata have been dissected by the Washita River and its tributaries to produce a distinct dendritic outcrop pattern in Custer and eastern Roger Mills Counties. West toward Texas, large areas are blanketed by Tertiary deposits. Quaternary alluvium is associated with the present river drainage. In addition, Quaternary terrace deposits parallel much of the Washita River in Custer County.

The study area is located along the northern flank of the Anadarko basin about 40 miles from the axis. The basin is an asymmetrical syncline with its steeper dipping limb adjacent to the Wichita and buried Amarillo Mountains. Its gently plunging axis trends west-northwest. It contains sediments as old as the Cambrian. The area was tectonically active throughout the Paleozoic. Increased orogenic activity during the Pennsylvanian caused a rapid deepening of the basin and a thick sequence of sediments was deposited. Most of the sediments were derived from the Amarillo-Washita Uplift, which was active at that time. Deformation lasted into the early Permian; then the basin filled with carbonates, evaporites, and detrital sediments during the remaining Permian time (Zabawa, 1976).

Mesozoic rocks are absent in the central Anadarko basin.

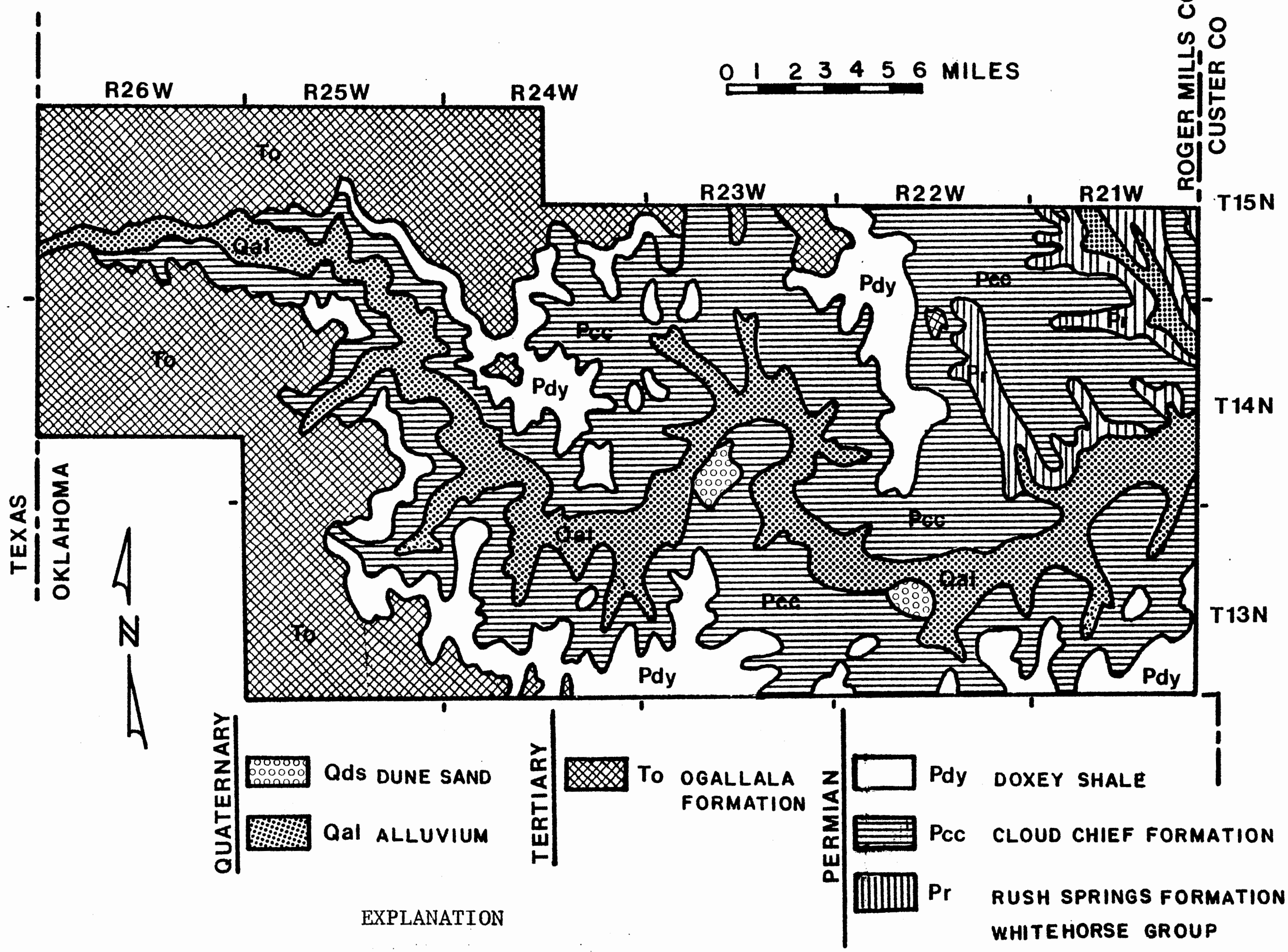


Figure 5. Geologic Map of Part of Roger Mills County, Oklahoma (Bowers, 1967; Lovett, 1960)

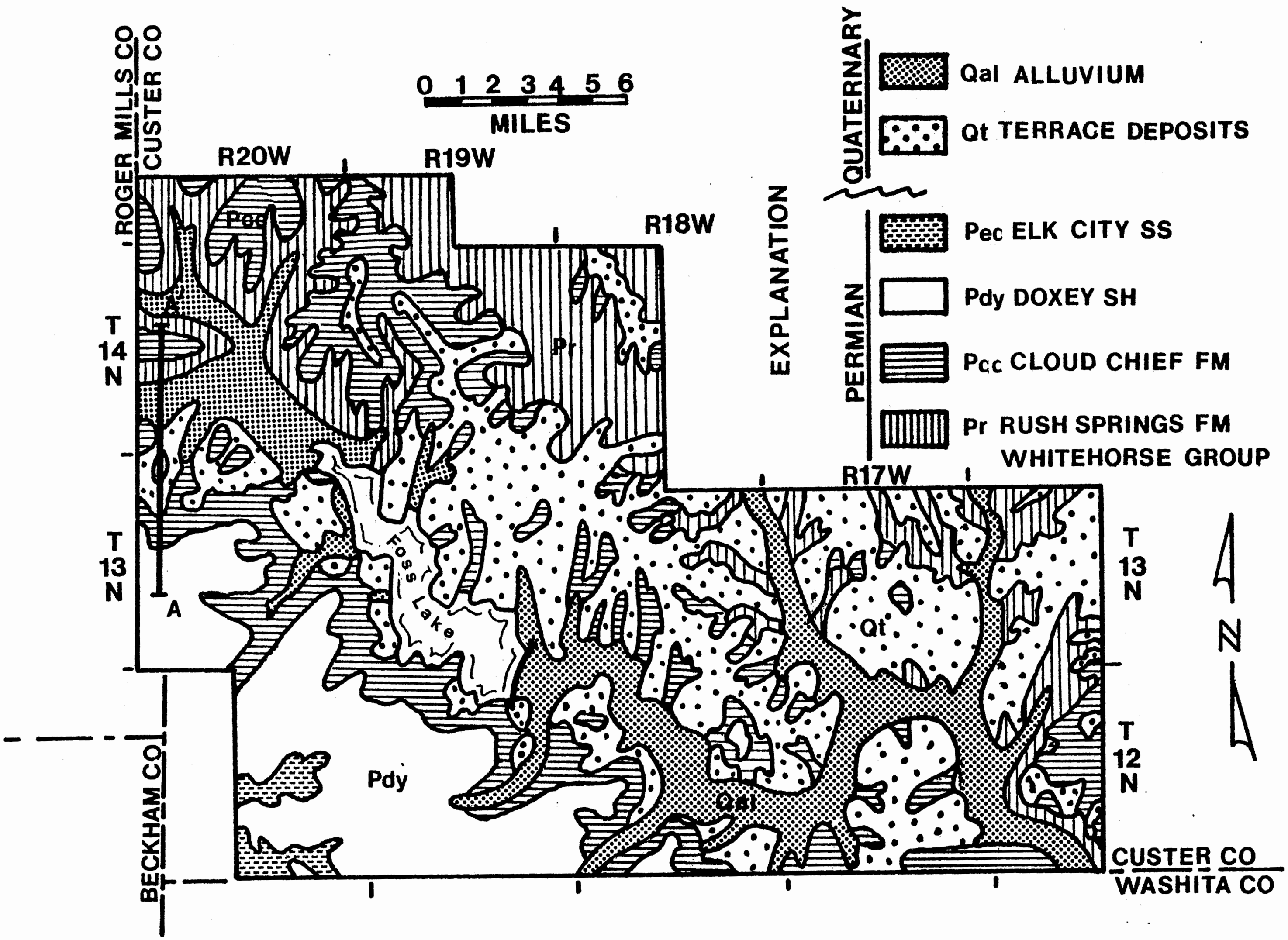


Figure 6. Geologic Map of Part of Custer County, Oklahoma (Lovett, 1967; Fay, 1978)

Subsequently, little is known about the depositional environment at that time. The Laramide Orogeny caused extensive uplift in the Rocky Mountain region in late Cretaceous and Tertiary time. As a result, sediments from the west spread out as a large alluvial apron and covered much of the west-central Great Plains (Kitt, 1959).

After the Tertiary, deposition in Oklahoma has occurred along the present day rivers in the form of river terraces and flood plains. The size of the rivers in many of these valleys cannot account for the thickness and extent of these deposits. It is believed that the cyclic glacial and interglacial periods during the Quaternary caused periods of large water supply and sediment load from the Rocky Mountains (Kitt, 1954). A generalized geologic column is shown in Figure 7.

The general dip in the study area is to the south toward the Anadarko basin at about 10 to 80 feet per mile (Figure 8). Strike direction shifts around the center of the basin. Strike changes from northwest in the east to west and southwest in the central and western part (Fay, 1978). Beds tend to thicken toward the axis of the basin. Some units change facies from shale and sandstone along the flank to evaporite deposits of anhydrite and gypsum further south where the syncline deepens (Lovett, 1960). Many small-scale structures in the area may not extend to depth and may be caused by collapse of underlying beds due to solution of salt and gypsum (Fay, 1978).

The Rush Springs Sandstone is the oldest rock outcropping in the study area (Figure 7). This Permian formation is primarily an orange-brown, fine-grained, calcite and gypsum cemented, quartzose sandstone. It outcrops on the northern side of the Washita River in Custer County (Figure 6). East of the study area it is up to 430 feet thick, but

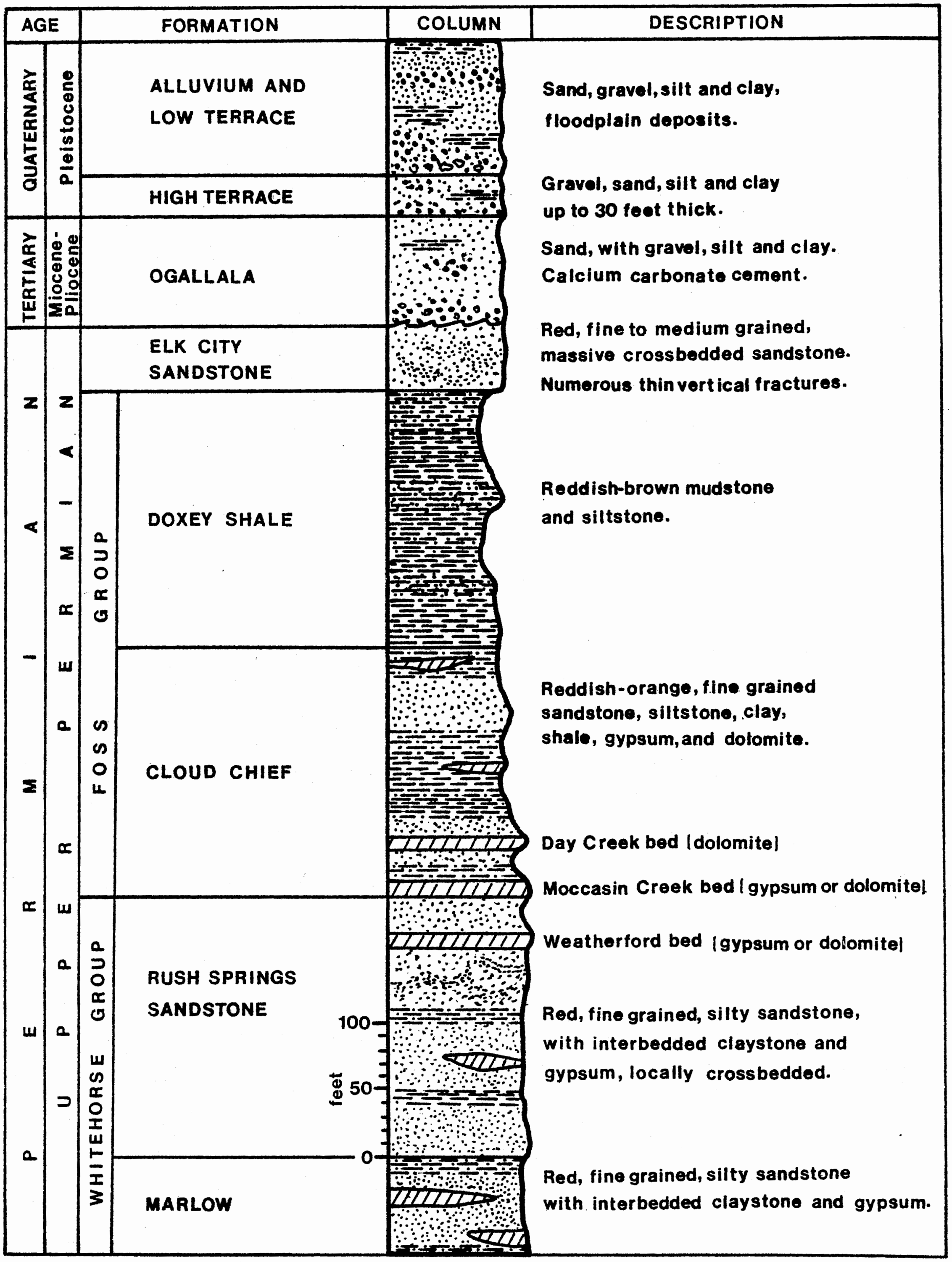


Figure 7. Geologic Column for the Roger Mills-Custer County Area (Lovett, 1960; Fay, 1978)

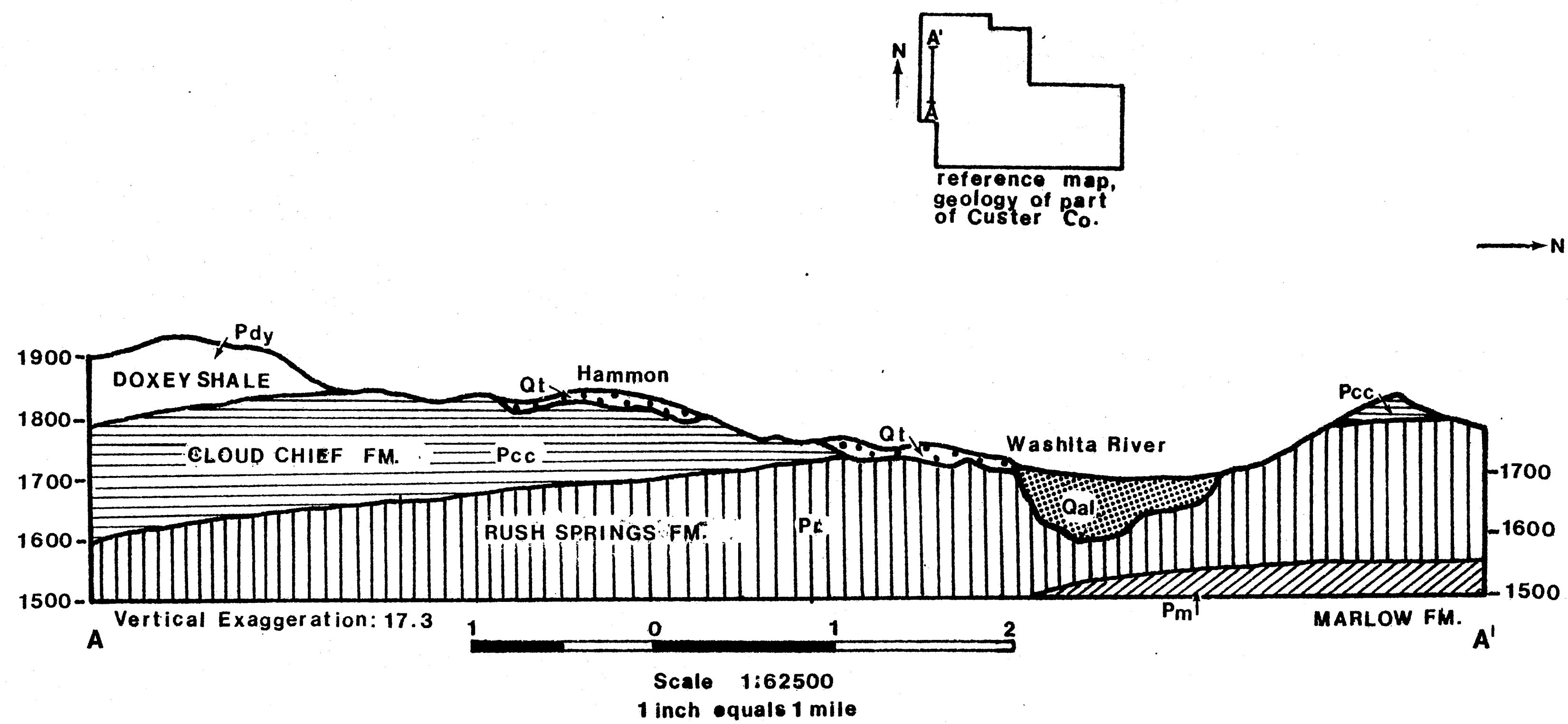


Figure 8. Geologic Section Along Line A-A' in Custer County, Oklahoma. Line A-A' Shown on Geologic Map of Part of Custer County, Figure 6 (Fay, 1978)

averages about 200 feet thick in western Custer County. In many places the sandstone is crossbedded. The Rush Springs contains some gypsum beds that are laterally continuous. One of these, the Weatherford bed, is a gypsum or dolomite and occurs near the top of the formation. It is up to eight feet thick and caps escarpments over much of Custer County (Fay, 1978).

East of the study area, wells in the Rush Springs commonly yield 200 to 700 gpm of water with suitable quality for municipal and irrigation use. In the study area, however, yields may be less than 50 gpm. Smaller yields are due mainly to a reduced saturated thickness. The decrease in yield is paired with a decrease in water quality. Water quality is poor, due to the percolation of water through the soluble gypsum in the overlying Cloud Chief Formation and in the Rush Springs, which causes higher concentrations of calcium sulfate. Use of water from the Rush Springs in the southwestern corner of Custer County is limited because the water is highly mineralized (Hart, 1978).

The Cloud Chief Formation outcrops both north and south of the river in a wide band that parallels the river course across the study area. Through most of this length, the Washita River alluvium rests upon the Cloud Chief. About 80 feet of the Cloud Chief is exposed in the Cheyenne area. The total thickness is about 190 feet (Bowers, 1967). Orange-brown shale and siltstone with some orange-brown sandstone make up most of the formation. Dolomite and gypsum are also found in the Cloud Chief. Two members, the Day Creek bed and the Moccasin Creek bed, have been named. They are both in the lower half of the formation and are each about five feet thick (Fay, 1978).

The tight-grained rocks of the Cloud Chief do not yield more than a few gallons of water a day to wells. The water is reportedly hard and has a high sulfate content (Hart, 1978).

The Doxey Shale overlies the Cloud Chief. The contact between the two can be distinguished by the darker more reddish-brown color of the Doxey. It outcrops throughout the study area. Recent erosion has reduced the thickness to about 70 feet in the Cheyenne area (Bowers, 1967). Fay reports the total thickness of the type section in Custer County at 195 feet. It is mostly shale and strongly factured siltstone. The siltstones are cemented with calcite and iron oxide, and the fractures are often veined with calcite. The Doxey does not contain beds and veins of gypsum as does the underlying Cloud Chief; however, there are small crystals of selenite interspersed throughout the Doxey section (Bowers, 1967). The Doxey is too fine grained to yield more than a meager supply of water to domestic wells (Hart, 1978).

The Elk City Sandstone outcrops along the southern edge of the Washita River drainage basin in the study area. It is a red, fine to medium grained, friable crossbedded sandstone. It is massively bedded and has numerous vertical to near-vertical fractures which are commonly filled with calcite or gypsum.

The Washita River alluvium within the study area consists of discontinuous layers of sand, silt, clay, and gravel derived from the Tertiary and Permian bedrock through which the river cuts. Drillers' logs show that its thickness is up to 223 feet northwest of Cheyenne in Roger Mills County. Well yields are more than 1000 gpm in several areas. Numerous irrigation wells are completed in the alluvium.

CHAPTER IV

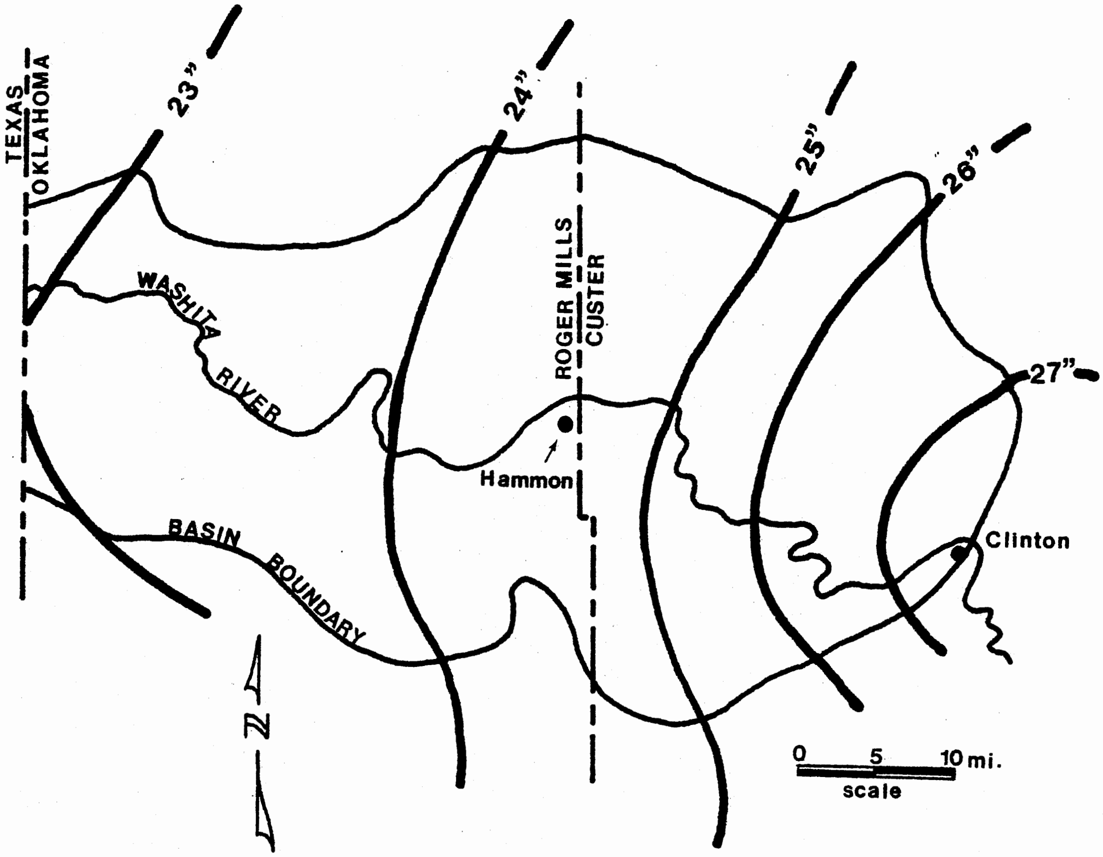
HYDROGEOLOGY

Climate

The climate in Roger Mills and Custer Counties is dry-subhumid. The average annual temperature is 60°F; prevailing winds in the study area are southerly. Pan evaporation is 64 inches annually. The growing season is approximately 200 days long beginning in early April and lasting through October.

The thirty-year (1941-1970) average of precipitation from stations throughout the region was plotted and contoured (Figure 9). The isohyetal method was used and showed that the effective uniform depth of precipitation over the study area was 24.7 inches. The thirty-year average precipitation (1951-1980) for the centrally located Hammon weather station was 24.01 inches (Figure 10). The amount of rainfall received decreases westward in the study area. Clinton, on the eastern edge of the study area receives about 27 inches of precipitation annually. Near the Texas border in western Roger Mills County, however, annual precipitation is 23 inches.

Eighty percent of precipitation comes during the frost-free period. Monthly distribution of precipitation at Hammon, Oklahoma, is shown in Figure 11. May is commonly the wettest month, and January the driest.



ISOHYETAL METHOD

To find effective uniform depth (E.U.D.) precipitation over the study area, using 14 regional stations.

Isohyet (in.)	Est. E.U.D. (in.)	Net Area (sq. mi.)	% Total Area	Weighted Precip. (in.)
27	27.5	60	3.8	1.04
26	26.5	214	13.5	3.58
25	25.5	225	14.2	3.63
24	24.5	550	34.8	8.52
23	23.5	506	32.0	7.52
22	22.5	27	1.7	.39
			Net E.U.D	24.7 inches

Figure 9. Isohyetal Determination of Average Precipitation Over the Washita River Basin From Clinton, Oklahoma, to the Texas Border. Rainfall Record 1941-1970 for 14 Regional 1st Order Climatological Stations.

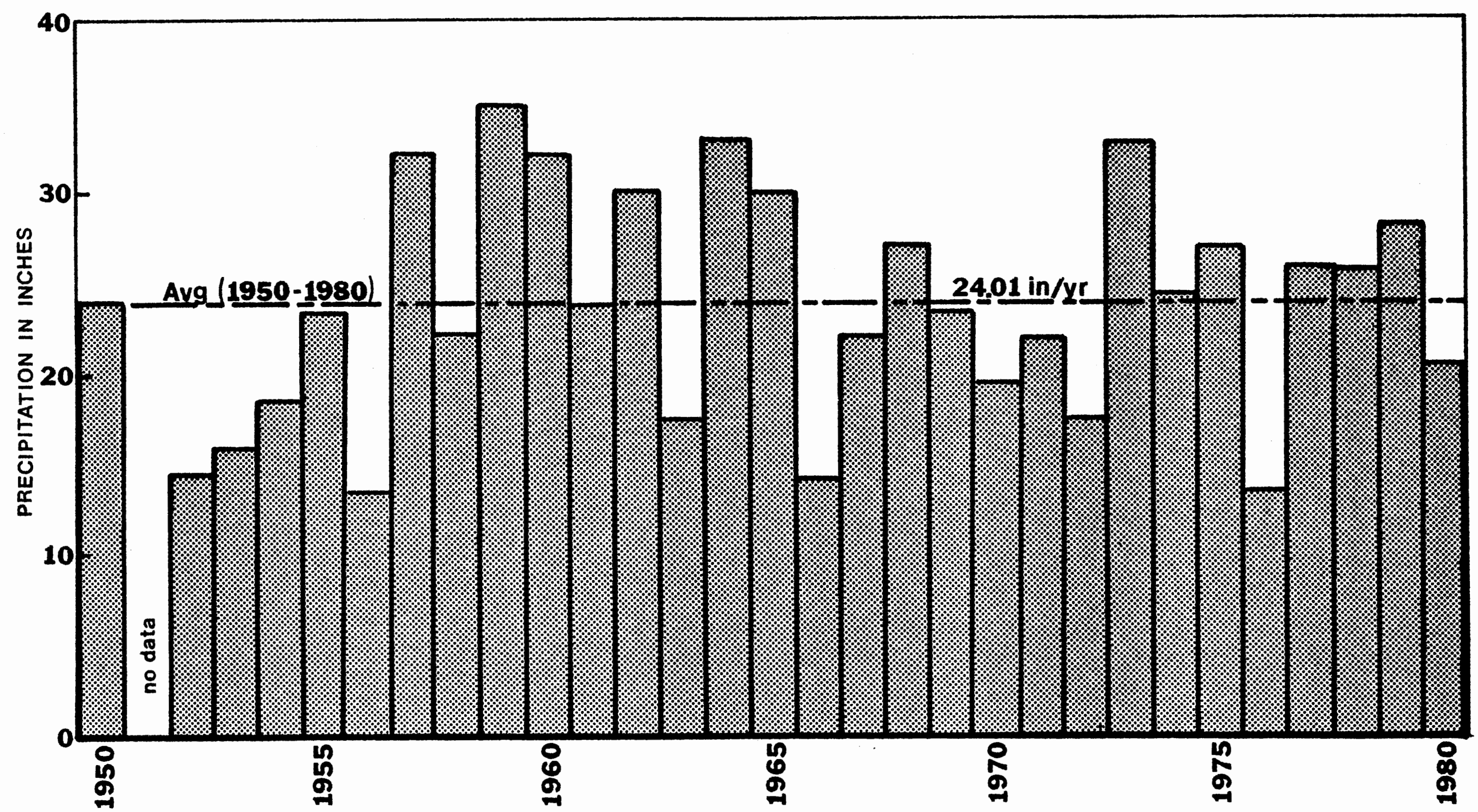


Figure 10. Annual Precipitation at Hammon, Oklahoma, 1950–1980

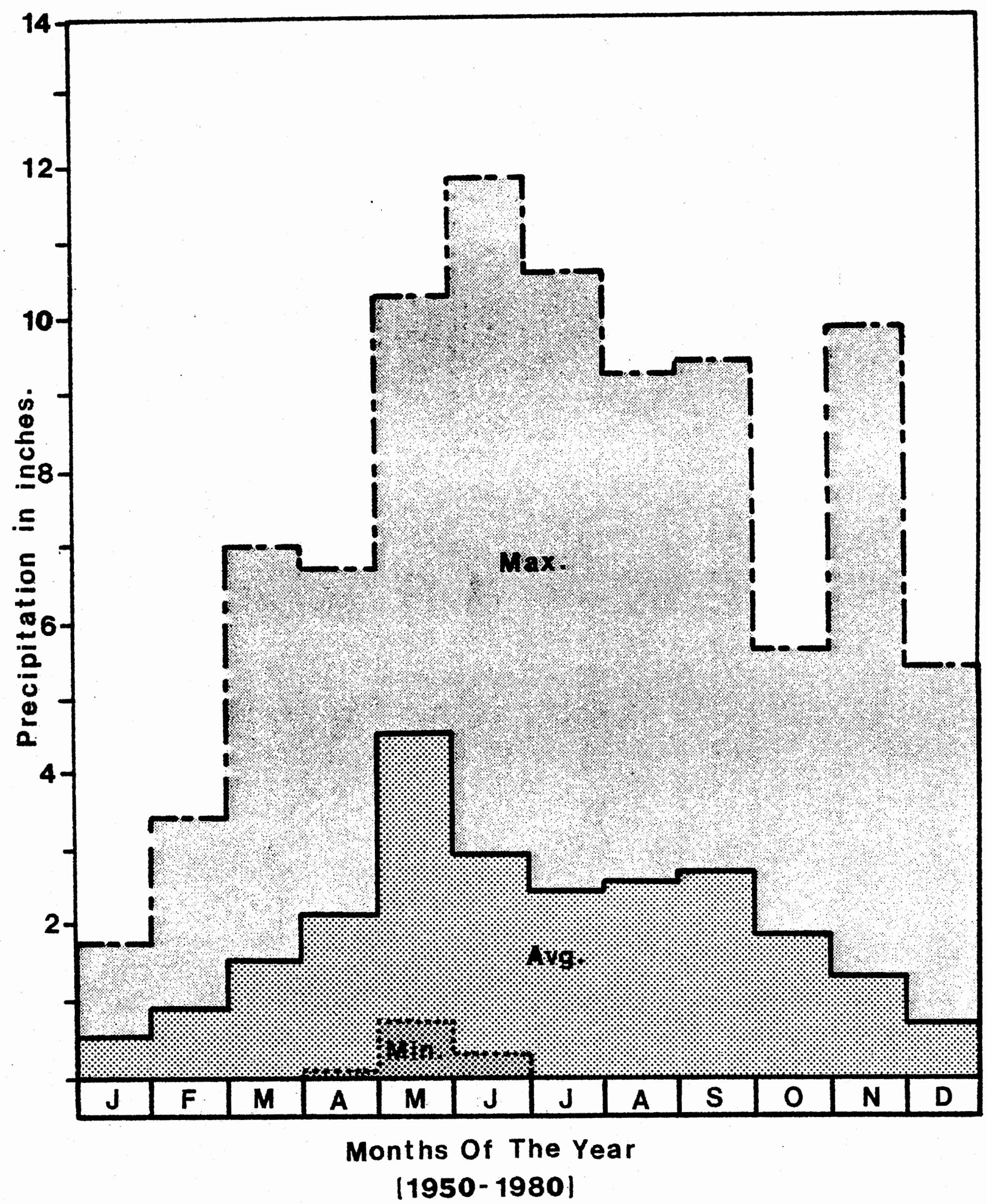


Figure 11. Monthly Precipitation at Hammon, Oklahoma, 1950-1980

Physical Description of Aquifer

The Washita River alluvium in the study area averages about 133 feet thick. Drillers' logs indicate that it is thickest northwest of Cheyenne,where it reaches 223 feet. This is a local maxiumum, however, and the average thickness in the Cheyenne area is about 164 feet. From Hammon east to Clinton, thickness ranges from 60 to 135 feet. The bedrock surface upon which the alluvium rests is irregular due to localized scouring by the river during flooding. Therefore, alluvial thickness can change significantly within a short distance. Water well data for the study area, including well depth, are shown in Table I (see page 30).

The composition of the alluvium varies vertically and horizontally. This is due to the lenticular nature of alluvial deposits. Sand and gravel, sand, silt, and clay in some combination make up the alluvium. The coarsest material is generally found in the lower part (Hart, 1978). Figure 12 shows a profile of the alluvium northwest of Cheyenne.

Alluvium occurs in the study area as high terrace deposits, lower younger terrace deposits, and present-day alluvium (Figures 5 and 6). According to Hart (1965), three cycles of erosion and deposition have occurred. The first cycle consisted of erosion of the bedrock into a broad shallow valley as the river moved laterally between its bedrock boundaries. Deposition of sand and gravel containing an abundance of quartzite and chert probably derived from the Tertiary deposits of the High Plains followed this period of erosion.

During the second cycle, the river cut into the older alluvial deposits. Subsequent deposition was not only of bedrock material, but also reworked material deposited during the first cycle.

During the third cycle, the stream cut into the second cycle

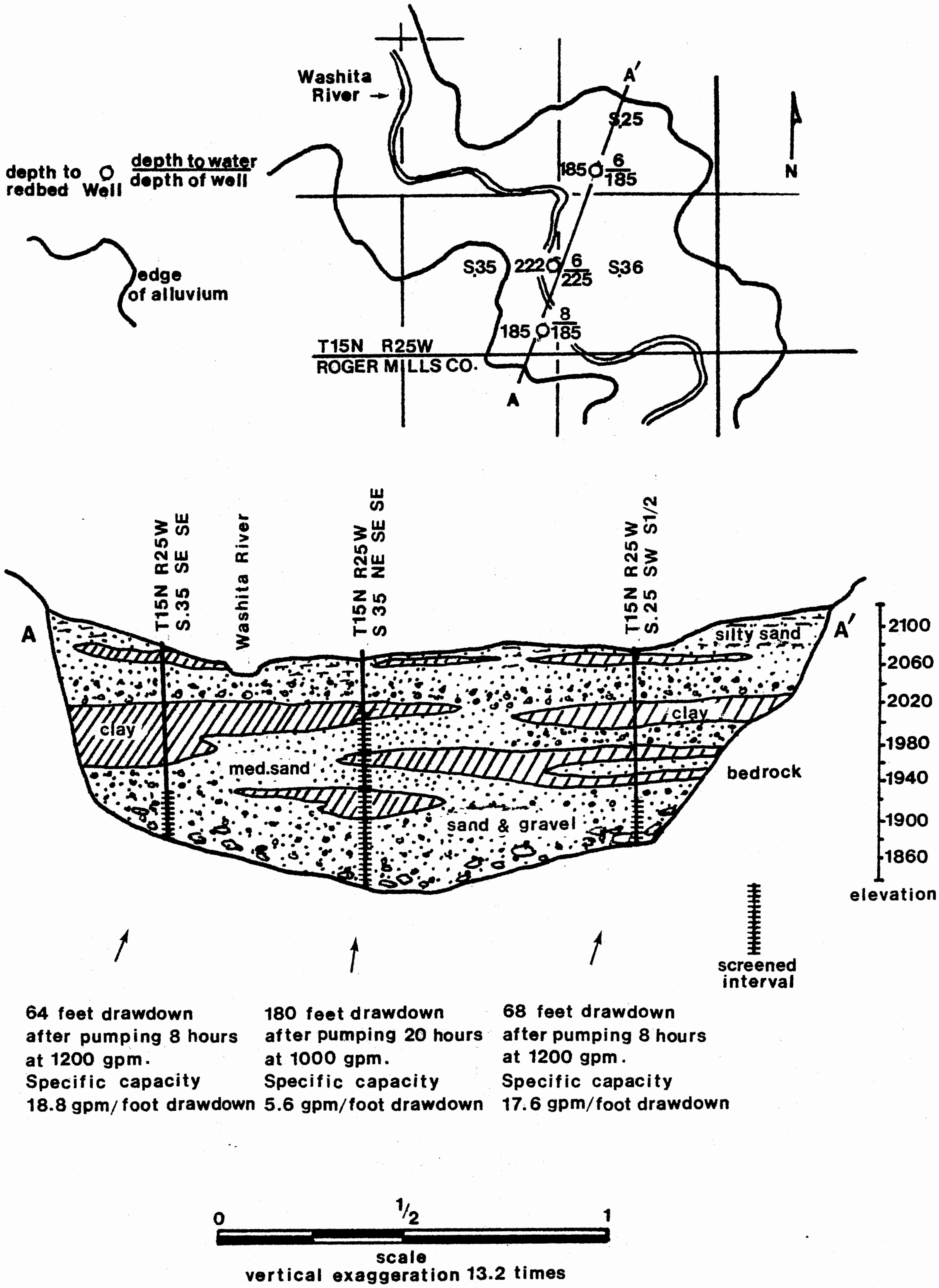


Figure 12. Valley Profile Northwest of Cheyenne, Oklahoma, Showing Typical Character of Alluvial Material With Well Completion and Yield Information for Three Wells

alluvial deposits, and in some places penetrated the underlying bedrock. This was again followed by the deposition of reworked alluvial deposits and bedrock material. Valley development is shown schematically in Figure 13.

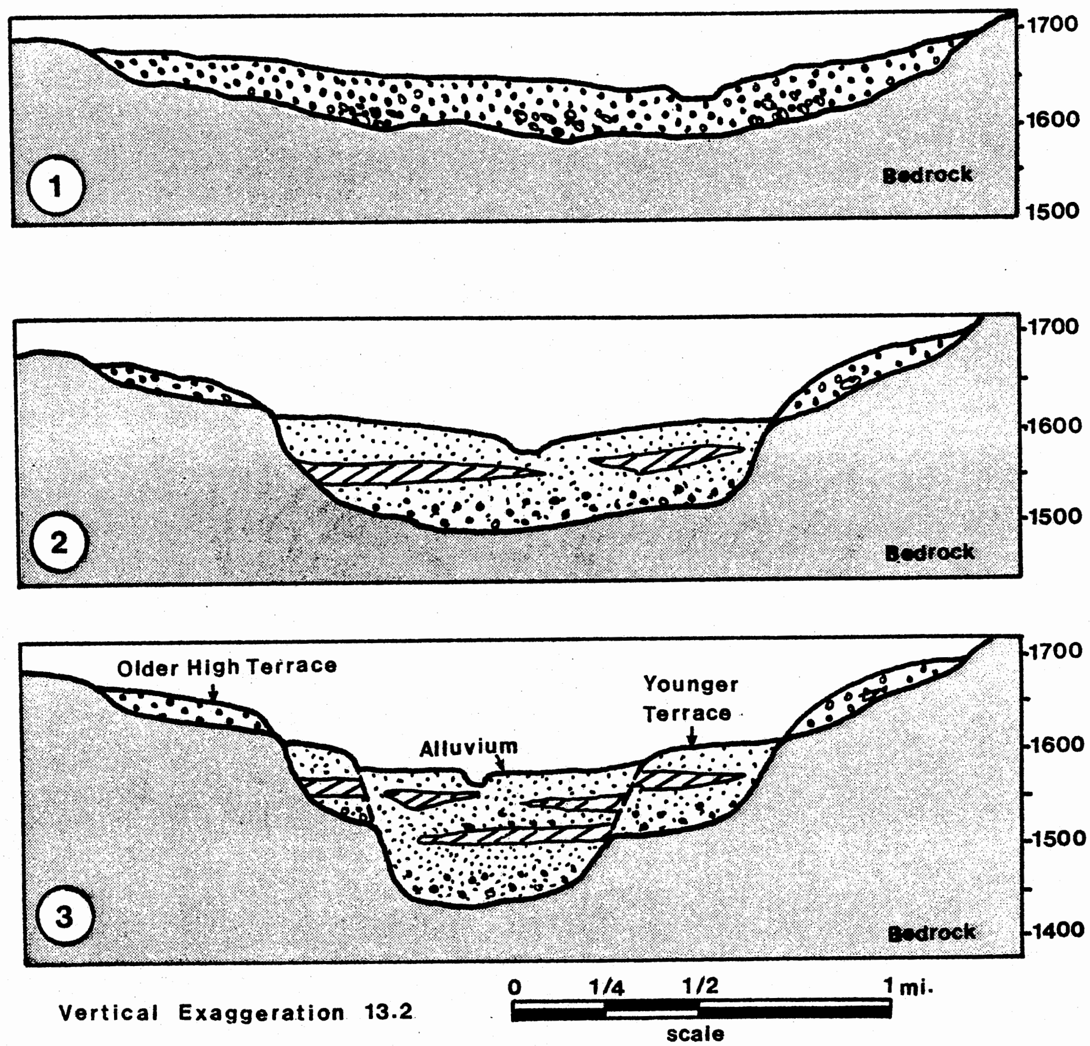
The remnants of high terrace deposits generally are separated from the younger deposits by bedrock outcrops and do not contribute water directly to the alluvium (Hart, 1965). This was confirmed by the author during visits to the study area in 1982.

The alluvial deposits above Clinton are commonly thicker and coarser than they are downstream. The coarse material is probably derived from the High Plains deposits of western Oklahoma and Texas. Steeper gradients in the area allowed the depositing stream to carry the finer materials downstream. Hart (1965) suggests that below Clinton, valley fill is derived mostly from Permian redbeds.

Hydrologic Properties

The Washita River alluvium is an unconfined or water-table aquifer although it may be locally confined by clay layers. Hydrologic continuity is maintained by areas where the clay is missing due either to non-deposition or river channel erosion. With water-table conditions, the storage coefficient is about equal to the specific yield (Sy). The storage coefficient of an aquifer is the volume of water it releases from or takes into storage per unit change in head (Lohman et al., 1972). It is a dimensionless number. The storage coefficient for the Washita River alluvium in the study area falls in the range from 0.20 to 0.30.

Transmissivity is a measure of an aquifer's ability to transmit



1. Stage One - Erosion of broad shallow valley and deposition of sand and gravel with quartzite pebbles, probably derived from Ogallala.

2. Stage Two - Downcutting followed by deposition of bedrock material and reworked first cycle sand and gravel.

3. Stage Three - Further downcutting, in many places penetrating the underlying bedrock, followed by deposition of reworked alluvial deposits and bedrock material.

Figure 13. Schematic Valley Development of Washita River in Roger Mills and Custer Counties, Oklahoma (from discussion by Hart, 1965)

water. It is the rate at which water will move through a unit width of the aquifer under a unit gradient. The rate may be expressed in units of gpd/ft or ft^2/day (Lohman et al., 1972). Transmissivity of the alluvium in the study area ranges from 4000 gpd/ft in areas of lower permeability and/or saturated thickness up to 70,000 gpd/ft in areas where coarser material predominates and saturated thickness is high. The overall average is 28,600 gpd/ft. Permeability and transmissivity maps are included in Appendices F and G, respectively.

Depth-to-water over the study area averaged about 17.0 feet. Saturated thickness varies locally. In the upper modeled reach near Cheyenne it averaged about 150 feet. The middle section near Hammon averaged 91 feet, and in the lower modeled reach near Clinton it was about 93 feet. Mean saturated thickness for the entire study area is approximately 118 feet. Depth to water and saturated thickness maps for 1973 are included in Appendices H and I, respectively.

The Cloud Chief and Rush Springs Formations underly the alluvium in the study area. They are much less permeable than the alluvium, and form the lower boundary of the aquifer. A subcrop map showing their distribution is shown in Figure 14.

Well Design and Well Yield

Irrigation wells completed in the Washita River alluvium in the study area generally use 14 to 16-inch casing. This is slotted or screened opposite water-bearing zones, and the annular space around the casing is usually gravel-packed.

Several wells completed in the alluvium in the study area produce over 1000 gpm, and a few produce up to 1400 gpm. Drillers' logs also

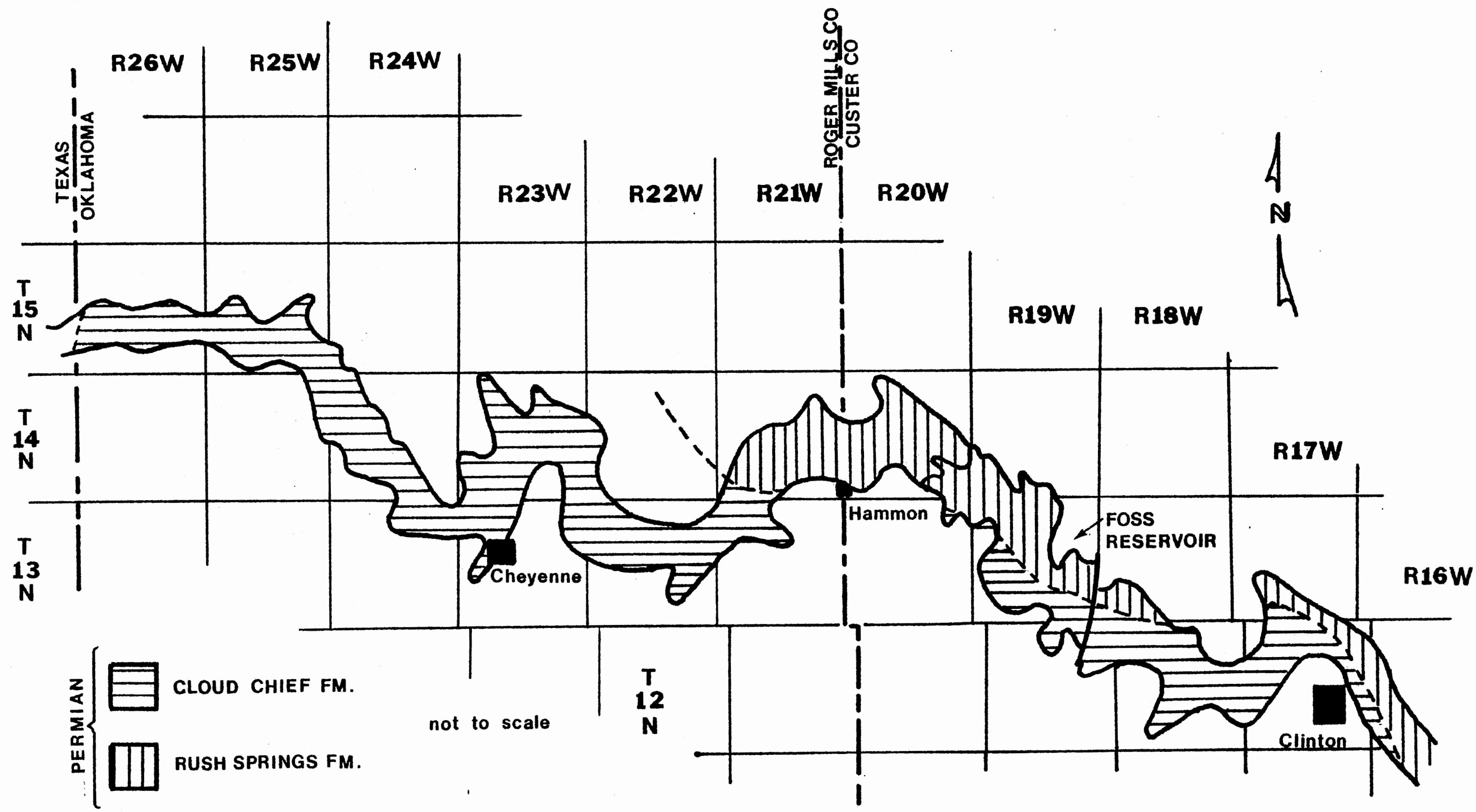


Figure 14. Subcrop Map Showing Bedrock Units Underlying the Alluvium in the Study Area (geologic contacts from Lovett, 1967; Fay, 1978)

show that some wells produce less than 100 gpm. The average yield for the study area is about 600 gpm. Much variation in yield is caused by differences in permeability and saturated thickness. Permeability is affected by the lenticular nature of the deposits and their varying composition. Saturated thickness may often change laterally due to the irregularity of the underlying redbed surface. The type of well completion used will also affect well yields. Water-well data for the study area are listed in Table I.

Land Use, Irrigation, and Return Flow

About half of the agricultural land in the study area is used for crops, and the other half serves as pasture. In order of importance by income, the major crops are wheat, cotton, grain sorghum, barley, oats, and alfalfa (Oklahoma Water Resources Board, 1969). Cotton and alfalfa are the major irrigated crops and are grown mainly in the bottom lands.

Prior appropriative rights are water rights that were held prior to 1973. Owners declared them at that time, and those rights became legally established. The Oklahoma Water Resources Board provided data which included names and acreage under irrigation and the annual amount of pumping. These data were reduced to pumping per acre and then distributed over the appropriate nodes. Maps of the distribution of prior rights over the study area are shown in Figures 15, 16, and 17. Prior rights for Roger Mills and Custer Counties supplied by the Oklahoma Water Resources Board show the heaviest irrigation to be in the Cheyenne area. Pumping is also concentrated north and northeast of Hammon. Prior rights in the Washita River alluvium in Roger Mills and Custer Counties total 17,115 acre feet /year. These are distributed over 11,520 acres,

TABLE I

WATER WELL DATA FOR SELECTED WELLS

Location	Basic Data: Total*1 Depth (ft)	Depth to Static Water Level (ft)	Test Yield (gpm)	Test Pumping Duration (hrs)	Test Pumping Drawdown (ft)	Calculated Data: Specific Capacity (gpm/ft of Drawdown)	Transmissivity from Specific Capacity T from SC x 1.66 *2	(1) Permeability from Specific Capacity	(2) Permeability from Geologic Log (see class value pg 58)	Average Permeability (1) + (2) / 2	Average Permeability from Specific Capacity Data Only x Adjustment Factor *3
SW SE NW 22-15N-26W	105	25	60	1	5	12	16,600	208	108	158	
SE SW SE 20-15N-25W	151	14	1,200	8	62	19	32,000	232			232
SE NW 21	60	7	600	24	21	29	60,000	1,130			1,130
SE SW NW 21	185	12	750	6	125	6	11,665	68	295	181	
SE SE SE 21	103	30	350	6	70	5	9,160	127	312	219	
NE NE SW 22	134	12	400	3	100	4	7,500	62	66	64	
SW SW NE 25	185	6	1,200	8	60	20	45,000	250	284	268	
NW SE SE 27	163	8	750	24	38	20	46,660	301	211	256	
NE SE SE 35	223	7	1,000	20	167	6	10,830	50	144	97	
SE SE 35	185	8	1,200	8	75	22	45.000	250	259	255	
SE SE 36	182	6	1,200	12	32	38	66,800	392			392
NE 7-14N-24W	185	22	60	1	30	2	1,670	11	57	34	127
NW SE NW 18	170	3	1,000	24	90	11	20,750	127			
SW NE 20	190	15	1,400	12	90	16	26,560	152	142		147
SW NE 28	181	14	1,400	30	56	25	41,665	378	243	311	
SE SE 34	185	7	1,400	60	70	20	46,670	261	262	262	
SE NW 9-14N-23W	135	12	500	-	125	4	7,010	57			57
SW SW 10	141	20	600	3	120.	5	9,170	76	46	61	
SW NW 15	150	8	860	30	62	14	37,500	264	280	272	
SW NW SE 15	144	12	30	0.5	30	1	1,670	13	70	42	
SE SW 15	120	10	750	30	50	15	38,330	348	273	311	
NE NE 16	142	20	600	4	100	6	14,940	123			123

*1-Total depth is usually indicative of depth to bedrock.
*2-Correction factor assuming 60% well efficiency. Transmissivity units are gpd/ft.
*3-Permeability values from specific capacity only in a modeled reach are adjusted to permeability values for same modeled reach found with $\frac{(1) + (2)}{2}$ Adjustment factors are upper reach 1.0; middle reach 0.72; lower reach 1.03.

TABLE I (Continued)

Location	Total*1 Depth (ft)	Depth to Static Water Level (ft)	Test Yield (gpm)	Test Pumping Duration (hrs)	Test Pumping Drawdown (ft)	Specific Capacity (gpm/ft of Drawdown)	Transmissivity from Specific Capacity T from SC x 1.66 *2	(1) Permeability from Specific Capacity	(2) Permeability from Geologic Log (see class value pg 58)	Average Permeability (1) + (2) / 2	Average Permeability from Specific Capacity Data Only x Adjustment Factor *3
	Basic Data					Calculated Data					
SW SW 22	163	30	1,500	16	50	30	66,670	501	489	495	
NE NE C 25	140	7	750	30	28	27	60,000	450	245	348	
SE NE 25	148	6	1,000	4	59	17	36,520	257			257
SW NW 28	161	20	450	24	35	13	26,670	189	168	179	
NW SE 32	86	30	259	14	65	4	10,000	178	430	304	
NE NE 33	75	20	60	8	2	30	58,330	1,060	282	671	
SE SW 24-14N-21W	90	16	550	24	80	7	19,920	269			194
SE SE 24	85	21	600	12	50	12	18,260	285			205
SW 25	137	10	1,000	4	83	12	17,500	138	158	148	
NW SE 26	130	10	600	-	100	6	-	-	-	-	-
NE NE 26	130	14	1,000	30	110	9	20,750	179			129
NE SW SW 27	128	50	700	30	60	12	26,560	340			245
SE SE 32	110	9	600	12	75	8	16,600	164			118
NW NE 36	77	19	600	45	30	20	44,950	775			558
NW SW 36	68	20	90	2	4	23	43,300	902			650
SW 2-13N-24W	155	30	40	1	20	2	2,500	21	79	50	
SW NE SW 3	140	47	60	1	10	6	9,670	104	132	118	
NE 11	50	8	550	30	46	12	76,360	1,818			1,818
NE NW 12	60	15	1,000	4	15	67	116,200	2,592			2,592
NW 13	97	30	200	48	67	3	13,280	198			198
SW SW 4-13N-23W	157	10	1,000	10	100	10	18,500	126	344	235	
NE SE 7	130	14	650	30	93	7	-	-	-	-	

*1-Total depth is usually indicative of depth to bedrock.
*2-Correction factor assuming 60% well efficiency. Transmissivity units are gpd/ft.
*3-Permeability values from specific capacity only in a modeled reach are adjusted to permeability values for same modeled reach found with $\frac{(1)+(2)}{2}$. Adjustment factors are upper reach 1.0; middle reach 0.72; lower reach 1.03.

TABLE I (Continued)

Location	Total*1 Depth (ft)	Depth to Static Water Level (ft)	Test Yield (gpm)	Test Pumping Duration (hrs)	Test Pumping Drawdown (ft)	Specific Capacity (gpm/ft of Drawdown)	Transmissivity from Specific Capacity T from SC x 1.66 *2	(1) Permeability from Specific Capacity	(2) Permeability from Geologic Log (see class value pg 58)	Average Permeability $\frac{(1) + (2)}{2}$	Average Permeability from Specific Capacity Data Only x Adjustment Factor *3
	Basic Data					Calculated Data					
NW NE C 8	170	10	1,000	10	100	10	18,500	117	257	187	
NE NE SW 8	150	10	1,000	120	60	17	43,330	308	332	320	
SW NW 8	53	13	300	24	38	8	25,000	625	107	366	
SE NW NW 17	131	20	350	10	70	5	9,170	83	181	132	
NW NW NW 17	135	20	250	8	28	9	20,000	182	94	138	
NE 18	130	20	450	24	75	6	16,600	151			151
NW C 7-13N-22W	141	8	600	11	100	6	11,665	87	340	214	
NW SW NE 14	100	6	100	2	50	2	2,500	27	99	63	
SW NW 16	128	10	1,000	30	21	47	116,600	988	278	633	
SE SE 34	96	10	500	3	34	15	23,330	271	254	263	
NE 16-13N-21W	118	18	500	24	100	5	12,450	125			90
NE NE NW 17	60	12							331		331
NE SW NE 10-14N-20W	35	19	400	12	12	33	76,360	4,772			3,436
SW SW SW 21	32	16	200	36	14	15	38,330	2,395	500	1,448	
C 22	89	20	700	24	47	15	38,330	556	159	357	
SW SW 22	77	10	450	24	56	8	16,660	249	107	178	
SW NE NE 28	100	3	477	24	53	9	20,000	206	178	192	
NE NE NW 28	97	24	600	24	43	14	37,500	514	159	336	
NE C 30	140	60	60	1	10	6	9,670	121	72	97	
NE SE SW 34	85	30							500		
SW SE SW 35	92	32	640	27	64	10	34,860	581			418
NW SE 32-13N-17W	191	15	1,000	24	160	7	19,920	113			117

*1-Total depth is usually indicative of depth to bedrock.
*2-Correction factor assuming 60% well efficiency. Transmissivity units are gpd/ft.
*3-Permeability values from specific capacity only in a modeled reach are adjusted to permeability values for same modeled reach found with $\frac{(1) + (2)}{2}$. Adjustment factors are upper reach 1.0; middle reach 0.72; lower reach 1.03.

TABLE I (Continued)

Location	Basic Data: Total*1 Depth (ft)	Depth to Static Water Level (ft)	Test Yield (gpm)	Test Pumping Duration (hrs)	Test Pumping Drawdown (ft)	Calculated Data: Specific Capacity (gpm/ft of Drawdown)	Transmissivity from Specific Capacity T from SC x 1.66 *2	(1) Permeability from Specific Capacity	(2) Permeability from Geologic Log (see class value pg 58)	Average Permeability (1) + (2) / 2	Average Permeability from Specific Capacity Data Only x Adjustment Factor *3
SE NW 32-13N-18W	111	12	600	72	60	10	23,330	236	200	218	
SW SE 32	107	13	650	30	60	11	22,500	239	119	180	
NW SW NW 8-12N-18W	117	12	800	2.5	80	10	16,600	163			168
SE SE SW 29	116	20	310	36	62	5	10,290	107	138	123	
SW 1-12N-17W	110	14	250	24	63	4	10,830	113	131	122	
SW NE SW 3	126	18	980	30	82	12	23,330	216	196	206	
SE NW 4	124	17	650	-	93	7	19,170	180			129
NW 9	52	13	150	40	30	5	10,170	248	268	258	
NE 10	125	12	920	14	115	8	16,600	147			152
SW NE SE 30-12N-16W	44	21	100	1	20	5	8,670	377	78	227	

*1-Total depth is usually indicative of depth to bedrock.
*2-Correction factor assuming 60% well efficiency. Transmissivity units are gpd/ft.
*3-Permeability values from specific capacity only in a modeled reach are adjusted to permeability values for same modeled reach found with $\frac{(1)+(2)}{2}$. Adjustment factors are upper reach 1.0; middle reach 0.72; lower reach 1.03.

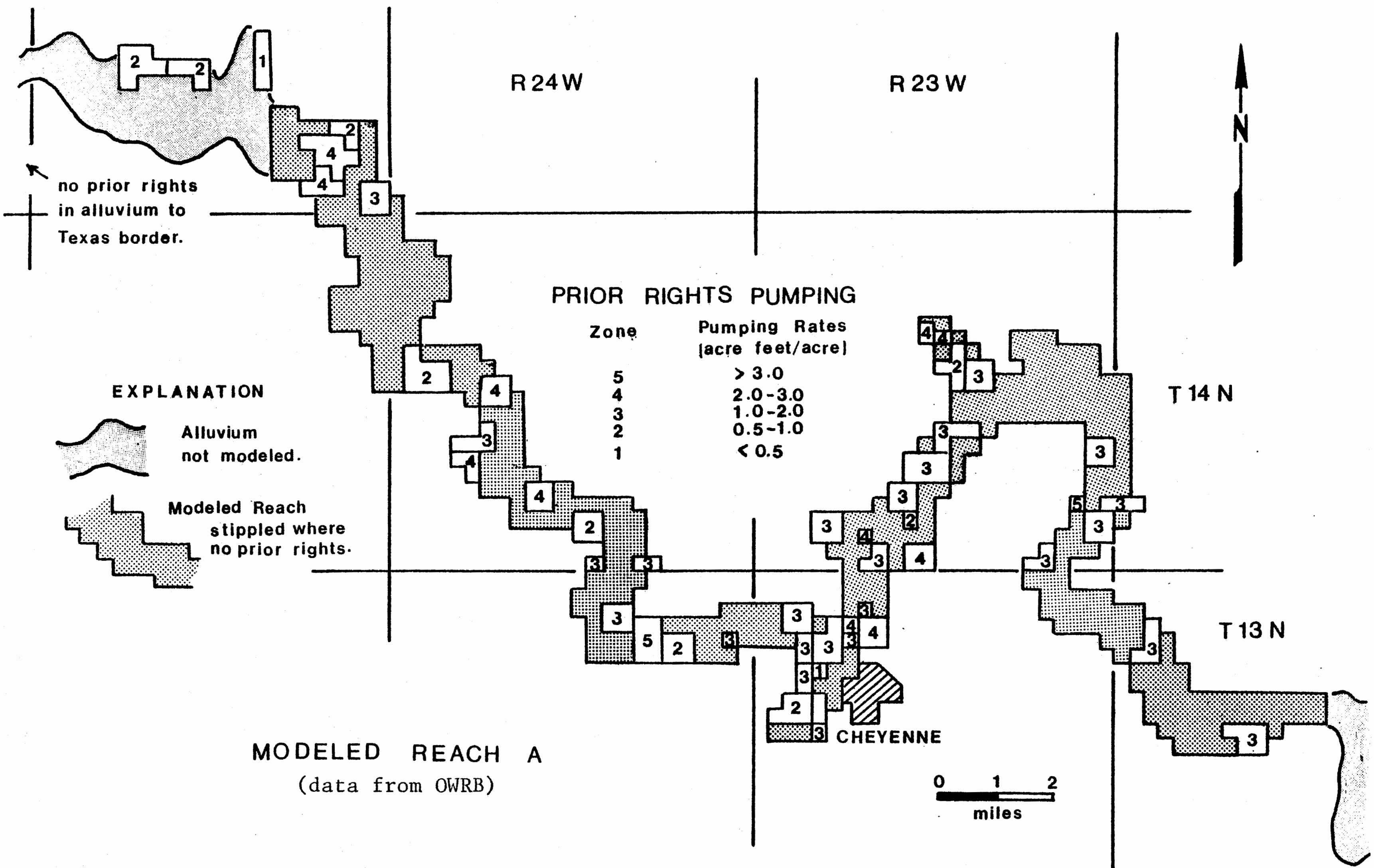


Figure 15. Distribution of Prior Rights Pumping, Upper Modeled Reach (Part A) and Adjacent Areas

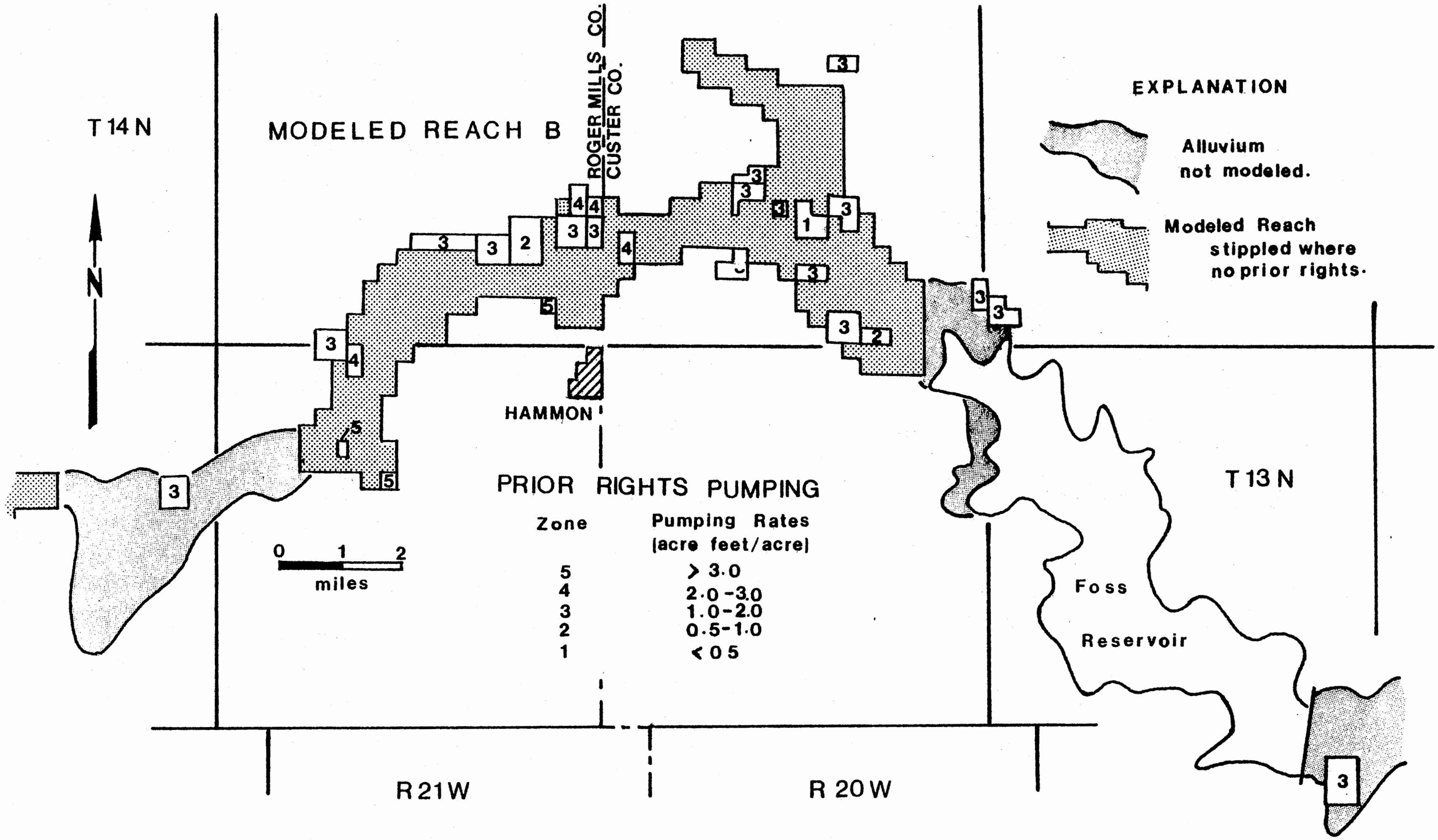


Figure 16. Distribution of Prior Rights Pumping, Middle Modeled Reach (Part B) and Adjacent Areas (data from OWRB)

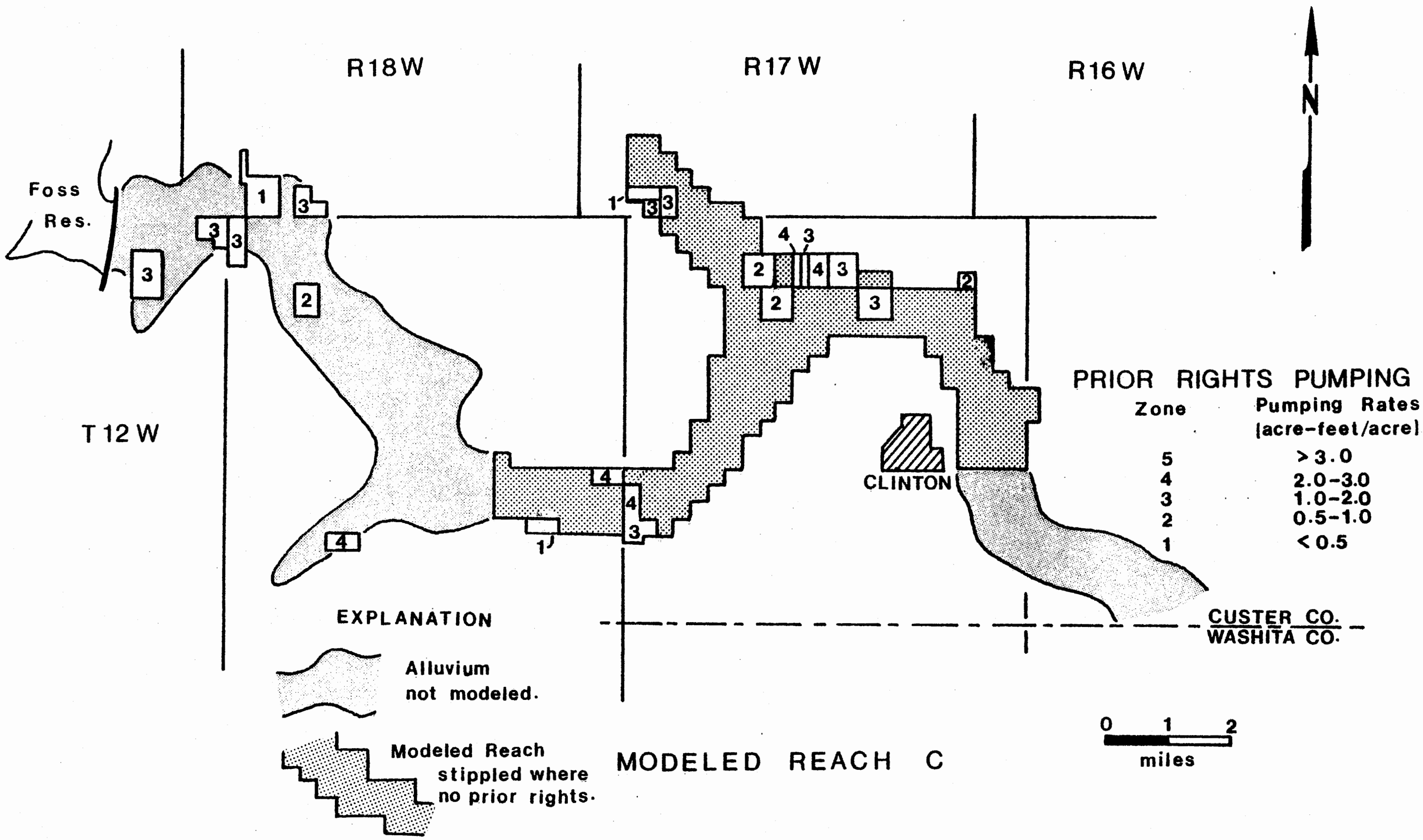


Figure 17. Distribution of Prior Rights Pumping, Lower Modeled Reach (Part C) and Adjacent Areas (data from OWRB)

which makes the average prior right about 1.5 acre foot per acre per year. If the prior rights are distributed evenly over the aquifer by dividing by the area (94 sq mi), the amount becomes 0.3 acre foot per acre per year.

Return flow from irrigation has been estimated at 15 to 25 percent of pumping based on studies by the Oklahoma Water Resources Board and others. A return flow of 15 percent was used for the Washita River alluvium, based on water budget analyses and evapotranspiration estimates.

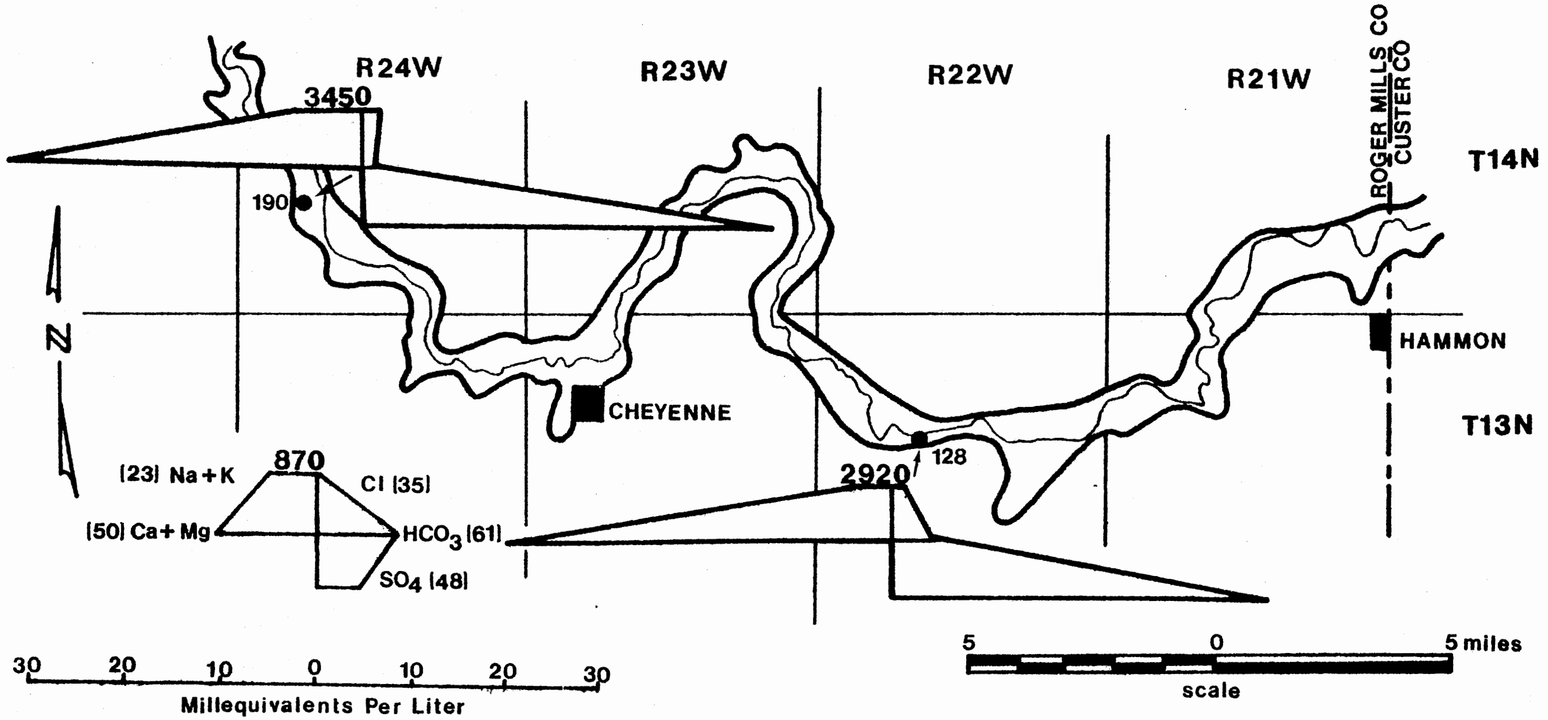
Water Quality

The water quality in the Washita River alluvium is affected by the composition of the underlying bedrock and the alluvium itself. If water from the bedrock is characteristically high in dissolved solids, and if the bedrock contributes appreciable water to the alluvium through upward leakage, then this should be reflected in the water quality of the alluvium. The Cloud Chief Formation underlies the alluvium for most of the study reach except for relatively short reaches near Hammon and Clinton, where the alluvium rests on the Rush Springs (Figure 14). The Cloud Chief contains interbedded gypsum with two gypsum and dolomite members up to eight feet thick identified in the lower part of the formation. The Rush Springs Formation also contains interbedded gypsum. The Weatherford gypsum and dolomite is up to eight feet thick (Fay, 1978) and occurs near the top of the Rush Springs. Quality of runoff which may at times be added to the ground-water storage can also influence the water quality in the alluvium.

Two analyses of water from the Washita River alluvium were included in the Clinton Hydrologic Atlas (Carr et al., 1976). They are presented in Figure 18. Both wells are located in the Cheyenne area; drillers' logs do not mention penetrating redbed in either case. The well northwest of Cheyenne is 190 feet deep and produced water with total dissolved solids of 3450 mg/l. The second well is east of Cheyenne and is 128 feet deep. Coarse sand and gravel were penetrated in the lower 52 feet. It reportedly yielded 1000 gpm upon completion; total dissolved solids were 2920 mg/l. Hardness (Ca + Mg) and sulfate (SO_4) are the main cause of the relatively high values of dissolved solids (Figure 18). The hardness and sulfate are probably related to the gypsum ($CaSO_4 \cdot 2H_2O$) in the underlying Cloud Chief and Rush Springs.

Analyses of 15 water samples from the Cloud Chief Formation (Carr et al., 1976), showed an average dissolved solids of 2850 mg/l. Hardness averaged 1700 mg/l and the average sulfate concentration was 1700 mg/l. Four water samples taken from the Rush Springs Formation in the Washita River basin above Clinton had an average dissolved solids of 2428 mg/l with an average hardness of 1488 mg/l and sulfate concentration of 1416 mg/l. Further east in Caddo County, water quality in the Rush Springs is better, and dissolved solids average about 280 mg/l. The higher dissolved solids in the Rush Springs in the study area is probably due to solution of gypsum in the overlying Cloud Chief. Downward percolation carries the dissolved minerals into the Rush Springs Formation. Gypsum contained in the Rush Springs may also contribute to poor quality.

Quality analyses of water collected from the Washita River at the Hammon Gaging Station have been done by the USGS since 1970. They show that dissolved solids in the river water range from 300 to 2500 mgl;



● 128

Sample Well Locations
Number indicates well depth.

WATER QUALITY DIAGRAMS

Number on top of diagram indicates total dissolved solids in milligrams per liter
Number in brackets is a multiplying factor.
Multiply it by millequivalents to get milligrams per liter.

CHEMICAL ANALYSIS, WATER FROM ALLUVIUM

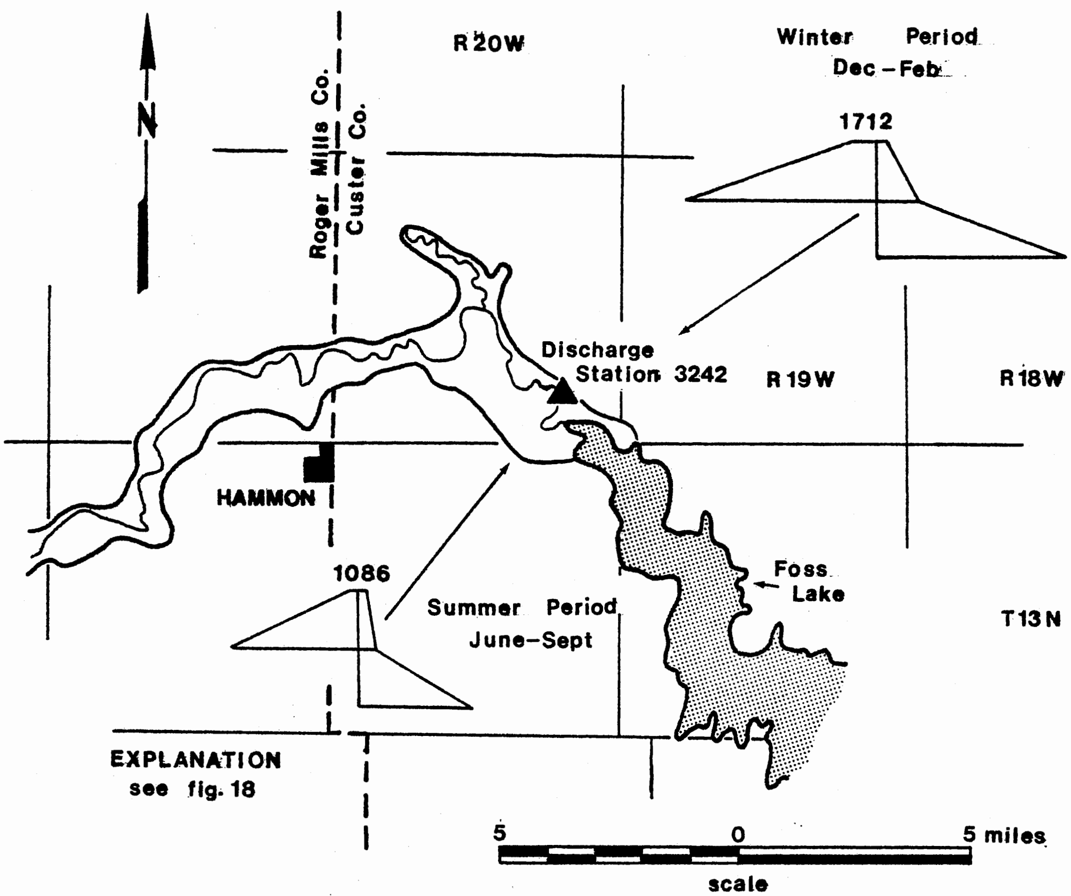
	sw ne sec. 20 T14N R24W depth – 190 ft.	sw nw sec. 16 T13N R22W depth – 128 ft.
Na + K	207	115
Ca + Mg	1900	2000
Cl	70	42
HCO_3	61	244
SO_4	2112	1872
dissolved solids ROE at 180°C	3450	2920

Figure 18. Water Quality Analyses of Water Samples From the Washita River Alluvium Near Cheyenne, Oklahoma (Carr et al., 1976)

the average is about 1400 mg/l. Calcium carbonate ($CaCO_3$) and sulfate (SO_4) are the predominant dissolved minerals.

Chemical analyses of river water for both the winter and summer periods are given in Figure 19. Values are based on ten years of records from 1970 to 1979. Chemical analyses were performed about three times per month, flow permitting. Records from the Hammon Gaging Station indicate that the river water quality changes seasonally. Quality is best from June to September, when concentrations of dissolved solids average about 1080 mg/l. The highest concentrations of dissolved solids usually occur December through February, and average about 1720 mg/l. The seasonal difference suggests that the ground-water component of stream flow is greater during the winter.

The Oklahoma Water Resources Board has set 5000 mg/l dissolved solids as the upper limit for fresh water. This applies to agricultural use. By this standard, water in the Washita River alluvium is fresh. Water in the Cloud Chief and Rush Springs Formations in the study area is also fresh. No analysis of water from the Cloud Chief or Rush Springs Formations in the study area presented by Carr et al. (1976) exceeded the limit of 5000 mg/l dissolved solids.



CHEMICAL ANALYSIS, RIVER WATER

Water Quality Records From 1970 To 1979
Discharge Station 3242
Near Hammon, Ok.

	Winter Period Dec– Feb mean	Summer Period June – Sept mean
Na	75	39
Ca+Mg	1044	740
Cl	40	27
HCO_3	245	169
SO_4	961	598
dissolved solids ROE at 180 C°	1712	1086

Figure 19. Water Quality Analyses of Water Samples From the Washita River Near Hammon, Oklahoma, Showing the Seasonal Effect on River Water Quality (USGS Records from 1970 to 1979)

CHAPTER V

COMPUTER MODELING

Part 1 - Simulation Procedure

General

This study used a two-dimensional finite difference model to simulate the response of the aquifer to pumping stress over a period of time (20 years). The model used was originally written by Pinder (1970) and revised by Trescott, Pinder, and Larson (1976). The model has options for artesian, water-table, or combined aquifers. The water-table version was used for the Washita River alluvium.

Ground-water flow in an unconfined aquifer is described by the following equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\, b\, \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\, b\, \frac{\partial h}{\partial y}\right) = Sy\, \frac{\partial h}{\partial t} + W\,(x,y,t) \qquad (1)$$

where

K_{xx}, K_{yy} = components of permeability

h = hydraulic head

Sy = specific yield of the aquifer

b - saturated thickness of the aquifer

W(x,y,t) = net inflow rate per unit surface of the aquifer

Equation (1) has no general solution. The solution can be approximated, however, with the finite difference method which divides the aquifer region into discrete areas which are treated as points or nodes. Each node is represented by a finite difference approximation with an assigned value of permeability, storage coefficient, and net inflow. The aquifer becomes a set of algebraic equations which are solved simultaneously with the use of a digital computer. Head values in future time, the unknowns, are found by starting with the known head values of each node (initial head). Then, as the program advances into time, the solutions of one time step becomes the knowns, or initial heads, for the next step. Initial boundary conditions must also be specified.

Several finite difference schemes have been developed. The Trescott model (1976) has the option to use SIP (strongly implicit procedure), LSOR (line-successive overrelaxation procedure), or ADIP (alternating direction implicit procedure). This study used the ADIP scheme. For a more complete explanation of the mathematical theory, the reader is referred to Trescott, Pinder, and Larson (1976), Remson, Hornberger, and Molz (1971), or Wang and Anderson (1982).

Matrix Design

The area and boundary of the aquifer were taken from geologic maps of the vicinity and the Hydrologic Atlas for the Clinton Quadrangle (1976). The aquifer was divided into three modeled reaches (Figure 2). They were selected on the basis of well density and the distribution of prior rights. Square nodes, 1/4 mile on a side, having a 1/16 square mile area (40 acres) were used. These could accommodate the narrowness of the alluvium which averages only about one mile wide. A node grid which best fit the natural boundary of the aquifer was constructed (Figures 2, 3, and 4). Allocation rates determined for the modeled reaches have been extended to adjacent, unmodeled areas of the aquifer.

Foss Reservoir is not included in the modeled reaches. A significant amount of water may be entering the alluvium below the dam as seepage underflow. It was assumed, however, that the effect on ground water levels does not extend very far downstream. Local changes in ground-water storage possibly caused by seepage through the dam were considered negligible when compared to the total aquifer ground-water storage in the study area. Also, water-level data are lacking in the area below the dam.

Boundary Conditions

The Washita River alluvium is bounded on its bottom and sides by Permian bedrock. As described earlier, the permeability of the bedrock is quite low when compared to the alluvium. The water table in the bedrock slopes toward the Washita River; therefore under present conditions, water is not lost from the alluvium into the bedrock (Leonard et al., 1958). For the purpose of the model, the Permian bedrock was considered an impermeable or no-flow boundary. Transmissivity values of zero were assigned to bedrock nodes bordering the alluvium and to the bottom of the aquifer.

Data show that the water quality in the alluvium is quite similar to that in the underlying bedrock. This supports the statement by Leonard (1958) that the bedrock water-table gradient is toward the river, and further suggests that some amount of water is being added to the alluvium by upward leakage from the bedrock. In the model, upward leakage is included as a part of recharge.

Constant gradient nodes were placed at the upstream and downstream boundaries of the modeled reach. They allow subsurface inflow and outflow. The calculation of inflow or outflow across the constant gradient boundary is made with the Darcy equation.

$$Q = mKI, \text{ or } Q = TI \tag{2}$$

where

Q = the amount of inflow or outflow

m = saturated thickness of the adjacent node (set at the beginning of each time step)

K = permeability of the constant gradient node

T = transmissivity of the constant gradient node

I = selected change in head from constant gradient node to adjacent node (positive for inflow, negative for outflow)

Equation (2) is a simplification of $Q = K(Wm)\frac{\Delta H}{L}$. The cross-sectional width (W) of the node and the distance between the node centers (L) are cancelled out when using a square node size.

Simulation Period

Each year of simulation was divided into 36 time steps of 10 days each. A time step is the period of time in which the model readjusts water-table elevations in response to recharge to and/or discharge from the system. Each time step requires several iterations to calculate changes in water levels. These calculations are performed for each iteration until the difference between subsequent iterations converges on an arbitrary error factor. The error factor was set at one-tenth of a foot. The limit on the number of iterations in one time step was set at 50.

For the 20-year simulation runs, each year was divided into a four-month pumping period (June 1 to September 30) and an eight-month period where no pumping occurs. Annual pumping was divided evenly over the four-month pumping period.

Computer Runs

The modeling approach used can be broken down into three phases. First, the data and matrices were entered and checked for errors. Then five-year calibration runs were made. The purpose of these was to make adjustments to the system until simulated results matched patterns observed in the actual aquifer. Next, 20-year computer simulation runs of only prior appropriative pumping were made. These show the effect of 20 years' pumping if full prior rights are used. Finally, simulation runs for 20-year allocation/prior appropriative pumping were executed. In these runs, a constant allocation in acre feet per acre per year is assigned to every node in the aquifer. If the allocation rate is greater than the prior rate for a node, then it supercedes the prior rate. If the prior rate is greater than the allocation rate, pumping in that node remains at the prior rate.

Allocation was adjusted until a rate was found that caused 50 percent of the nodes to go dry after a 20-year pumping period (July 1, 1973, to July 1, 1993). A node is considered dry if its saturated thickness is reduced to 5.5 feet or less.

Part 2 - Data Input

Data Input Format

Data input format and model options used are listed below. The several options contained in the program make it possible to simulate diverse hydrologic situations. Options relevant to this study are included below.

Fixed Value:

1. Grid spacing in X-direction (DELX)
2. Grid spacing in Y-direction (DELY)
3. Number of rows in model (DIML)
4. Number of columns in model (DIMW)
5. Number of pumping periods in the total simulation time (NPER)
6. Length of time steps in hours (DELT)
7. Number of days per period (TMAX)
8. Number of iterations per time step (ITMAX)
9. Error criteria for convergence of the mathematical model (ERR)

Adjustable Scalar:

10. Evapotranspiration rate (QET)
11. Depth at which evapotranspiration starts (ETDIST)
12. Allocation rate

Pattern Matrix:

13. River node permeability (RATE)

Non-uniform Matrix:

14. Land surface elevations (LAND)

15. Bottom of aquifer (BOTTOM)

16. Water-table elevations (STRT)

17. Permeability of alluvial material (PERM)

18. Prior appropriative pumping (WELL)

19. Constant gradient nodes (GRAD)

Uniform Matrix:

20. Specific yield (SY)

21. Recharge rate (QRE)

22. Effective distance from river (M)

Computer-generated Non-uniform Matrix:

23. Transmissivity (T)

24. Saturated thickness

25. Bottom river and/or top aquifer (TOP); set from STRT matrix

26. Water elevations in river (RIVER); set from STRT matrix

Assignment of Input Values

Land. The surface elevation of each node was entered into the LAND matrix. This was accomplished by superimposing the node grid onto topographic maps and estimating the elevation for the center of each node.

Drillers' Logs. Water table (STRT) bottom (BOTTOM), and permeability (PERM) were found with information contained in drillers' logs obtained from the Oklahoma Water Resources Board. There were 102 logs on file for the study area. The logs were made by the driller as the well was drilled, completed, and tested. They contain lithologic description of the material encountered during drilling. Also included are well completion details such as casing size, perforation intervals, and gravel pack. Additionally, most logs have well yield information. They give a duration and rate of pumping and the resultant drawdown. From this, specific capacity can be found. Specific capacity is the number of gallons per minute a well can produce for each foot of drawdown. Water-well data from the drillers' logs are summarized in Table I.

Water Table and Bottom. Within a given year, some change in water-table elevation may occur in response to such factors as precipitation, pumping, and evapotranspiration. Greater changes may result if there are several consecutive dry years or if irrigation use is heavy for a period of years. Water-level elevations were taken from drillers' logs which were filled out at the time a well was completed (Table I). Consequently, there is a lack of recorded water-level data for a specific period of time. Because the data span several years, average water levels were plotted and contoured. The resulting water-table contour map represents a span of time during which it was assumed that an approximate equilibrium existed between inflow and outflow.

An initial water level was assigned to each node by estimating the water-table elevation. The water-level elevations were entered into the STRT matrix. The initial water-table configuration, July 1, 1973, is shown in Figures 20 and 21.

Many of the geologic logs for wells in the study area reported the depth at which redbed was encountered. These were plotted and a contour map of the redbed surface underlying the alluvium was made. Average bedrock elevation of each node was entered into the BOTTOM matrix. Bedrock contour maps of the three modeled reaches are shown in Figures 22 and 23.

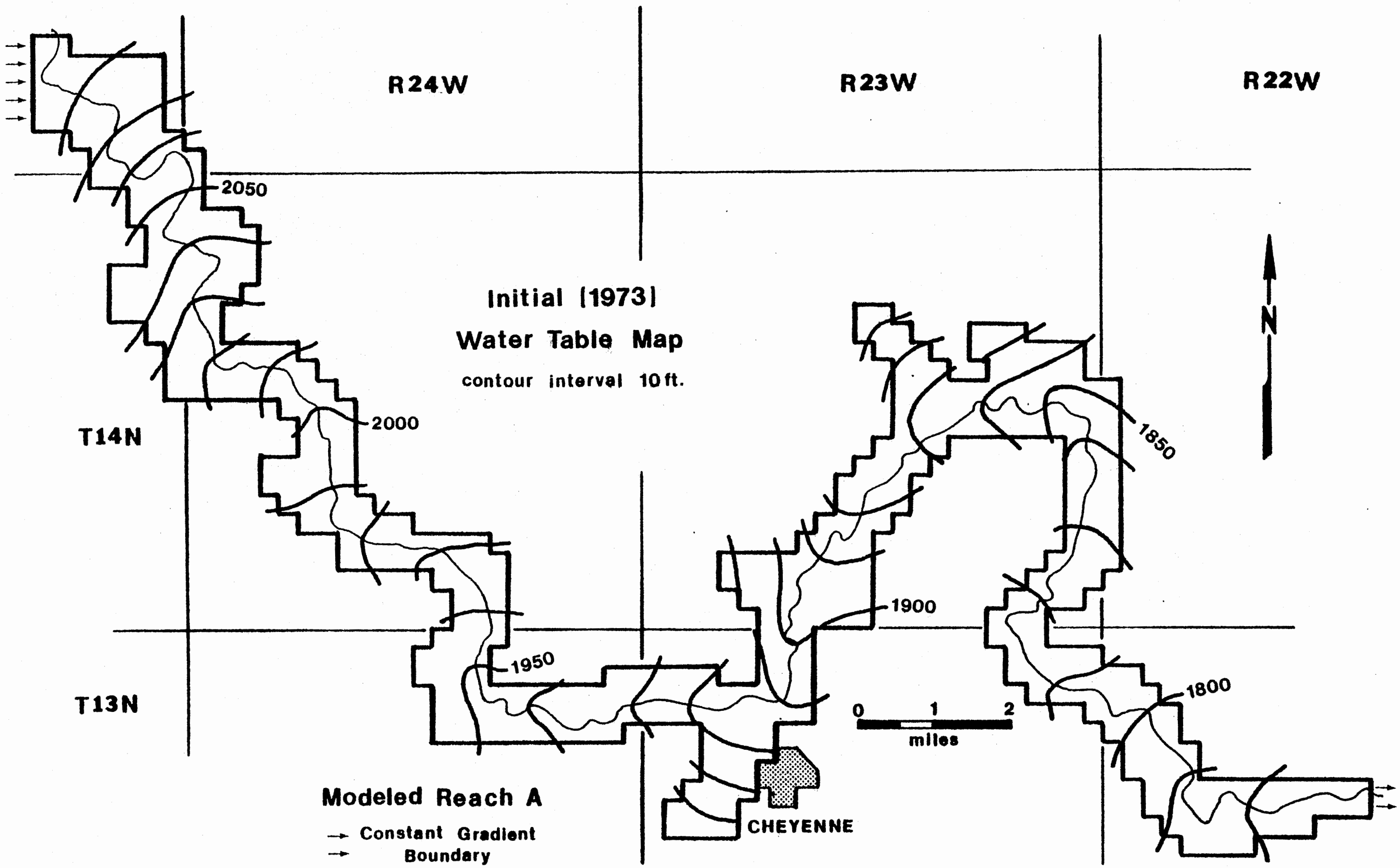


Figure 20. Water Table Map, July 1, 1973, Upper Modeled Reach (Part A) (from Drillers' Logs, Table I)

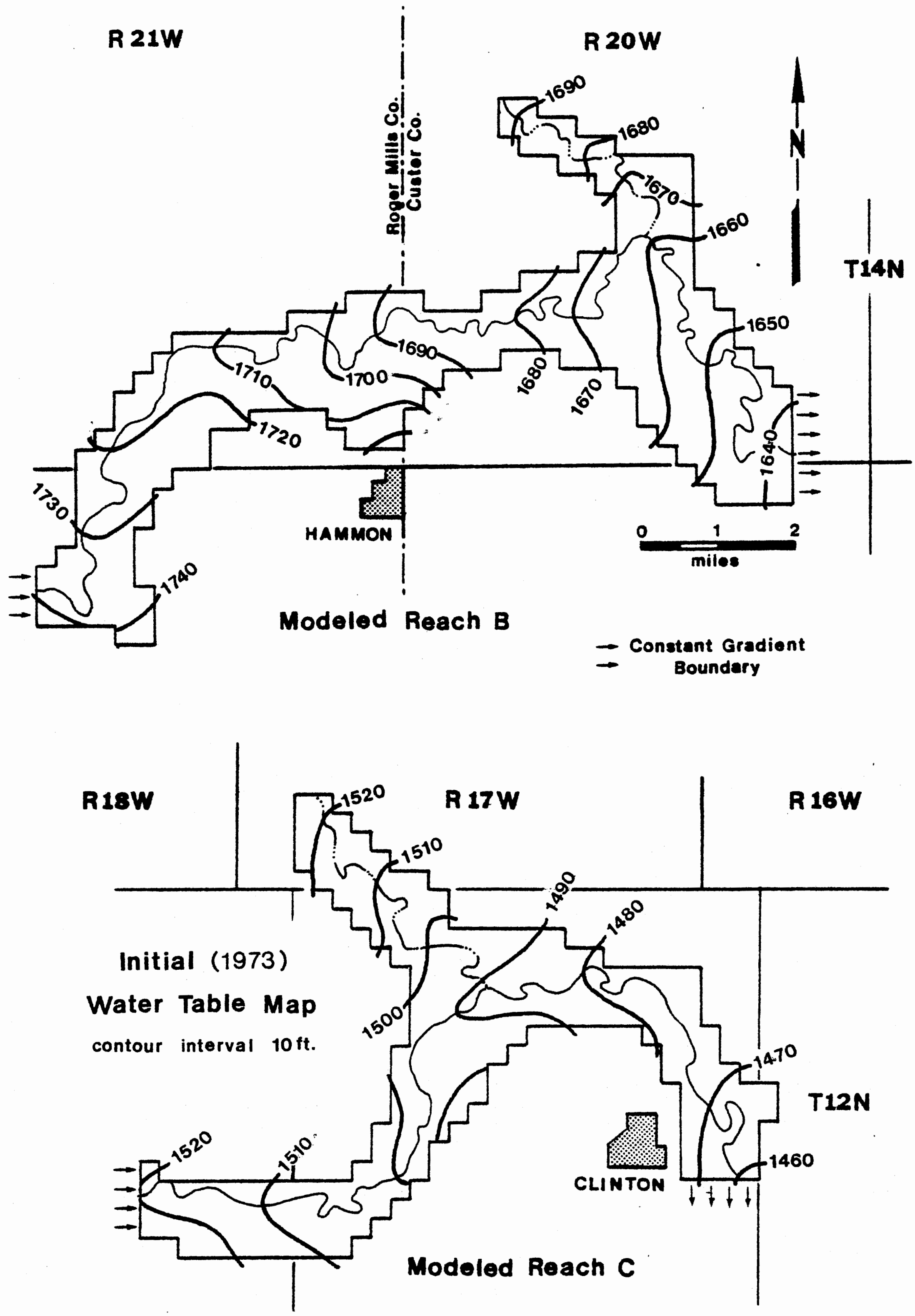


Figure 21. Water Table Map, July 1, 1973, Middle and Lower Modeled Reaches (Parts B and C) (from Drillers' Logs, Table I)

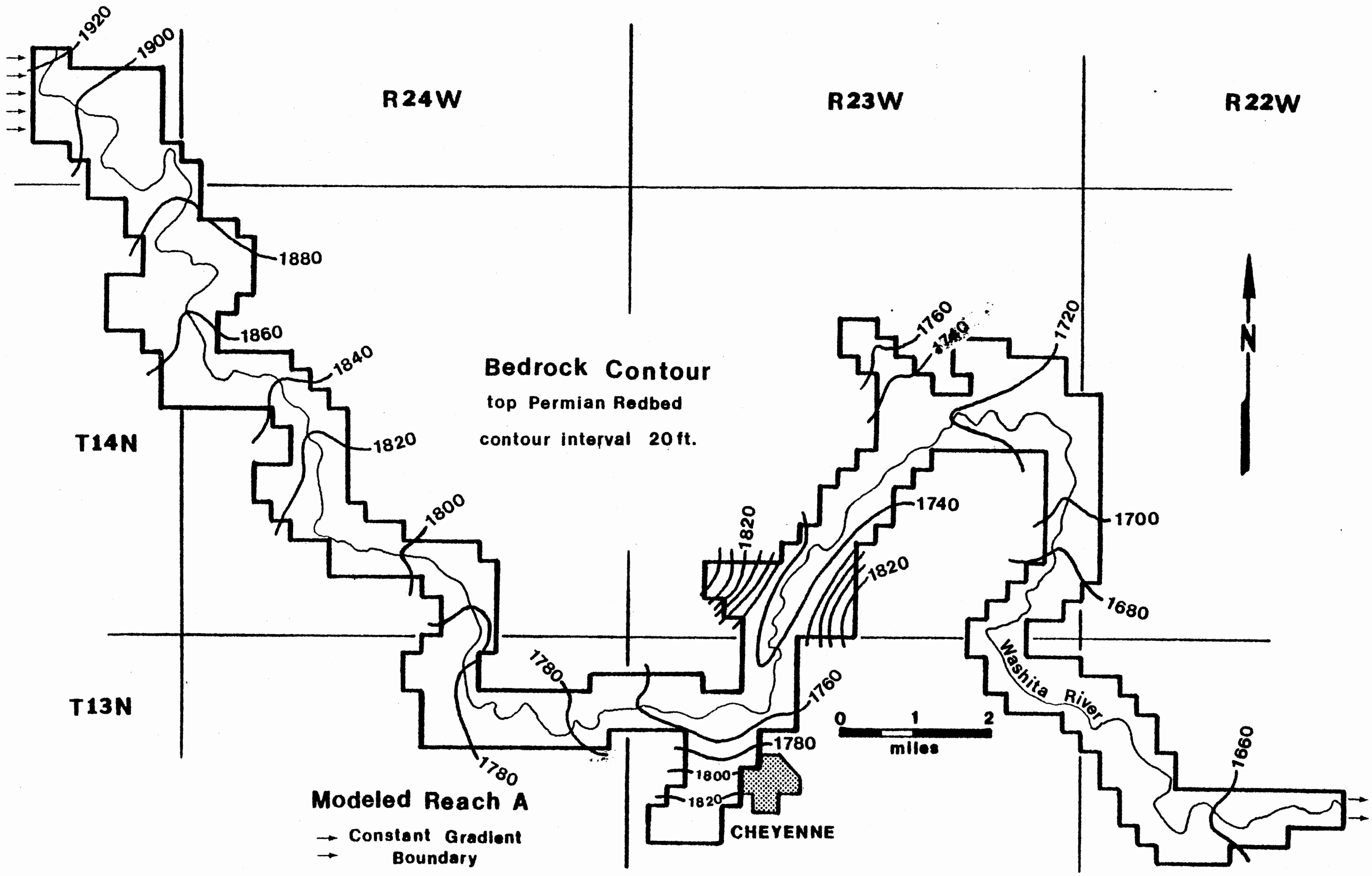


Figure 22. Bedrock Contour, Top Permian Redbed, Upper Modeled Reach (Part A) (from Drillers' Logs, Table I)

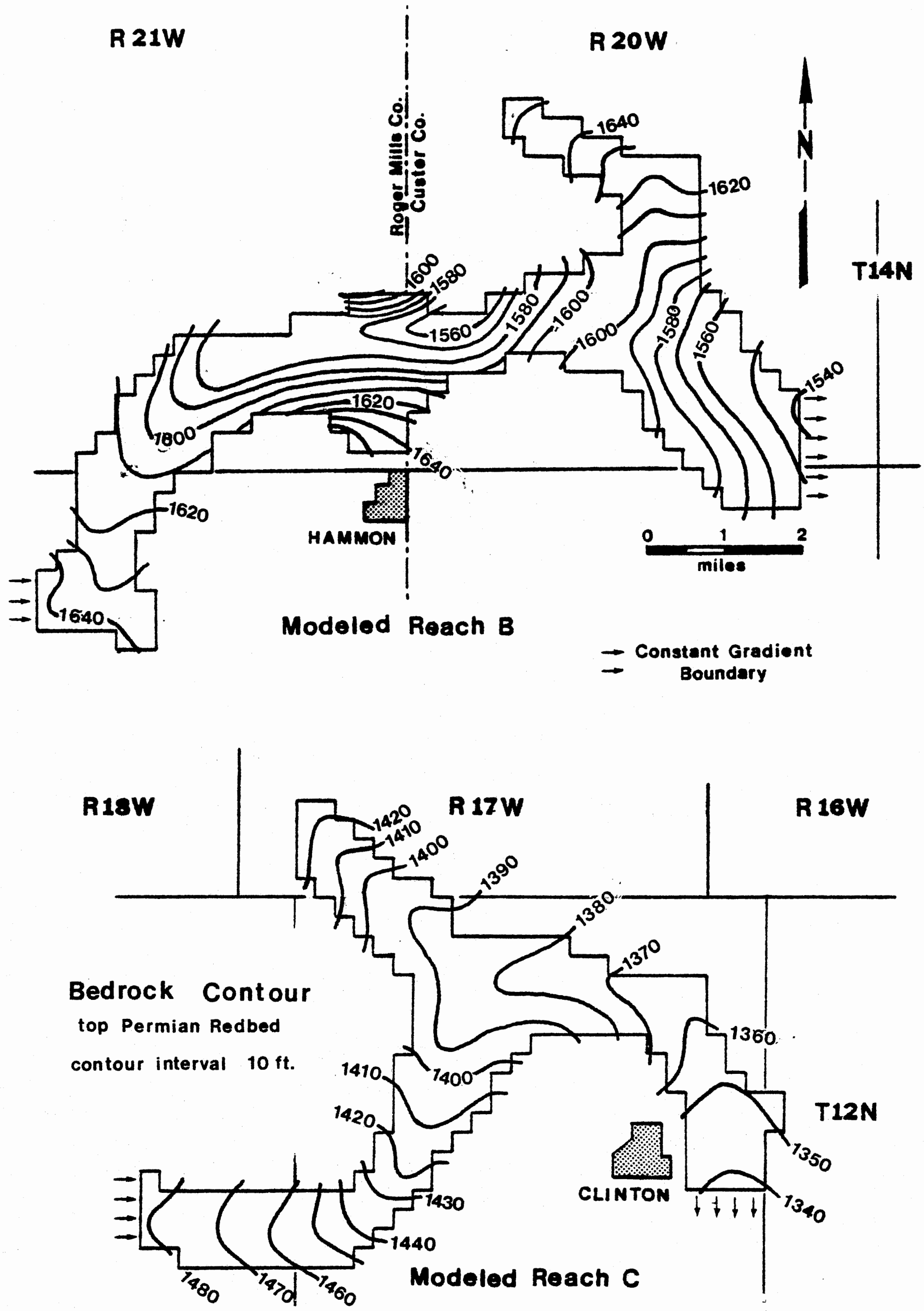


Figure 23. Bedrock Contour, Top Permian Redbed, Middle and Lower Modeled Reaches (Parts B and C) (from Drillers' Logs, Table I)

Permeability (K). Generally, aquifer properties of permeability and storage coefficient are determined by running aquifer tests. Most commonly, a well is pumped for a period of time at a constant rate and the changes in drawdown in the pumped well and nearby wells, through time, are noted. Several techniques can be used to find permeability and storage coefficient from the data (Lohman, 1972).

Aquifer test data for the alluvium in the study area were not available. Therefore, determination of permeability was made with information contained in drillers' logs. Two methods were used. Walton lists an equation which relates a well's specific capacity to transmissivity. Transmissivity divided by saturated thickness equals permeability. Another method developed by Kent et al. (1973) shows the relationship between grain size of the aquifer material and permeability.

Permeability (K) From Specific Capacity. The equation presented by Walton to find transmissivity from specific capacity is:

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

where

$\frac{Q}{s}$ = specific capacity in gpm/ft drawdown

Q = discharge in gpm

s = drawdown in feet

T = coefficient of transmissivity in gpd/ft

S = storage coefficient, fraction

r_w = nominal radius of well, in feet

t = time after pumping started, in minutes

Specific capacity data were taken from drillers' logs and are included in Table I. A graphical method (Walton, 1970) was used to solve Equation (3) and is shown in Figure 24.

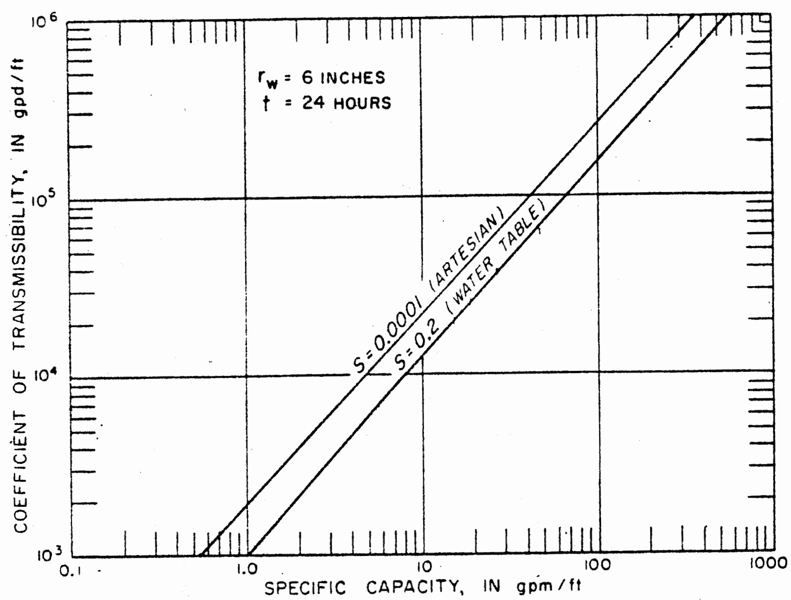


Figure 24. Graphs of Specific Capacity vs Coefficient of Transmissibility for a Pumping Period of 24 Hours (from Walton, 1970)

Equation (3) assumes one hundred percent well efficiency. Well completion methods and pumping rates for wells in the Washita River alluvium and the author's experience suggest that sixty percent would be a reasonable estimate of average well efficiency. Therefore transmissivity values found with Equation (3) were divided by 0.60. The method presented above was used to estimate permeability for wells that had specific capacity data. Values are shown in Table I.

Permeability (K) From Geologic Log. Lithologic descriptions from drillers' logs were used to estimate permeability. The aquifer material is grouped into permeability classes. Each class corresponds to a range in grain size as shown below. The same information is shown graphically in Figure 25.

Class	Permeability Range, gpd/ft^2	Type Material
1	1- 10	silt and clay
2	10- 70	very fine to fine sand
3	70- 300	fine to medium sand
4	300-1500+	medium to coarse sand, sand and gravel

The first step in finding the average permeability for a well is to assign each lithologic interval to its proper class. Only saturated material is included. The thickness of each class is summed and then divided by the total saturated thickness. The resulting fraction is multiplied by the permeability of the respective class. The average permeability is found by summing the answers of each respective class. Note the following example for a well at T15N-R25W-Sec. 35, NE SE NE northwest of Cheyenne:

Class	Thickness (ft)		Total Saturated Thickness (ft)		Fraction of Saturated Thickness		Assigned Class Value (gpd/ft^2)		
1	40	÷	216	=	.185	x	1	=	.185
2	49	÷	216	=	.226	x	20	=	4.5
3	87	÷	216	=	.402	x	115	=	46.3
4	40	÷	216	=	.185	x	500	=	92.6
					Average permeability			=	144 gpd/ft^2

Assigning respective class values of permeability can be done by finding wells within the study area which have both lithologic logs and aquifer test results. The class values are adjusted until the

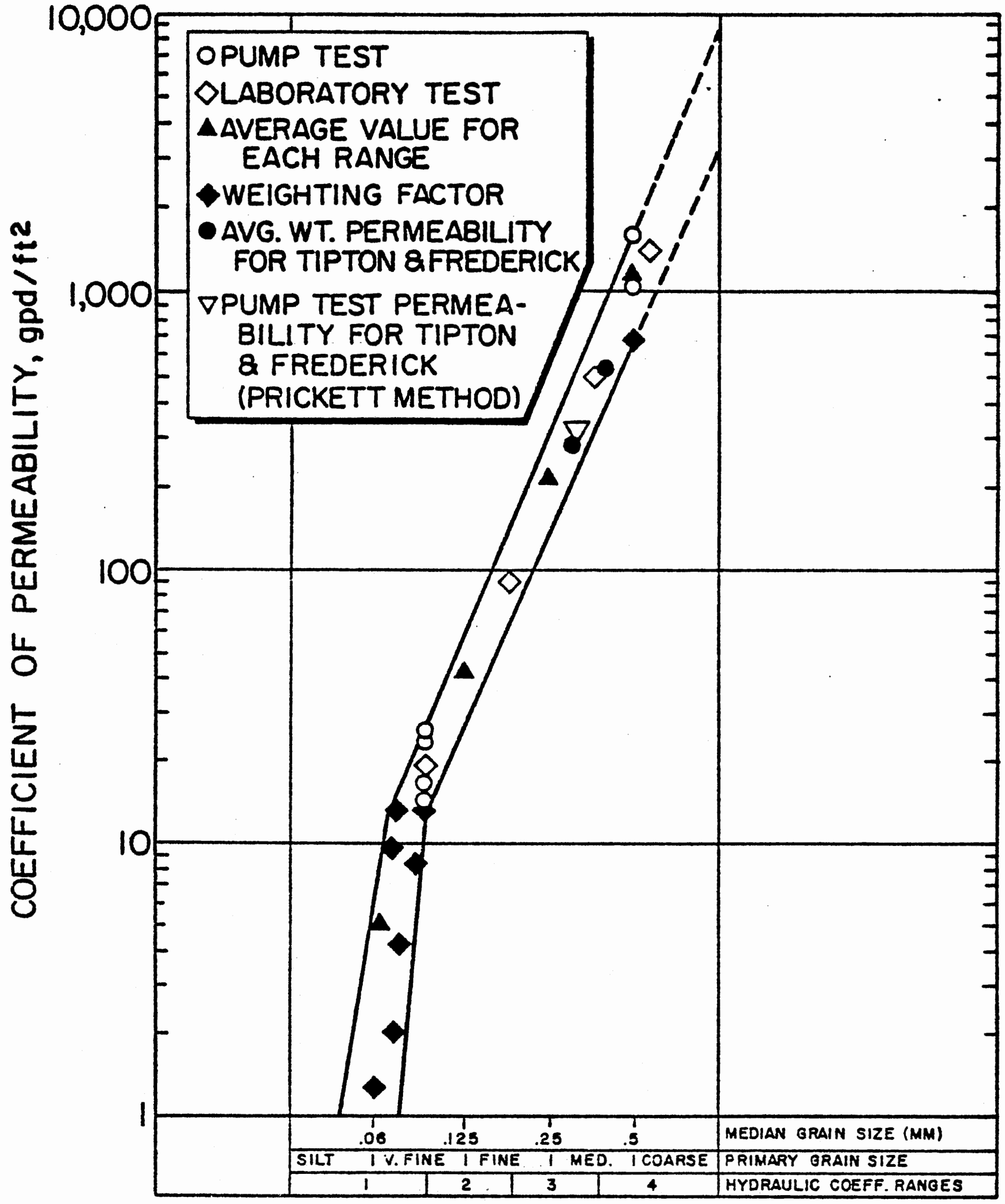


Figure 25. Coefficient of Permeability versus Grain-Size Envelope (Kent et al., 1973)

permeabilities approximate those found with aquifer test data. Aquifer test data for wells in the study area were not found, but most wells did have specific capacity data. Class values were determined by adjusting to permeabilities found with specific capacity data. The assigned class values used in this study are shown below.

Class	Permeability (K) gpd/ft^2
1	1
2	20
3	115
4	500

Assignment of Permeability (K). If the data for a specific well included both a lithologic log and specific capacity, then two values of permeability were found by using the methods described above. The average of the two was used for permeability of the well. Some wells had only specific capacity data. For these, a permeability based on specific capacity was determined and then adjusted to the average permeability of wells with both lithologic logs and specific capacity for a modeled reach. Specific capacity data and the resulting estimates of permeability are included in Table I. The correction factors used to adjust permeability values calculated with specific capacity data only are also shown.

Permeability values were plotted and contoured. The average permeability of each node was entered into the PERM matrix. Maps showing the distribution of permeability are presented in Appendix F. Maps of initial transmissivity, July 1, 1973, are shown in Appendix G.

Specific Yield. Johnson (1969) studied the relationship between grain size and specific yield. Kent (1978) used the relationship between grain size and permeability to modify Johnson's results so that specific yield could be correlated with permeability data from the Washita River alluvium (Kent, 1973). The value of specific yield for a modeled reach was determined from the relationship between permeability and specific yield (Figure 26). The specific yield was based on the average permeability of the modeled reach. The value of specific yield was entered as a uniform matrix. Aquifer test data were not found for any wells in the study area. As a result, specific yield values were not determined with aquifer test data. The values used are listed below:

	Permeability gpd/ft^2	Specific Yield %
Upper modeled reach (A)	239	26.6
Middle (B)	333	27.5
Lower (C)	229	25.0
Entire area (average)	257	26.3

Part 3 - Calibration

General

Calibration of the ground-water model is achieved when the values of inflow and outflow produced in simulation approximate those estimated with collected data. Recharge is the principal source of inflow to the aquifer. Major components of outflow are pumping and ground-water discharge to the river as base flow. Adjustments to modeled recharge and modeled base flow to the river were made during the calibration process so that an approximate balance between inflow and outflow was produced. Base-flow was estimated with stream-flow records. Pumping rates were based on prior appropriative rights supplied by the Oklahoma Water Resources Board. Recharge was found through calibration of the model.

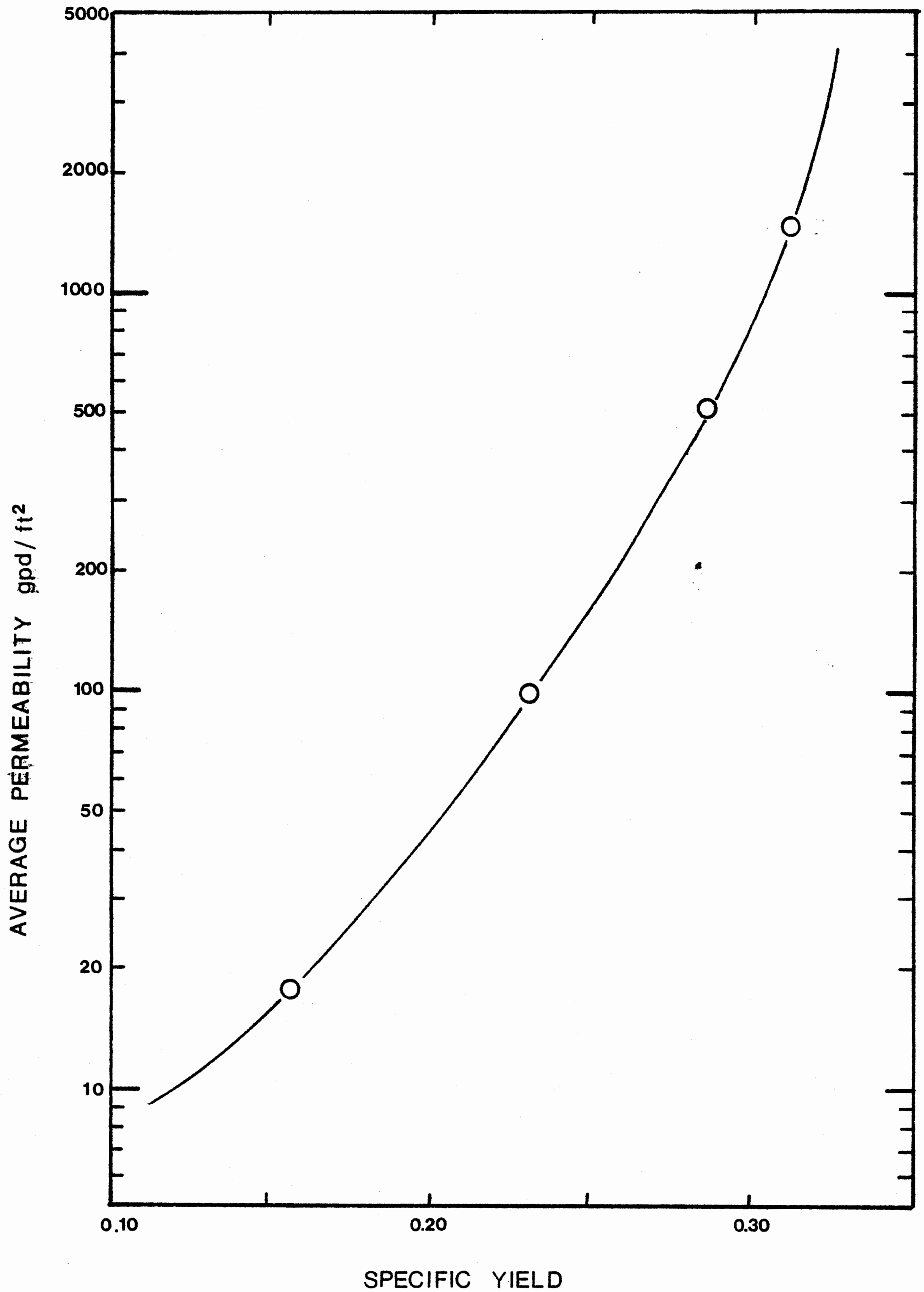


Figure 26. Relationship Between Permeability and Specific Yield (from Kent, 1978)

Recharge. Recharge to the alluvium in the study area probably occurs as direct infiltration of precipitation and as upward leakage from deeper bedrock zones less evapotranspiration. Leonard (1958) has identified the Washita River in the study area as a gaining stream. The similarity of water quality in the alluvium and underlying bedrock also suggests upward leakage.

In an undeveloped alluvial aquifer drained by a gaining stream, that is, a stream gaining flow from ground-water discharge, an equilibrium between net recharge and base flow usually exists. Base flow is the ground-water component of stream discharge. If equilibrium exists, ground-water storage remains constant. When a significant amount of ground water is being removed from the aquifer by pumping, however, a loss in stored ground water accompanied by a decline in base flow to the river may occur. For calibration purposes, the net ground-water recharge is assumed to be equivalent to the amount of water discharging from the aquifer as ground-water flow (base flow) to the river plus that being removed by pumping. The described relationship between net recharge and base flow can be stated simply as:

$$\text{net recharge} + \text{irrigation return flow} - \text{base flow} - \text{pumping} = \Delta\ \text{storage} \quad (4)$$

where:

$$\text{net recharge} = \text{natural infiltration} + \text{bedrock leakage} - \text{evapotranspiration} \quad (5)$$

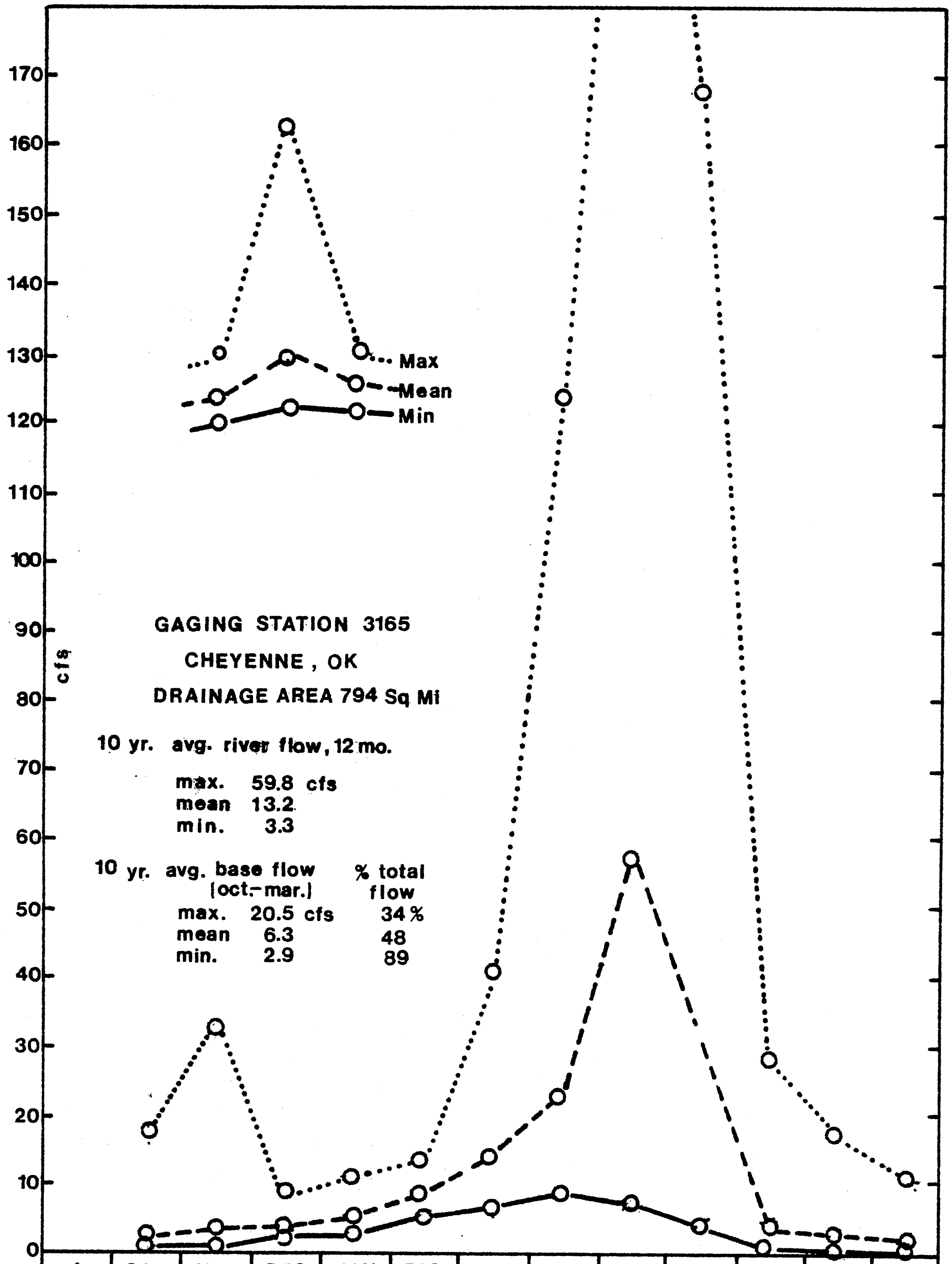
Subsurface inflow and outflow are assumed to be similar and therefore are not considered to be significant in the calibration.

For calibration, simulated pumping was set at one-half the prior appropriative rate. Pumping was adjusted automatically in the model to reflect a fifteen percent return flow. Base flow was initially determined from stream-flow records. During calibration, net recharge was adjusted until the simulated base flow agreed with that estimated using stream flow records [see Equation (4)]. For calibration it was assumed that no net change in storage occurs. This would meet the assumed condition of equilibrium (steady-state). A small loss in stored ground water did result from calibration.

Base flow at Cheyenne and Hammon was calculated with stream flow records for the period from 1970 to 1979. Clinton was not used because flow is regulated by Foss Reservoir. The 10-year monthly average of maximum, mean, and minimum flow for six winter months (October-March) was found. Then, mean and minimum flow for the winter period was calculated. The model was adjusted so that modeled base flow fell close to mean winter flow. Winter flow was used to estimate base flow because during that time of year most of the river flow is from ground-water discharge. Direct runoff is usally small in winter because precipitation is low (Figure 11). Additionally, irrigation pumping does not occur in winter months so base flow is not directly affected by pumping. Evapotranspiration is also less in winter. Figure 27 shows the monthly flow at Cheyenne (1970-79). The base flow from mean monthly winter flow was 6.3 cfs; the base flow from minimum monthly winter flow was 2.9 cfs.

Only the alluvium was considered as the source of base flow to the river. Some base flow is probably derived from bedrock leakage, but it must pass through the alluvium to get into the river and therefore it was not included as a separate source. The area over which base flow, recharge, and pumping is distributed is the area of the alluvium only.

The following equations were used to find the base flow in acre



cfs	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Max	17.0	33.4	7.52	11.2	13.8	40.1	123.4	247	16 9	27.9	16.7	10.5
Mean	1.15	41 0	4.04	5.4 1	8.37	14.7	23.0	57.6	32.7	3.95	2.34	1.34
Min	0.24	0.78	2.42	2.19	5.41	6.45	9.1	6.93	4.52	0.5 8	0.28	0.27

Figure 27. Maximum, Mean, and Minimum Monthly Flows Based on Ten-year Record (1970-1979)

feet/year contributed over a modeled reach:

$$\frac{\text{Drainage area above gaging station (sq mi)}}{} \times \frac{640 \text{ acres}}{\text{sq mi}} \div \frac{\text{Drainage basin area}}{\text{alluvium area}} = \text{Area in acres of alluvium above gaging station} \quad (6)$$

$$\text{Base flow (cfs) from gaging station records} \times 714.05 \text{ acre ft/yr} \times \frac{\text{area of modeled reach}}{\text{area of alluvium above gaging station}} = \text{Base flow ac ft/yr for modeled reach} \quad (7)$$

For the Cheyenne gaging station (upper modeled reach):

$$794 \text{ sq mi} \times \frac{640 \text{ ac}}{\text{sq mi}} \div 17.4 = 29{,}205 \text{ acres} = \text{aquifer area above Cheyenne}$$

$$\begin{matrix}6.36 \text{ cfs}\\ \text{mean base flow}\end{matrix} \times \frac{714.05 \text{ ac ft/yr}}{\text{cfs}} \times \frac{19960 \text{ ac}}{29205 \text{ ac}} = \begin{matrix}3075\\ \text{ac ft/yr}\\ \text{or}\\ 4.25 \text{ cfs}\end{matrix} = \text{mean base flow contributed by the modeled reach}$$

Base flow for the area above Cheyenne calculated with mean winter flow at Cheyenne, Oklahoma, was 6.3 cfs, which is 47 percent of the 10-year (1970-79) mean yearly discharge, 13.8 cfs. Final calibration of the same reach resulted in a base flow of 7.9 cfs or 60 percent of mean yearly discharge.

Net recharge was found through calibration of the model. Pumping values were set at one-half prior rights. Recharge was adjusted until simulated base flow was close to that estimated with stream flow records. Net recharge values are shown below. Average precipitation in the study area is about 25 inches per year. Net recharge values used in simulation fell between 12-13 percent of total precipitation.

Modeled Reach	Upper (A)	Middle (B)	Lower (C)
Avg. Prec. in./yr	23.5	24.7	27.0
Recharge Rate in./yr	3.0	3.2	3.4
% Prec.	12.8	12.9	12.6

Model River Option

To simulate ground-water flow to the river, the river option contained in the program was used. A separate matrix, RATE, was entered with a node pattern that approximated the course of the river.

Modeled flow into the river is governed by the Darcy equation. Consequently, the amount of ground water that enters the river is dependent upon thickness, perimeter area, and permeability of the river bed as well as the ground-water gradient to the river. These can be adjusted in the model, within reasonable limits, until base flow falls within the desired range.

River elevation (RIVER) in a river node is set equal to the water table elevation of that node. At the beginning of the simulation period, the water table, STRT, and the river elevation, RATE, are equal in the river nodes. River-node elevation remains constant through time, although the water-table elevation in corresponding nodes is free to move. At the end of a time step, the portion of ground water that has moved into the river nodes and lies above the river elevation is removed as base flow. If the water table in the aquifer is lowered, gradient to the river decreases and base flow to the river decreases. If the water table falls below the river, ground-water flow into the river is stopped by the program. When this occurs, the program allows no flow from the river to ground-water storage. If the water table is below the river bed, the river would not be a significant source of water. Initial calibration runs gave base flow greater than estimated with stream flow records. To restrict flow into the river nodes, river bed thickness was increased and area reduced. Subsequent calibration runs showed that a reduction in the base flow had occurred but it was found that too much restriction caused water to collect in nodes adjacent to the river. This was accompanied by increased evapotranspiration and a base flow that increased from year to year. With further calibration, values of river bed thickness, area, and permeability were determined which allowed the river to accept flow without problems.

Flow could also be adjusted by raising or lowering the river-water elevations. This also changed the initial water-table elevation in nodes corresponding to the river. Raising the river lessened the gradient to the river and decreased flow. Lowering the river elevation produced the opposite effect.

Calibration Results

The annual discharge of the Washita River at Cheyenne, Oklahoma, from 1930 to the present is shown in Figure 28. River discharge was decreased significantly even though precipitation has remained relatively constant (Figure 10). The cause has probably been irrigation pumping. Stream-flow records show the greatest change occurred in the late fifties and early sixties. Additionally, stream-flow records suggest that related changes, including a decrease in stream base flow and loss in stored ground water may be occurring.

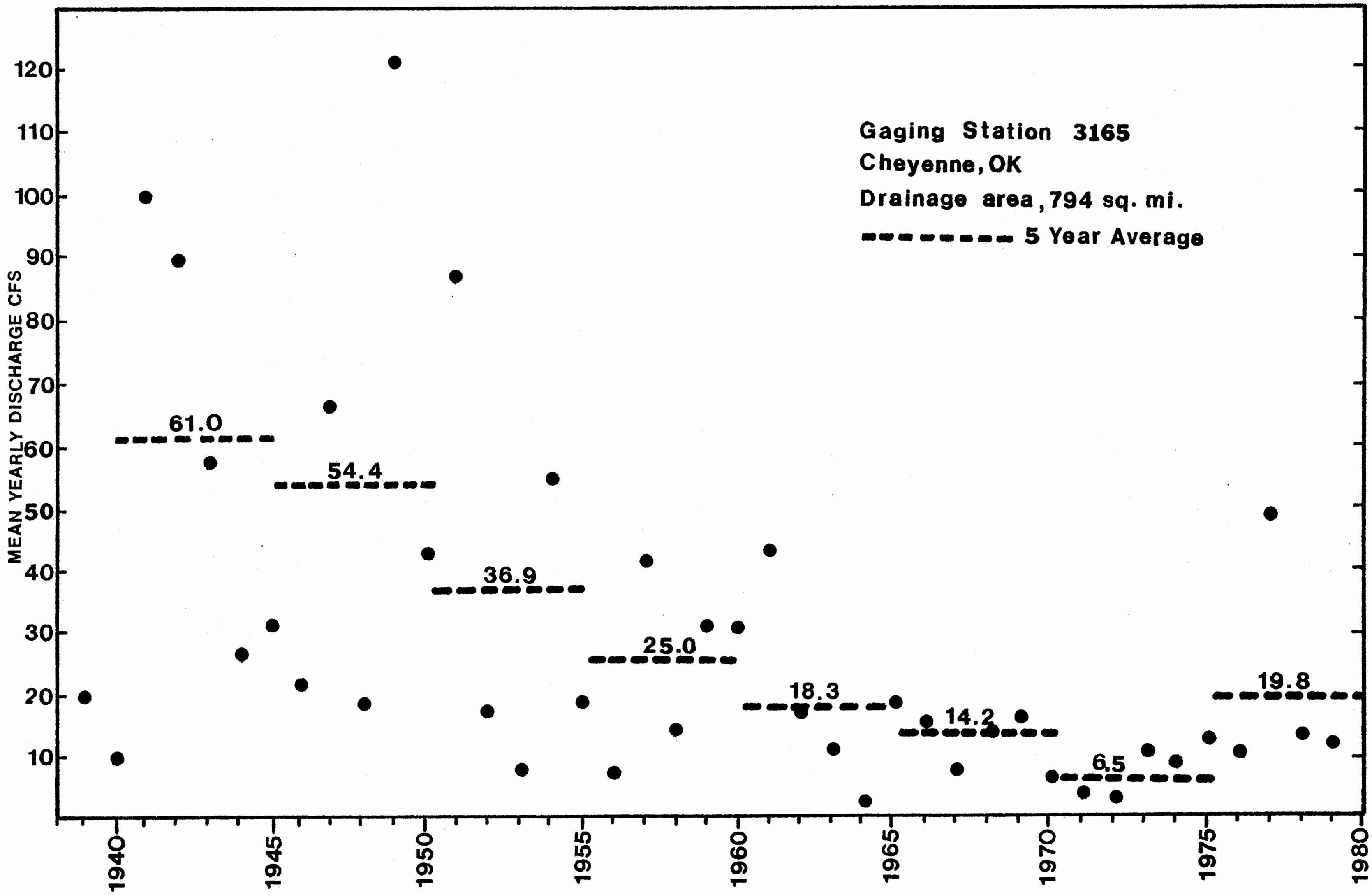


Figure 28. Mean Yearly Discharge of the Washita River at Cheyenne, Oklahoma, 1939-1980

A 5-year period was used for final calibration. With pumping set to one-half prior rights, a recharge amount was found that produced a base flow which agreed with that estimated from stream flow records. The calibration mass balance showed a net low in stored ground water. This suggests that some amount, perhaps up to 0.15 ac ft/ac/yr is being removed from storage by prior rights pumping. Removal of water from ground-water storage by irrigation pumping is probably a significant factor in the decline in stream flow at Cheyenne, Oklahoma. In the full allocation runs, ground-water flow to the river stopped after less than two years simulated pumping due to lowering of the water table below the river. At prior appropriative pumping rates, however, ground-water flow into the river continued at a reducing rate through the 20-year simulation period. Calibration run input and resulting base flow and evapotranspiration values for the upper modeled Reach (A) are shown in Table II. Calibration of the Middle (B) and Lower (C) reaches showed similar results.

TABLE II

UPPER MODELED REACH (Part A), CALIBRATION

	RIVER PARAMETERS				Time From	INFLOW		OUTFLOW		714.05 a.f.yr ≙ 1 c.f.s.		
Run	Bed K gpd/ft^2	Bed Th. ft.	Bed Area Factor*1	Δ River Elev.	Initial (1973) Years	S.I.*2 a.f.yr.	Recharge a.f.yr.	S.O.*3 a.f.yr.	Pumping a.f.yr.	Baseflow a.f.yr.	ET a.f.yr.	Δ Storage a.f.yr.
1	250	100	.075	0	1	279	4990	-111	-4105	-8063	-111	-7137
					2	274	4990	-112	-4105	-5424	-84	-4471
2	250	100	.02	0	1	279	4990	-112	-4105	-6122	-183	-5252
					2	274	4990	-112	-4105	-5174	-152	-4278
3	250	330	.02	0	1	279	4990	-112	-4105	-3378	-298	-2625
					2	274	4990	-113	-4105	-3920	-344	-3217
4	250	330	.075	+1	1	279	4990	-112	-4105	-4419	-329	-3695
					2	275	4990	-113	-4105	-4399	-324	-3675
5	250	330	.02	+1	1	279	4990	-112	-4105	-2255	-439	-1642
					2	275	4990	-113	-4105	-3100	-540	-2594
6	125	330	.02	+1	1	279	4990	-112	-4105	-1347	-489	-784
					2	275	4990	-113	-4105	-2100	-684	-1740
7	250	330	.075	+1	1	279	4990	-112	-4105	-4455	-254	-3656
	(Chosen as final calibration)				2	275	4990	-113	-4105	-4465	-225	-3642
					3	270	4990	-113	-4105	-3830	-196	-2982
					4	268	4990	-113	-4105	-3392	-169	-2520
					5	264	4990	-113	-4105	-3084	-150	-2196
8	250	330	.075	+1	1	279	8317	-112	-4105	-5563	-296	-1479
					2	276	8317	-113	-4105	-6360	-311	-2297
					3	272	8317	-113	-4105	-5972	-306	-1906
					4	270	8317	-114	-4105	-5648	-295	-1575
					5	267	8317	-113	-4105	-5405	-382	-1320

*1 River area factor

$\frac{\text{width river}}{\text{width node}}$ x area node

$\frac{100 \text{ ft}}{1320 \text{ ft}} = .075$

.075 x area node = area river bed per node

*2 Subsurface Inflow

*3 Subsurface Outflow

CHAPTER VI

RESULTS

Prior Appropriative and Allocation Pumping

The final 20-year simulation was conducted for the 1973 to 1993 period for both prior pumping and allocation plus prior pumping for each sub-area. After full prior pumping for 20 years, the simulated drawdown in the study area was 8.8 feet. This is a 7.5 percent reduction in saturated thickness from the 1973 average saturated thickness for the study area of 118 feet. The water table configuration at the end of 20 years' prior pumping, July 1, 1993, is shown in Appendix K.

Irrigation allocation rates were determined for each modeled reach. Maximum annual yield was found by adjusting the amount of allocated pumpage so that 50 percent of the nodes would go dry by the end of the simulation period (20 years). When the saturated thickness in a node became 5.5 feet or less, it was considered dry. A maximum annual yield of 131,062 acre feet or 2.18 acre feet per acre per year was determined for the entire area. Allocations by modeled area and for the entire aquifer area are shown in Table III. The allocation pumping was distributed over the four summer months (June 1 to September 30). No simulated pumping occurred during the other eight months. A node continued to pump for the duration of the 20-year simulation period unless the node became dry. The 2.18 acre feet per acre per year is equivalent to

TABLE III

WEIGHTED AVERAGE ALLOCATION FOR THE TOTAL AQUIFER AREA INCLUDING ALLOCATION BY MODELED REACH

	Area, Modeled Reach (acres)	Area, Extended Modeled Reach (acres)	Fraction		% Total Area		Allocation by Modeled Reach (ac ft/ac/yr)	Weighted Allocation (ac ft/ac/yr)
Upper Modeled Reach (A)	19,960	27,240	27,240 / 60,160	=	45.3	x	2.70	1.22
Middle Modeled Reach (B)	11,600	13,720	13,720 / 60,160	=	22.8	x	1.75	0.40
Lower Modeled Reach (C)	8,640	19,160	19,160 / 60,160	=	31.9	x	1.75	0.56
	Total aquifer area (acres)	60,160			Net allocation for total aquifer area			2.18

	Allocation by Modeled Reach			Weighted Allocation
	Upper Reach (A)	Middle Reach (B)	Lower Reach (C)	Total area, A, B, and C including unmodeled areas
Allocation ac ft/ac/yr	2.70	1.75	1.75	2.18

a continuous pumping rate during the four summer months of about 500 gpm per node. This assumes one well (500 gpm) for every forty acres (node).

A 20-year ground-water budget was completed for final computer allocation runs for each modeled reach and for the entire aquifer area (Figures 29, 30, 31, and 32). The method used to complete the water budget is described in Appendix M. In addition, a mass balance for full allocation pumping; Tables IV, V, and VI for prior appropriative pumping; Tables VII, VIII, and IX, for each modeled reach from July 1, 1973, to July 1, 1993, are included in Appendices B and J, respectively.

Computer-generated data were used to produce zoned maps such as shown in Figure 70 in Appendix L. Simulated changes in saturated thickness and areas that became dry within each modeled reach for 1973 and 1993 are shown in Figures 33, 34, 35, and 36. Saturated thickness for intervening years is given in Appendix E. Maps showing data input and simulation results that are presented as figures in the text are also included in the Appendices. Additionally, maps showing permeability, transmissivity, water depth, and water table contour maps showing the effect of prior rights pumping are found in Appendices F, G, H, and K, respectively.

Water Quality

Water quality in the alluvium and underlying formations is covered in detail in a previous section of this report. As discussed earlier, ground-water quality in the alluvium is similar to that in the underlying Cloud Chief and Rush Springs Formations. River water quality is usually better than that of the alluvium.

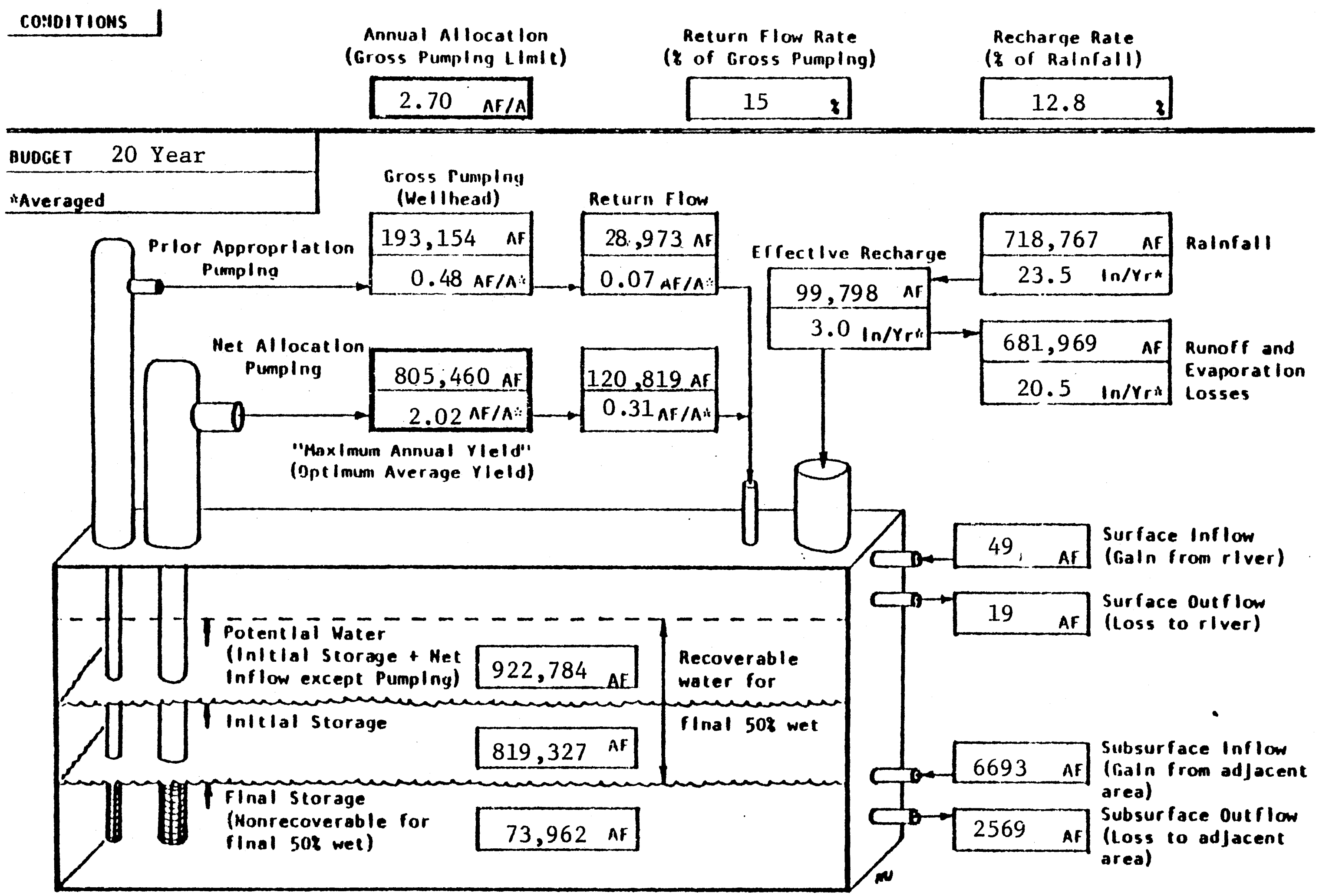


Figure 29. Water Budget, Upper Modeled Reach (Part A). (Sources of these data are further discussed in Appendix M.)

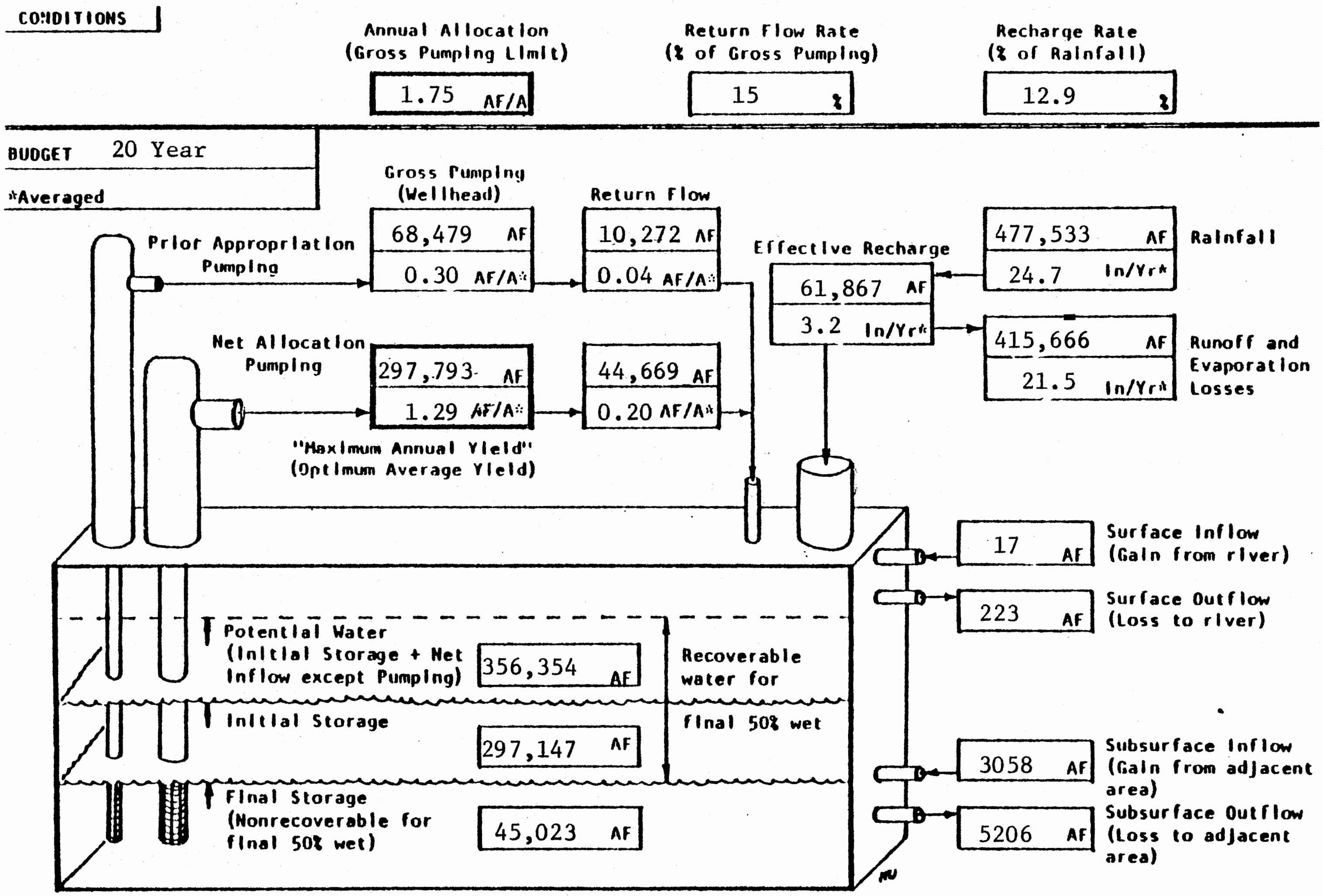


Figure 30, Water Budget, Middle Modeled Reach (Part B). (Sources of these data are further discussed in Appendix M.)

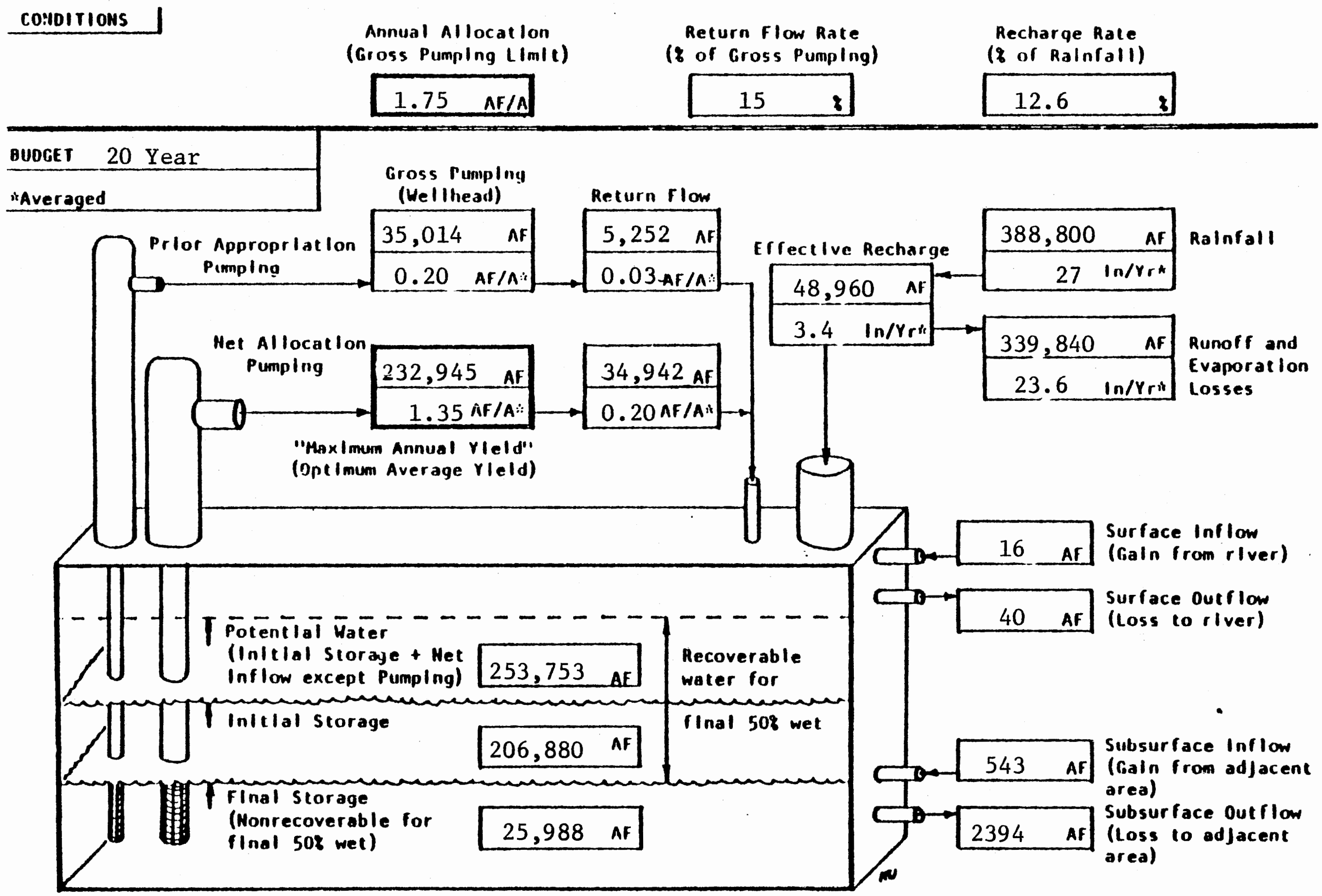


Figure 31. Water Budget, Lower Modeled Reach (Part C). (Sources of these data are further discussed in Appendix M.)

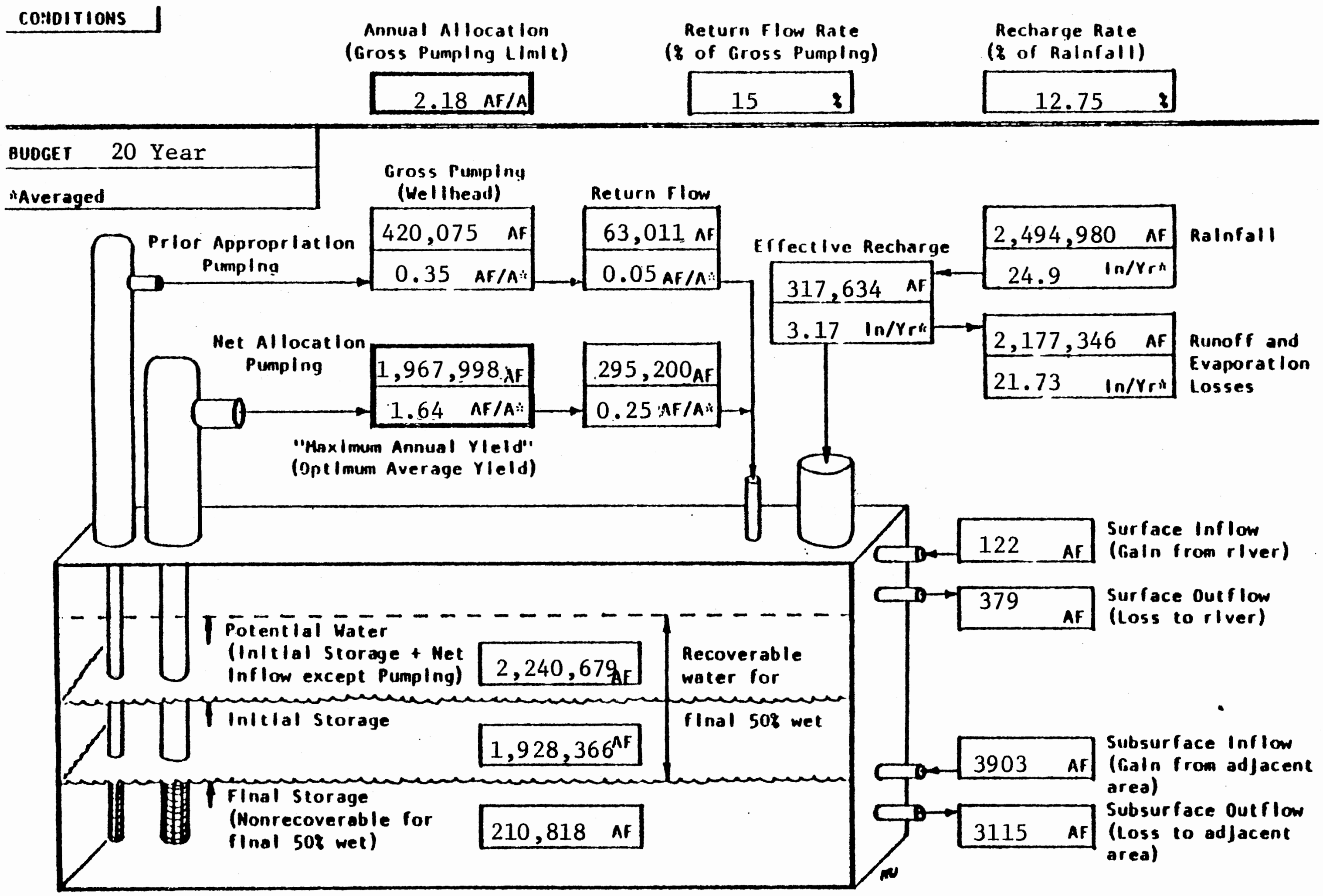


Figure 32. Water Budget, Entire Area, Parts A, B, and C, Including Unmodeled Areas. (Sources of these data are further discussed in Appendix M.)

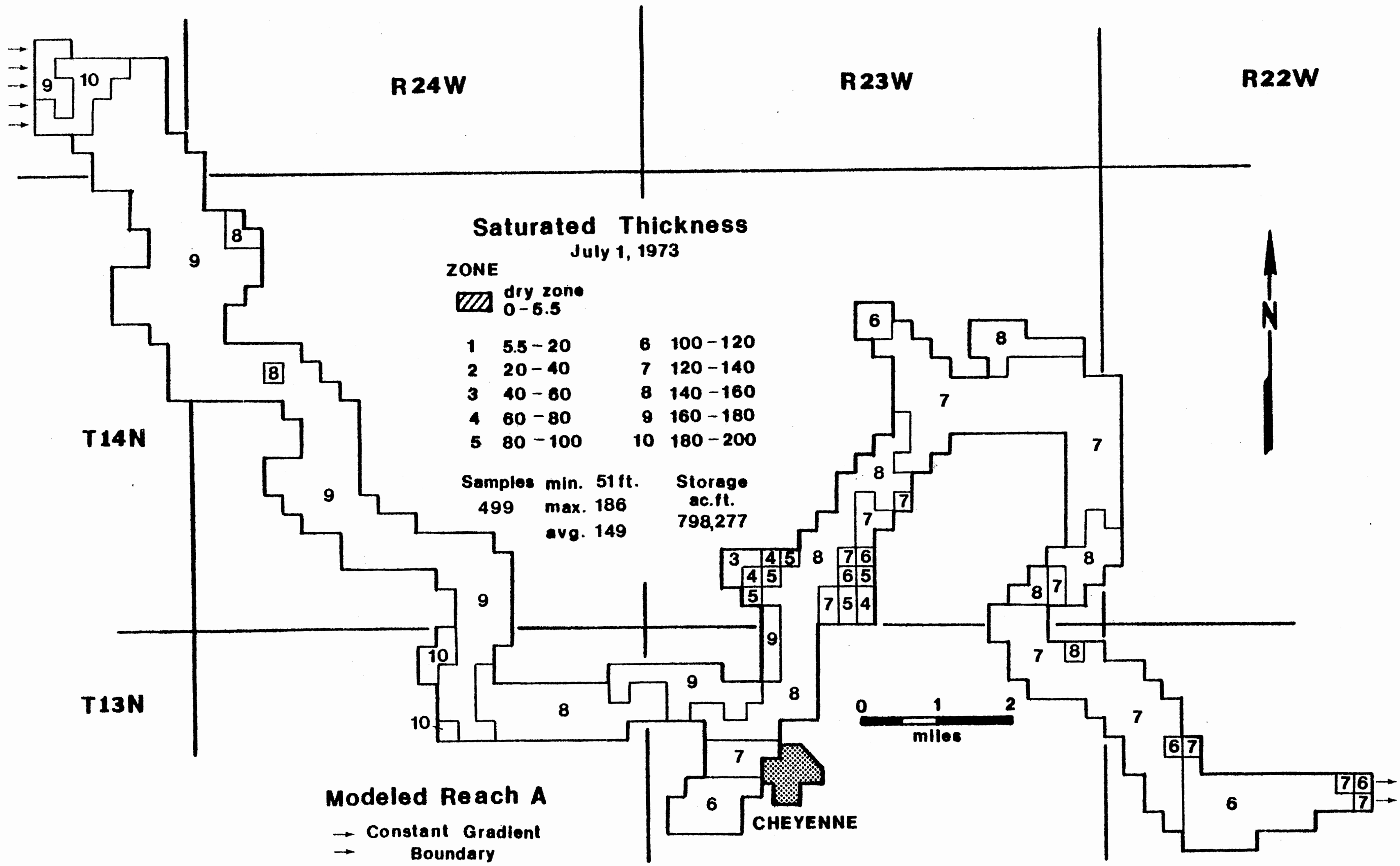


Figure 33. Saturated Thickness, July 1, 1973, Upper Modeled Reach (Part A)

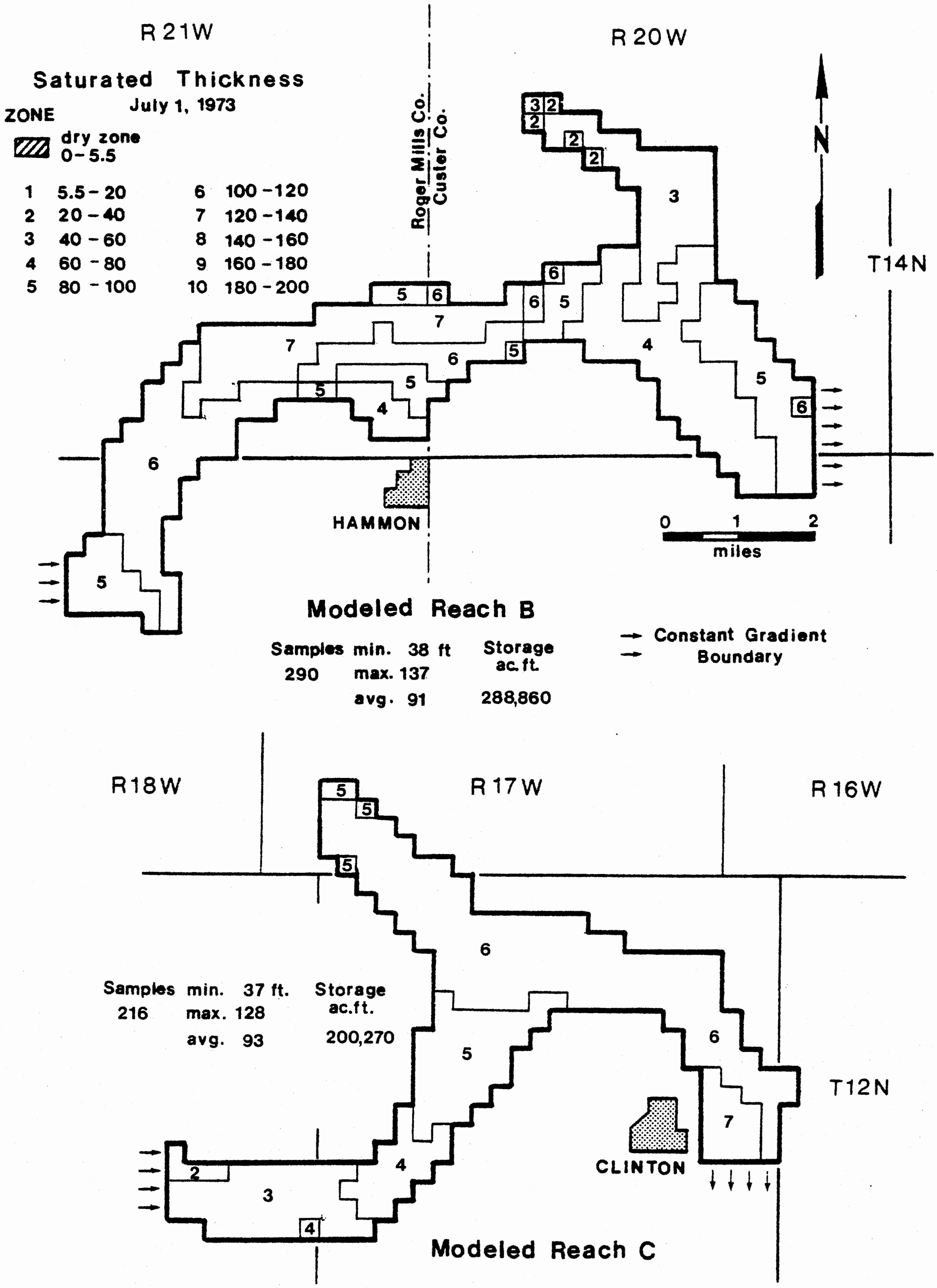


Figure 34. Saturated Thickness, July 1, 1973, Middle and Lower Modeled Reaches (Parts B and C)

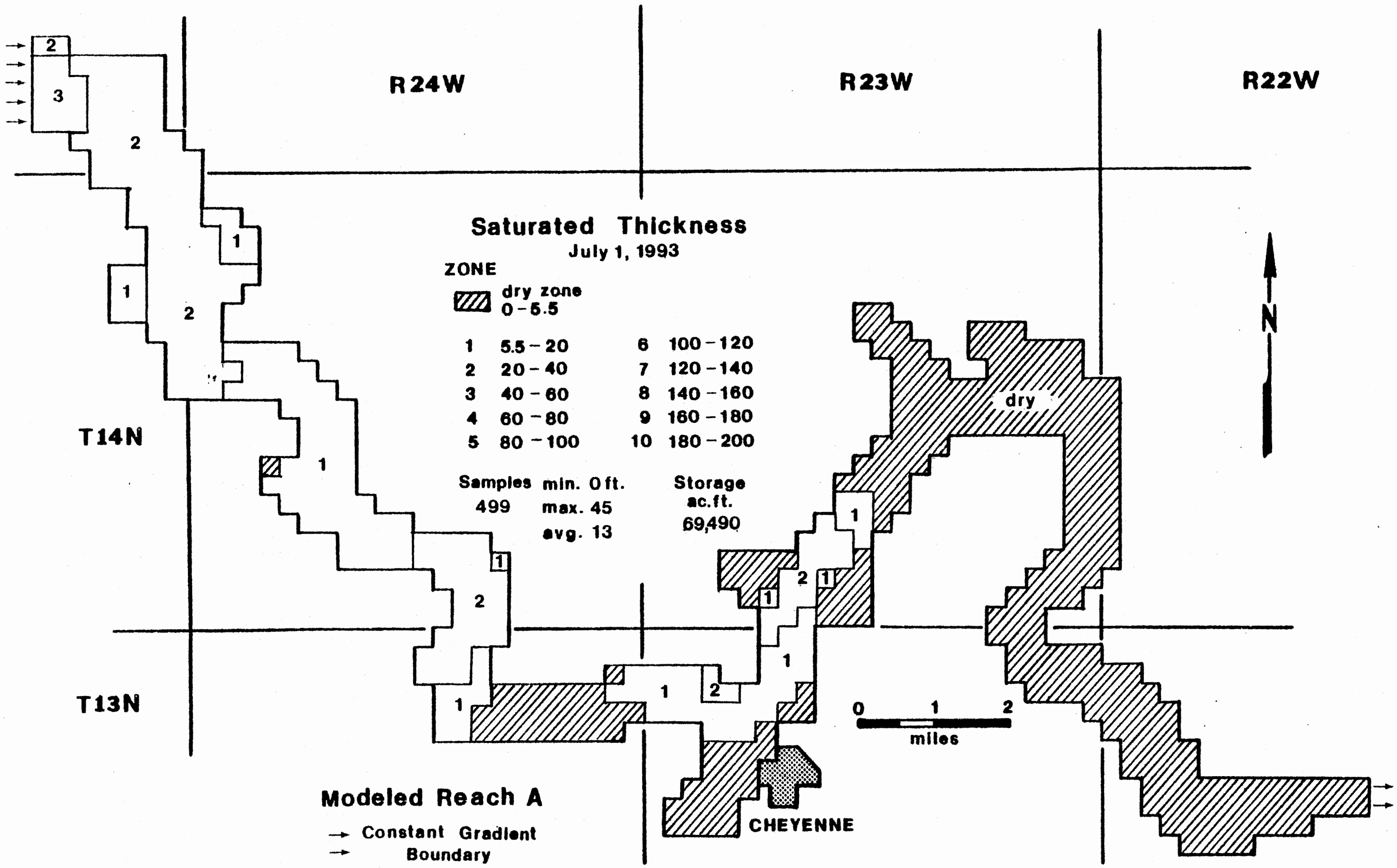


Figure 35. Saturated Thickness, July 1, 1993, Upper Modeled Reach (Part A)

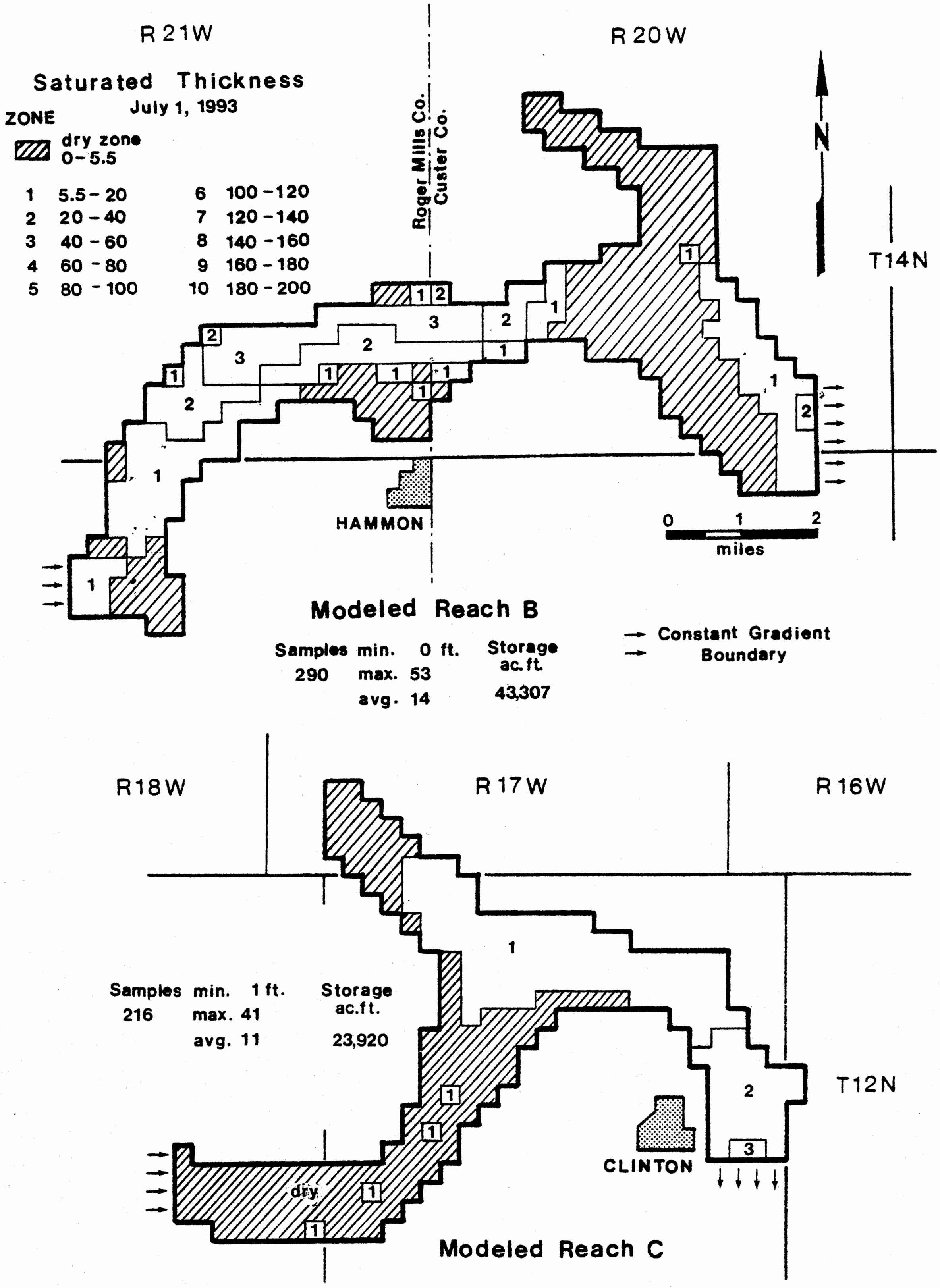


Figure 36. Saturated Thickness, July 1, 1993, Middle and Lower Modeled Reaches (Parts B and C)

Partial depletion of the aquifer would probably induce recharge from the Washita River to the alluvium. Additionally, lower head in the alluvium may increase the amount of upward leakage from the bedrock. Available data show that dissolved solids in water from both the underlying bedrock and the river do not exceed the limit for irrigation set by the Oklahoma Water Resources Board (5000 ppm). Therefore, additional flow from either source would probably not cause the dissolved solids of water in the alluvium to exceed the limit.

CHAPTER VII

CONCLUSIONS

Collected data, published reports, and field investigations were used to define the properties of the Washita River alluvium and enabled interpretation of the relationships within the aquifer. Based on the above, the following list of aquifer properties is presented:

Aquifer area, 94 sq mi = 60,160 acres

Avg. thickness, 133 ft

Avg. saturated thickness (1973), 118 ft

Storage coefficient, 0.263

Avg. transmissivity (1973), 28,600 gpd/ft

Well yields: Minimum, <200 gpm; Average, 600 gpm; Maximum, 1400 gpm

Base Flow	Upper Reach (A)	Middle Reach (B)
From minimum winter flow	2.0 cfs	1.2 cfs
From mean winter flow	4.3 cfs	2.4 cfs

Avg. precipitation, 24.9 in/yr

Recharge Rate, 3.17 in/yr

% Precipitation, 12.75%

Total prior rights, 17,115 ac ft/yr

Avg. over entire area, 0.3 ac ft/ac/yr

Avg. dissolved solids, water from alluvium, 3000 ppm

<u>The following assumptions were made for modeling purposes:</u>

1. Even though vertical and lateral changes in aquifer composition

do occur, the aquifer is considered isotropic and homogeneous. Values of permeability, storage coefficient, and recharge assigned to a node are uniform throughout that node. Methods used to determine permeability and storage coefficient take into account vertical changes in permeability.

2. The Permian redbeds underlying and adjacent to the aquifer are considered impermeable boundaries and are assigned a permeability value of zero.

3. The Washita River is a gaining stream. Vertical leakage from the bedrock to the alluvium is considered a component of ground-water recharge.

4. Net recharge is considered to be constant throughout the simulation period.

5. Stream-flow records show a significant decline in mean yearly river flow at Cheyenne, Oklahoma (Figure 26) since 1930. The corresponding decline in base flow suggests that there may be a net loss in stored ground-water through time, due probably to irrigation. During calibration, a small net loss in stored ground-water was observed.

The 20-year computer runs produced the following conclusions:

1. After 20 years' pumping (1973-1993) using prior-right pumping rates (17,115 acre ft/yr), the average drawdown over the study area was 8.8 ft. This is a 7.5% reduction in saturated thickness. No nodes were pumped dry.

2. The annual allocation for the entire area is 2.18 acre ft/ac. This corresponds to a maximum yield for the area of 131,062 ac ft/yr. The annual allocations by modeled reach are: Upper Reach near Cheyenne, 2.70 acre ft/ac; Middle Reach near Hammon, 175 acre ft/ac, and

Lower Reach near Clinton, 1.75 acre ft/ac.

3. The volume of water in storage in the aquifer (94 sq mi) as of July 1, 1973, is 1,875,165 ac ft; the final storage after full prior plus allocation pumping as of July 1, 1993, is 199,044 ac ft.

Recommendations for Further Work

1. Aquifer tests with observation wells could be run in the study area to determine values of transmissivity and specific yield. These would serve to evaluate the accuracy of values found with geologic logs and specific capacity data.

2. A network of 10 to 20 existing water wells could be used to establish an observation well network in the alluvium over the study area. Quarterly water-level measurements could be made for a period of years. Accurate documentation of water-level trends would aid in calibration of future computer simulations in the study area. Water level measurements through a period of time could also indicate whether the amount of ground-water in storage is changing.

3. Chemical analysis of water from selected wells could be performed on a yearly basis to document changes in ground-water quality that may occur.

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APPENDIXES

APPENDIX A

TWENTY-YEAR GROUND-WATER BUDGETS FOR THE UPPER, MIDDLE, LOWER, AND ENTIRE MODELED AREA

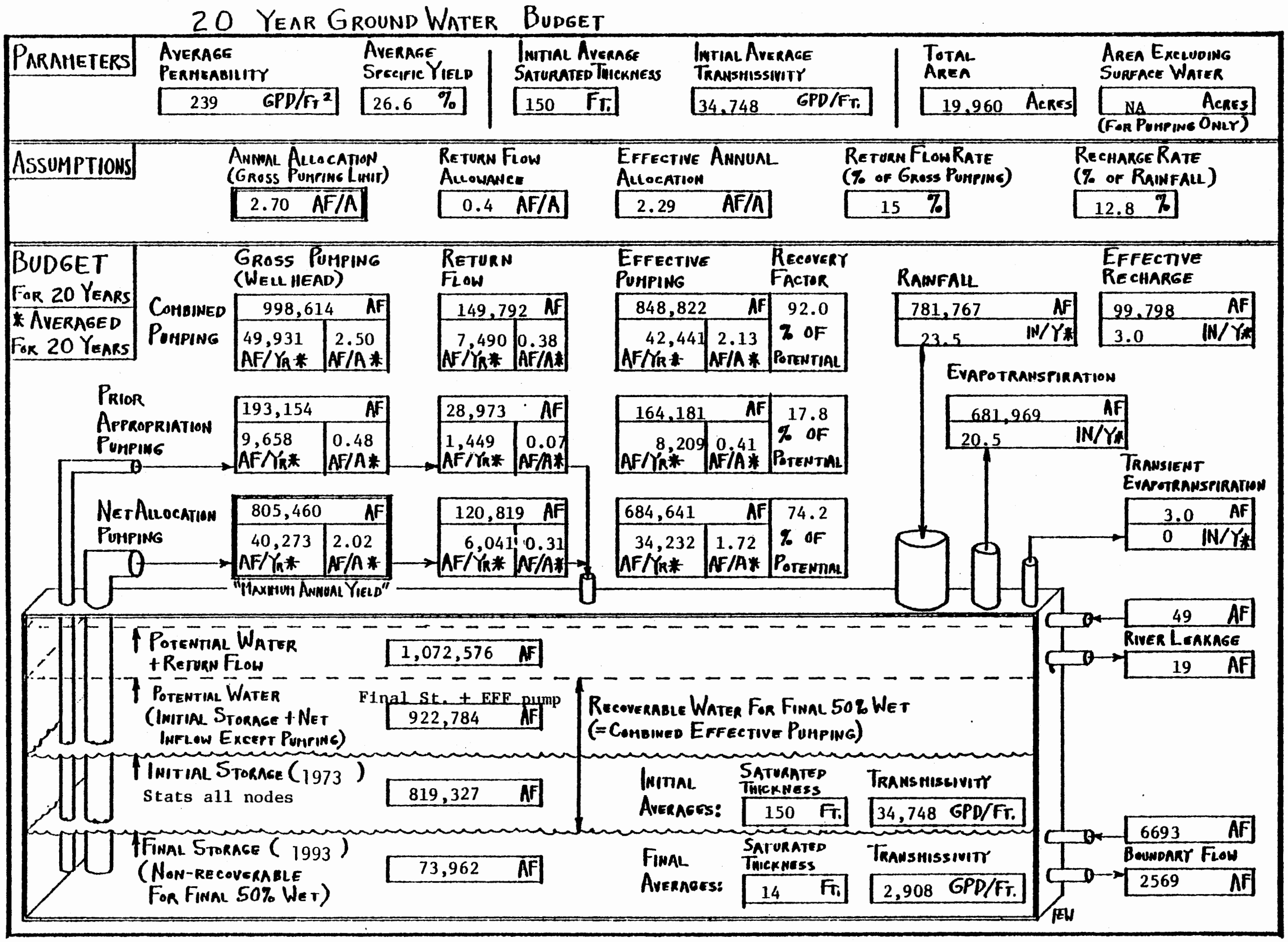

Figure 37. Water Budget, Upper Modeled Reach (Part A). (Sources of these data are further discussed in Appendix M.)

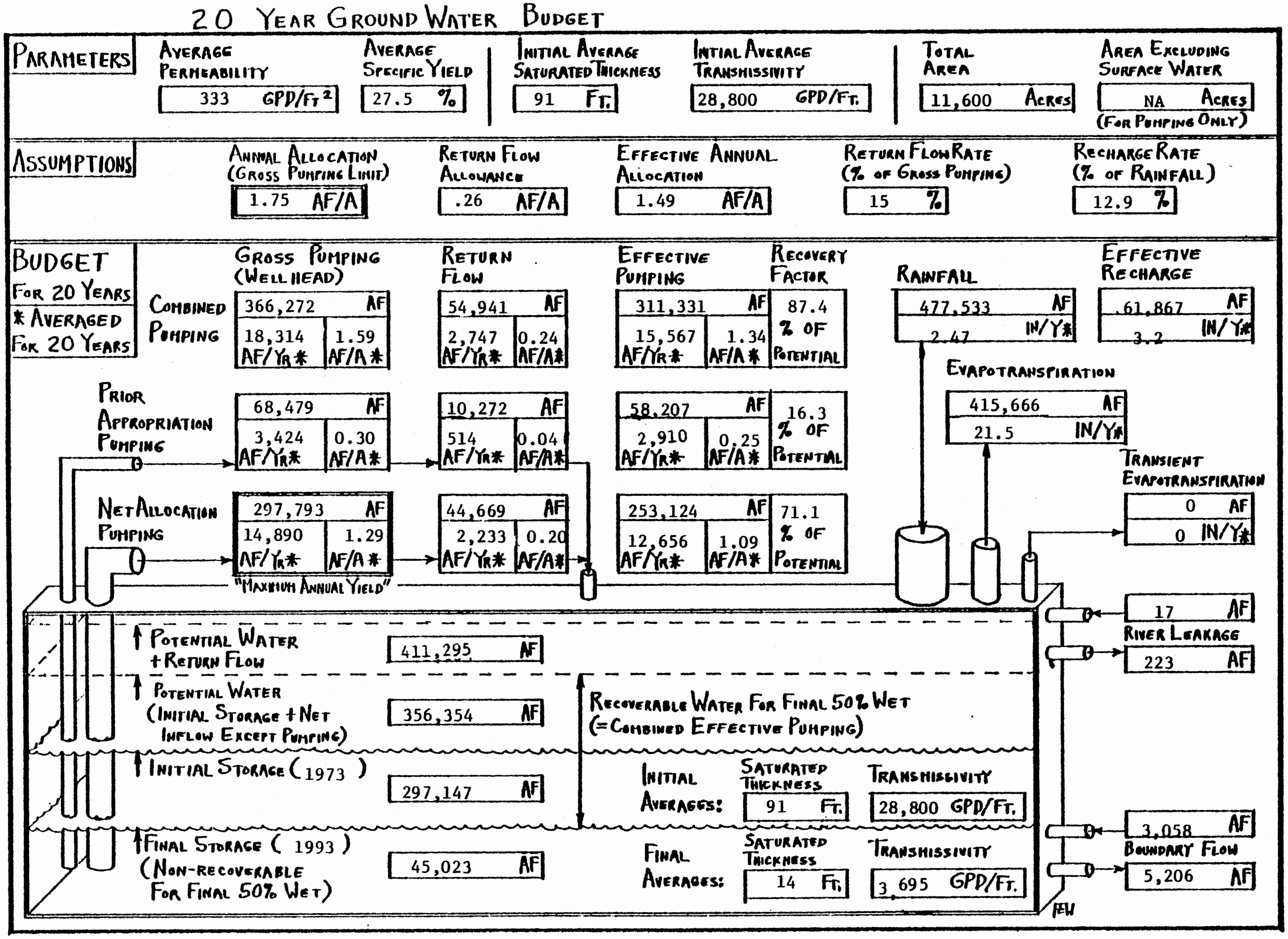

Figure 38. Water Budget, Middle Modeled Reach (Part B). (Sources of these data are further discussed in Appendix M.)

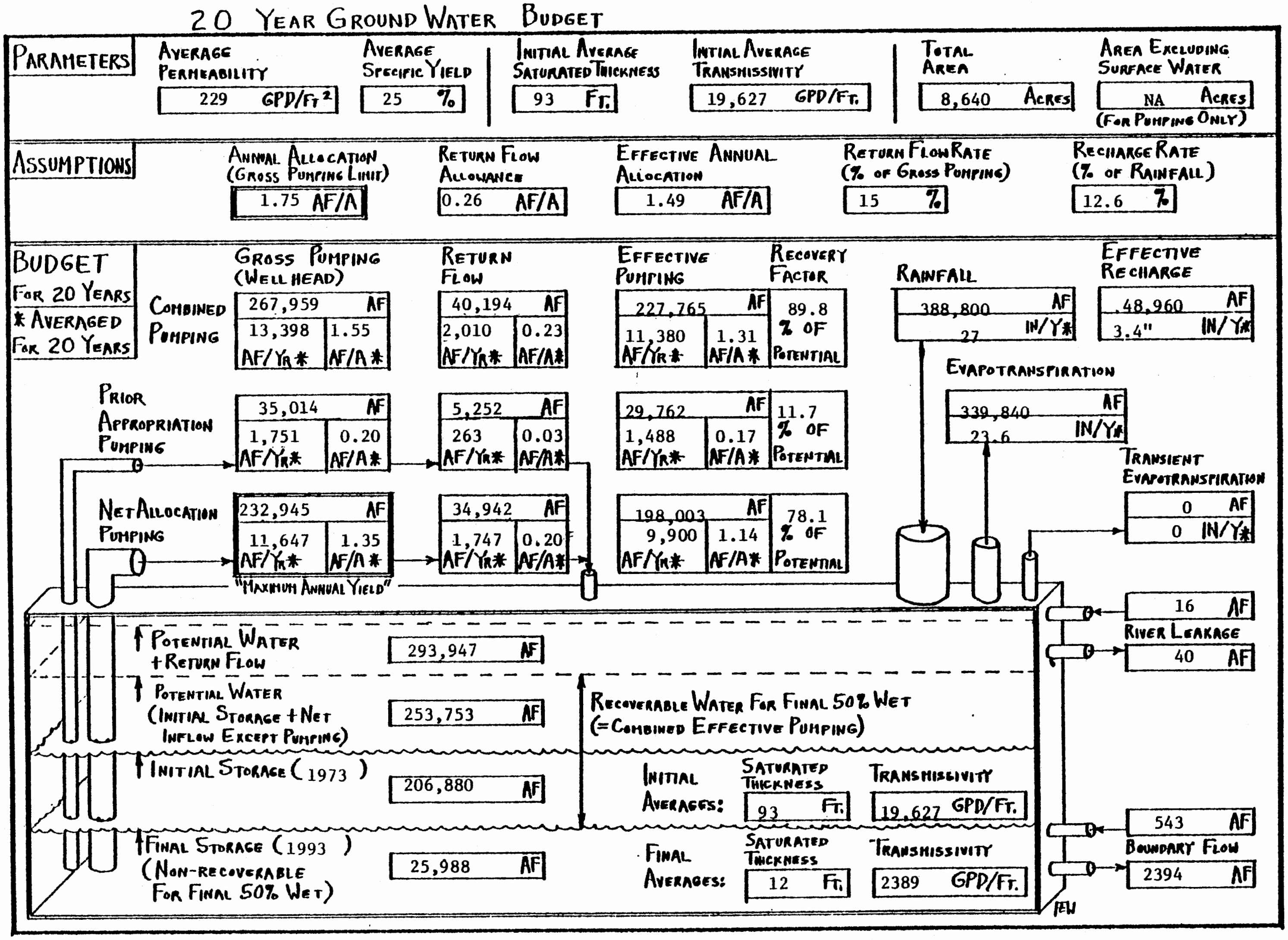

Figure 39. Water Budget, Lower Modeled Reach (Part C). (Sources of these data are further discussed in Appendix M.)

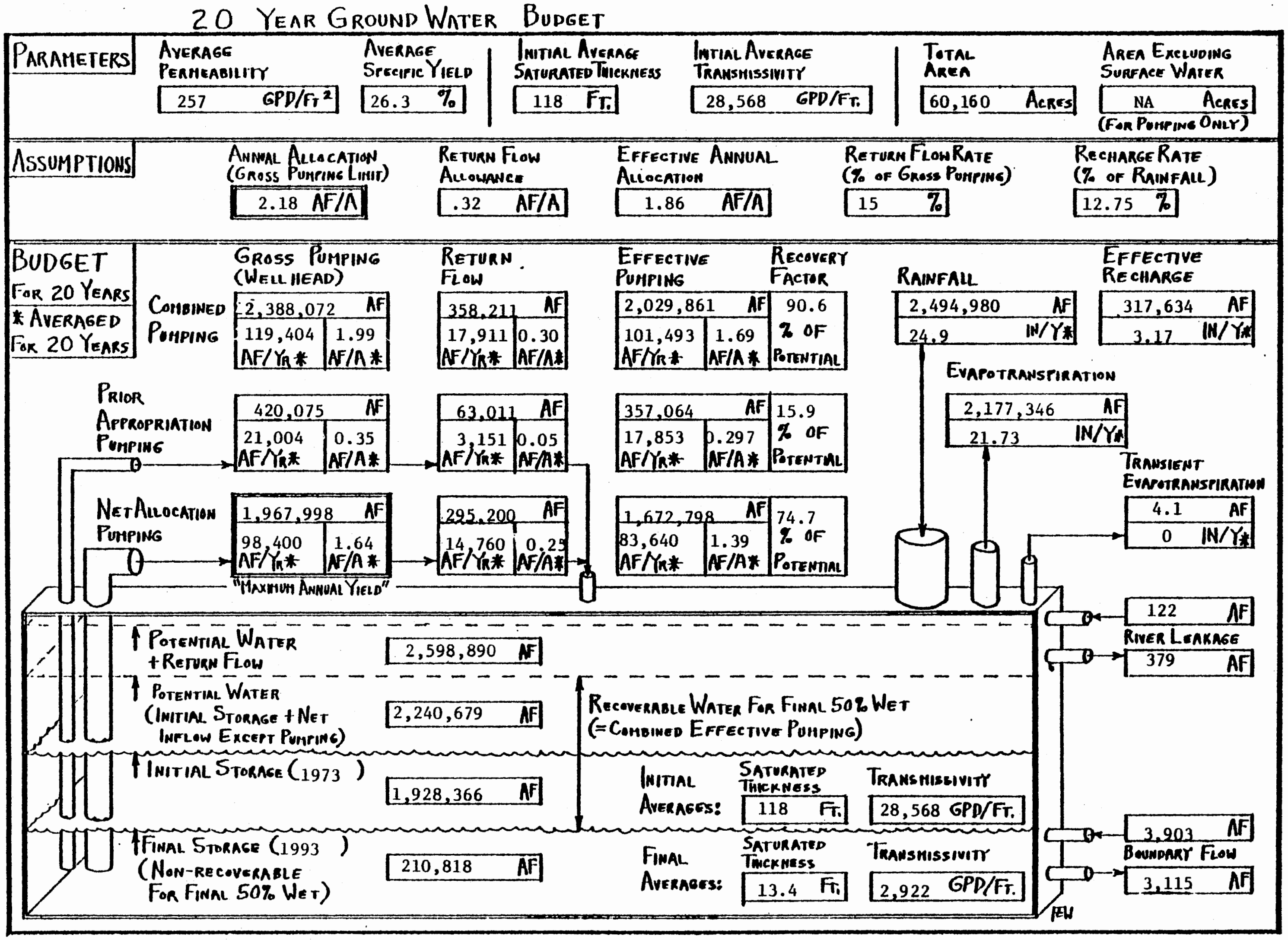

Figure 40. Water Budget, Entire Area, Parts A, B, and C, Including Unmodeled Areas. (Sources of these data are further discussed in Appendix M.)

APPENDIX B

MASS BALANCE OF FULL ALLOCATION PUMPING FROM JULY 1, 1973, TO JULY 1, 1993, FOR THE UPPER, MIDDLE, AND LOWER MODELED REACHES

TABLE IV

MASS BALANCE OF FULL ALLOCATION PUMPING FROM JULY 1, 1973, TO JULY 1, 1993
(Upper Reach, A)

	Average Annual (acre feet)		20-Year Total (acre feet)	
	Inflow	Outflow	Inflow	Outflow
Recharge	4,990		99,798	
Pumpage		-42,441		-848,822
River Leakage	2.5	-1	49	-19
Subsurface Flow	335	-128	6,693	-2,569
Evapotranspiration		0.2		-3
TOTALS	5,327	-42,571	106,539	-851,412
Net Storage		-37,244		-744,873

Irrigation allocation for Upper Modeled Reach is 53,892 ac ft/yr or 2.70 ac ft/ac/yr.

TABLE V

MASS BALANCE OF FULL ALLOCATION PUMPING FROM JULY 1, 1973
TO JULY 1, 1993
(Middle Reach, B)

	Average Annual (acre feet)		20-year Total (acre feet)	
	Inflow	Outflow	Inflow	Outflow
Recharge	3,093		61,863	
Pumpage		-15,567		311,331
River Leakage	.85	-11	17	-223
Subsurface Flow	153	260	3,058	-5,206
Evapotranspiration		0		0
TOTALS	3,247	-15,838	64,939	-316,760
Net Storage		-12,591		-251,821

Irrigation allocation for Middle Modeled Reach is 20,300 ac ft/yr or 1.75 ac ft/ac/yr.

TABLE VI

MASS BALANCE OF FULL ALLOCATION PUMPING FROM JULY 1, 1973,
TO JULY 1, 1993
(Lower Modeled Reach, C)

	Average Annual (acre feet)		20-year Total (acre feet)	
	Inflow	Outflow	Inflow	Outflow
Recharge	2,448		48,958	
Pumpage		11,388		-227,765
River Leakage	0.8	-2	16	-40
Subsurface Flow	27	-120	543	-2,394
Evapotranspiration		0		0
TOTALS	2,476	-11,510	49,517	-230,200
Net Storage		-9,034		-180,683

Irrigation allocation for Lower Modeled Reach is 15,120 ac ft/yr or 1.75 ac ft/ac/yr.

APPENDIX C

WATER-TABLE MAPS, JULY 1, 1973, FOR THE UPPER, MIDDLE, AND LOWER MODELED REACHES

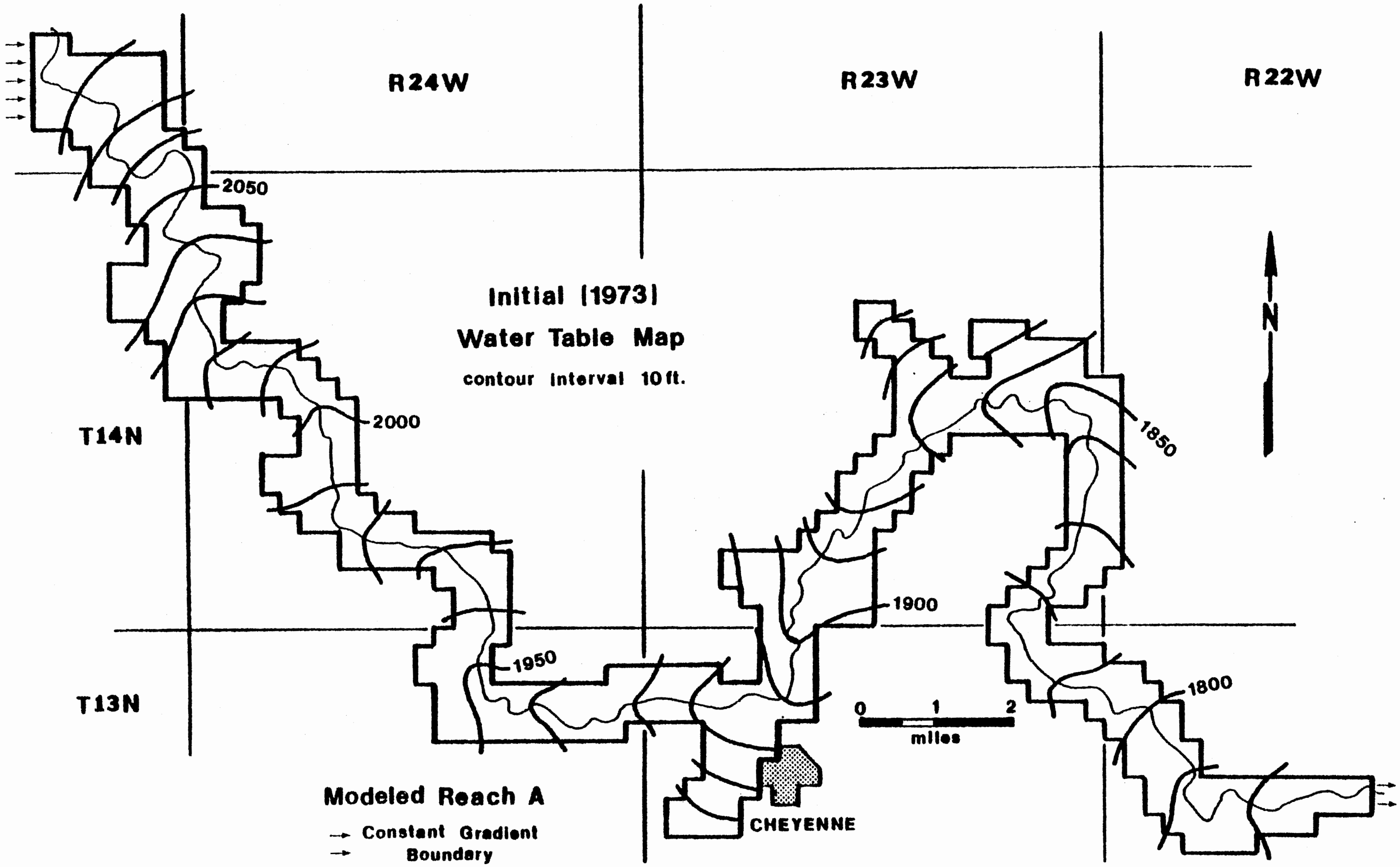

Figure 41. Water Table Map, July 1, 1973, Upper Modeled Reach (Part A)

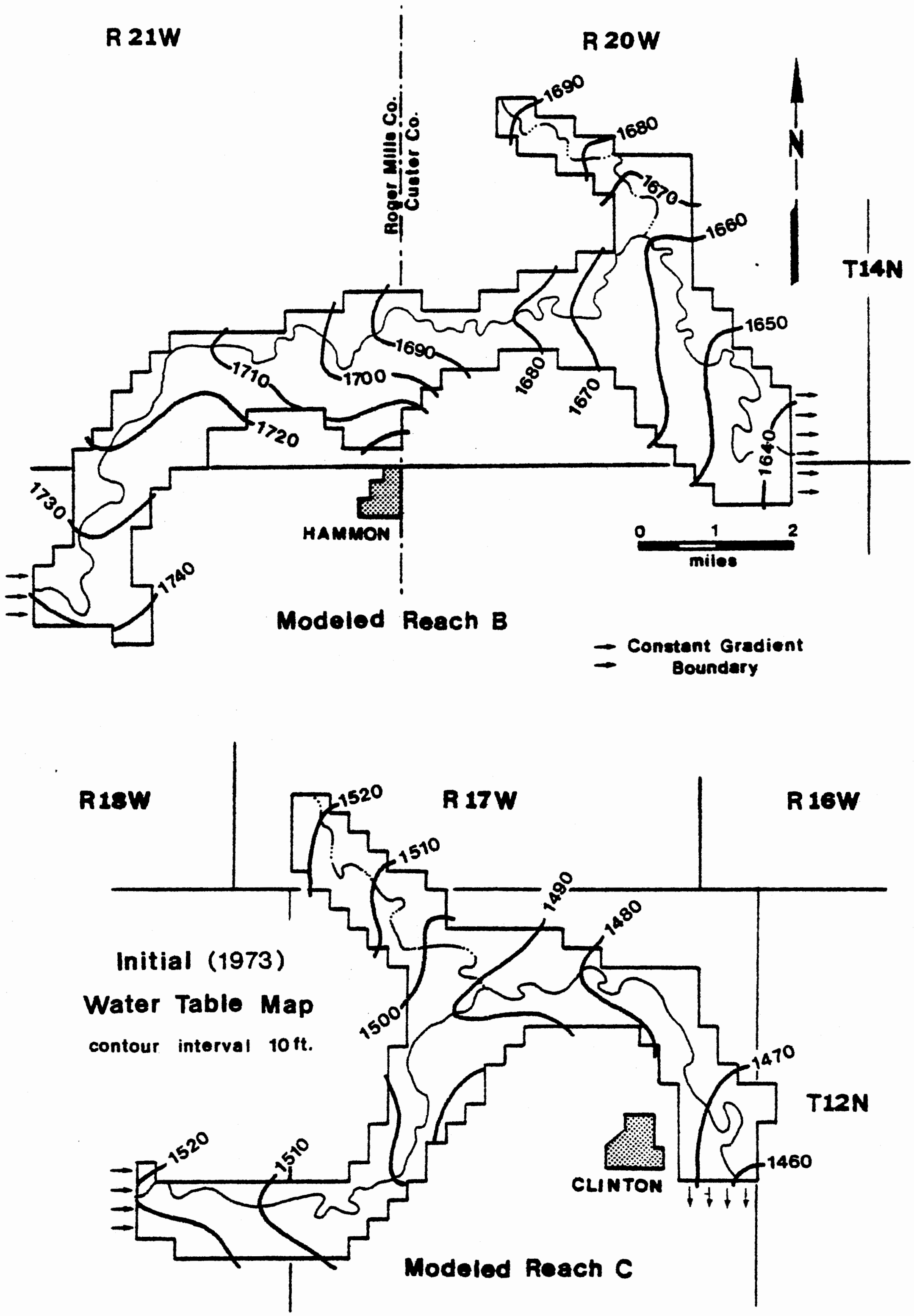

Figure 42. Water Table Map, July 1, 1973, Middle and Lower Modeled Reaches (Parts B and C)

APPENDIX D

BEDROCK CONTOUR MAPS FOR THE UPPER, MIDDLE, AND LOWER MODELED REACHES

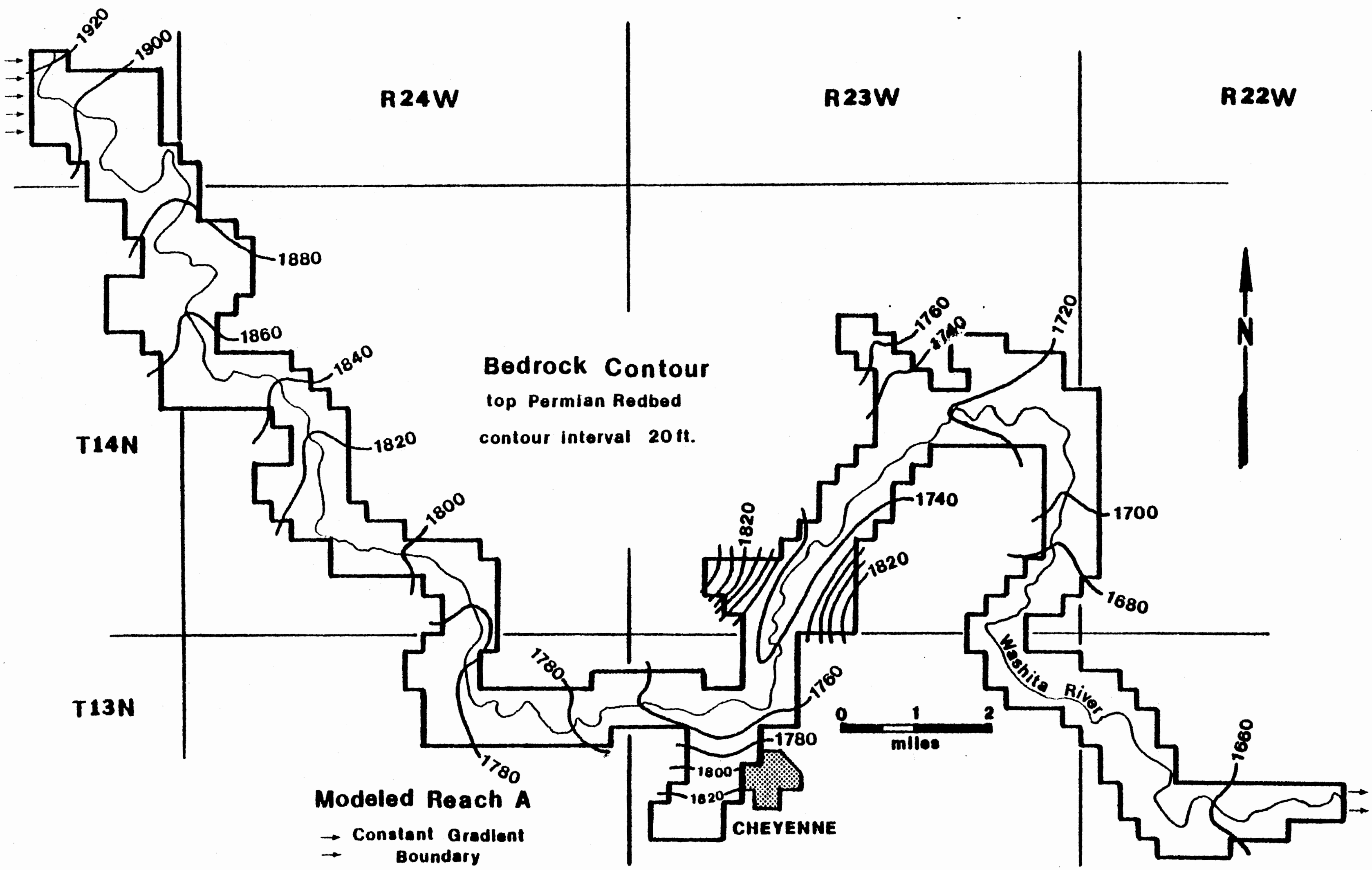

Figure 43. Bedrock Contour, Top Permian Redbed, Upper Modeled Reach (Part A)

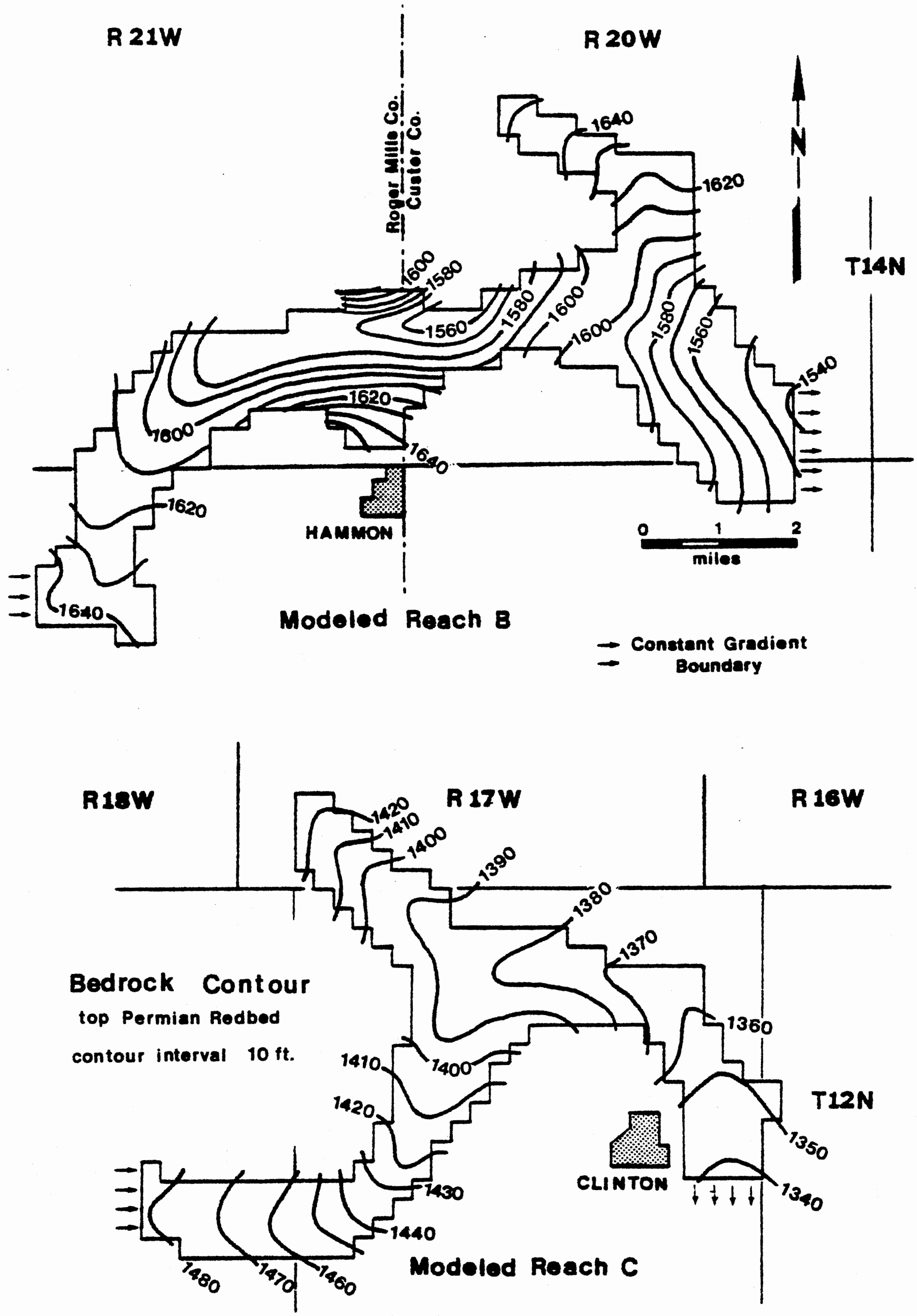

Figure 44. Bedrock Contour, Top Permian Redbed, Middle and Lower Modeled Reaches (Parts B and C)

APPENDIX E

SATURATED THICKNESS MAPS, JULY 1, 1973, 1978,

1983, 1988, AND 1993 FOR THE UPPER,

MIDDLE, AND LOWER MODELED REACHES

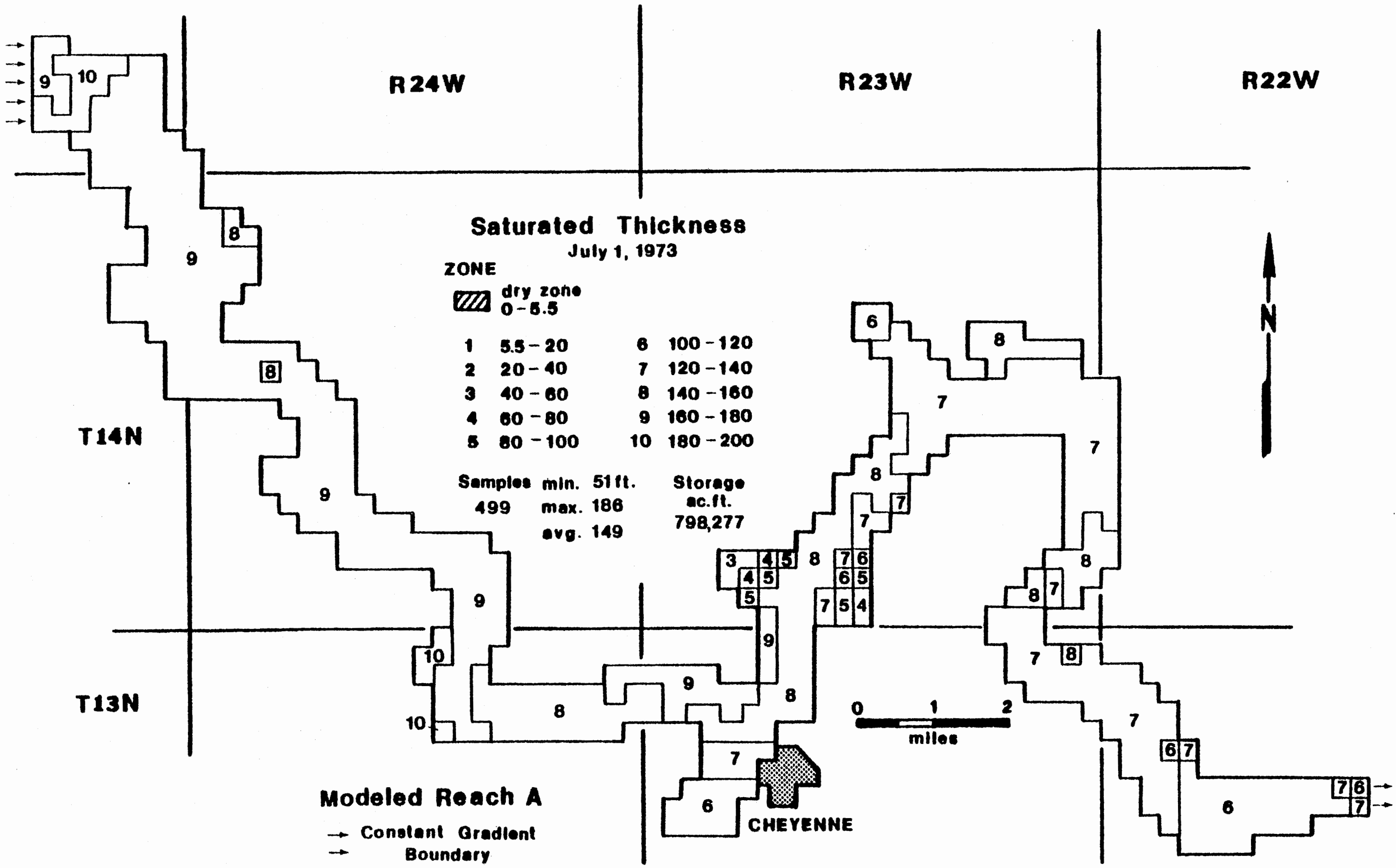

Figure 45. Saturated Thickness, July 1, 1973, Upper Modeled Reach (Part A)

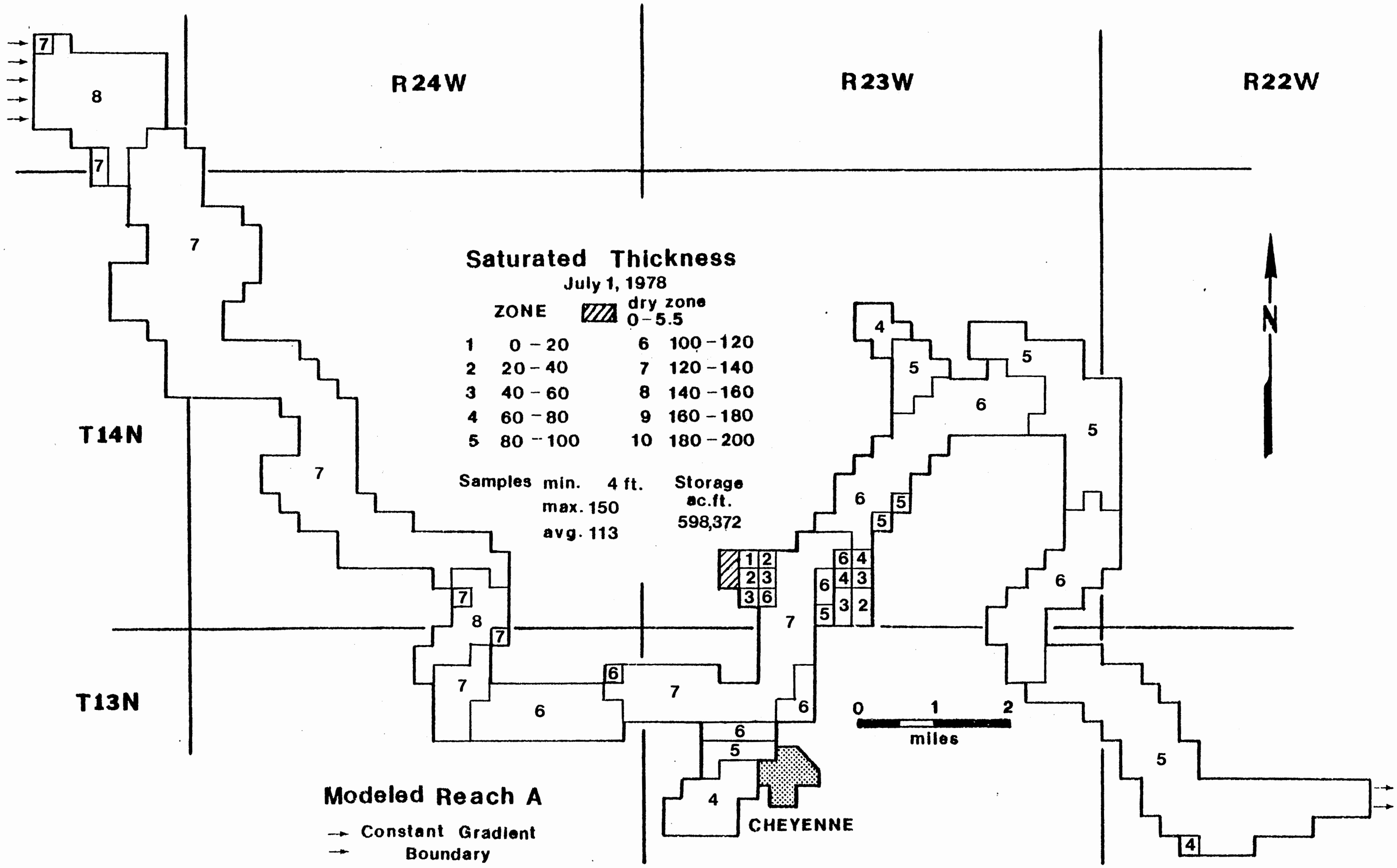

Figure 46. Saturated Thickness, July 1, 1978, Upper Modeled Reach (Part A)

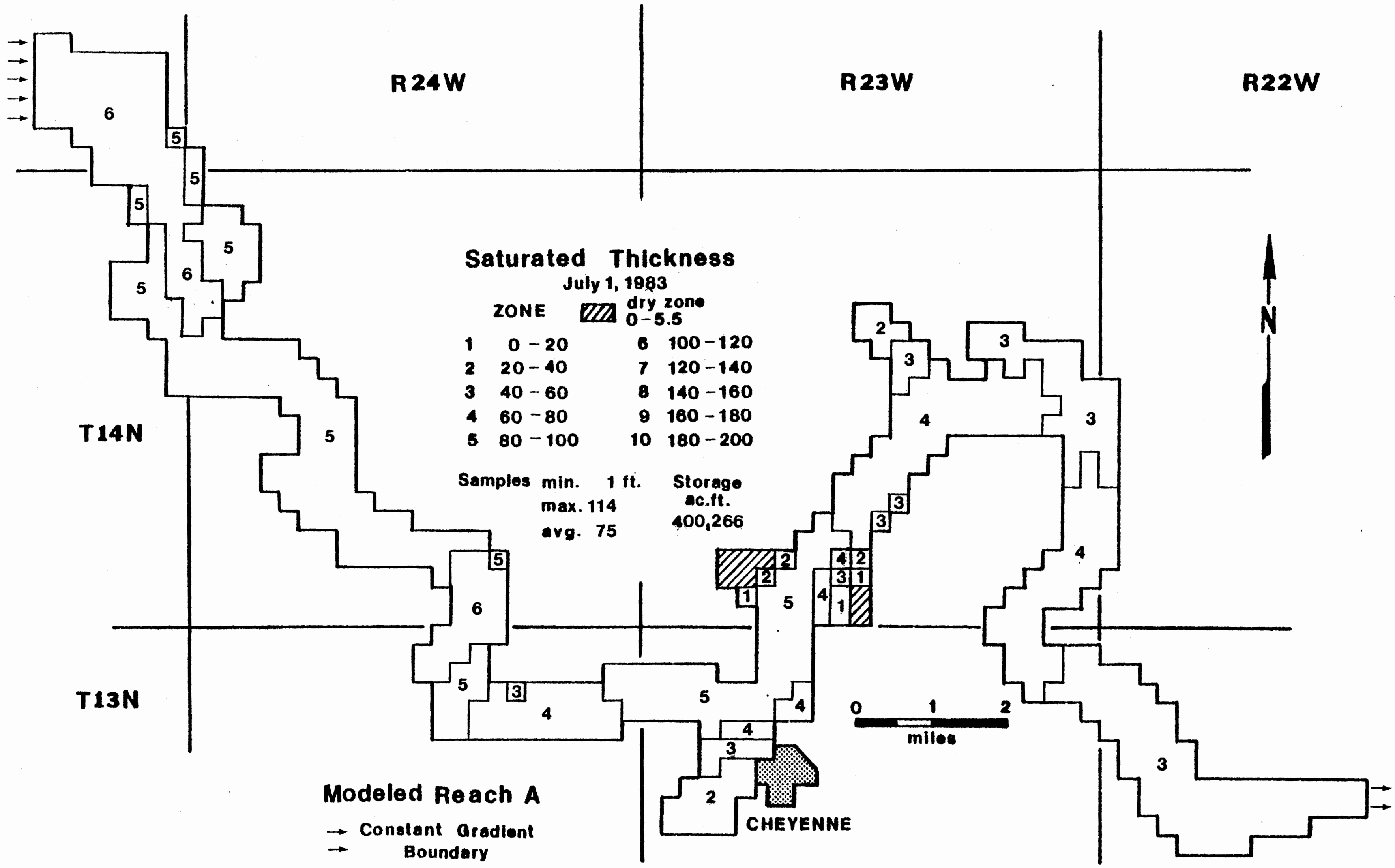

Figure 47. Saturated Thickness, July 1, 1983, Upper Modeled Reach (Part A)

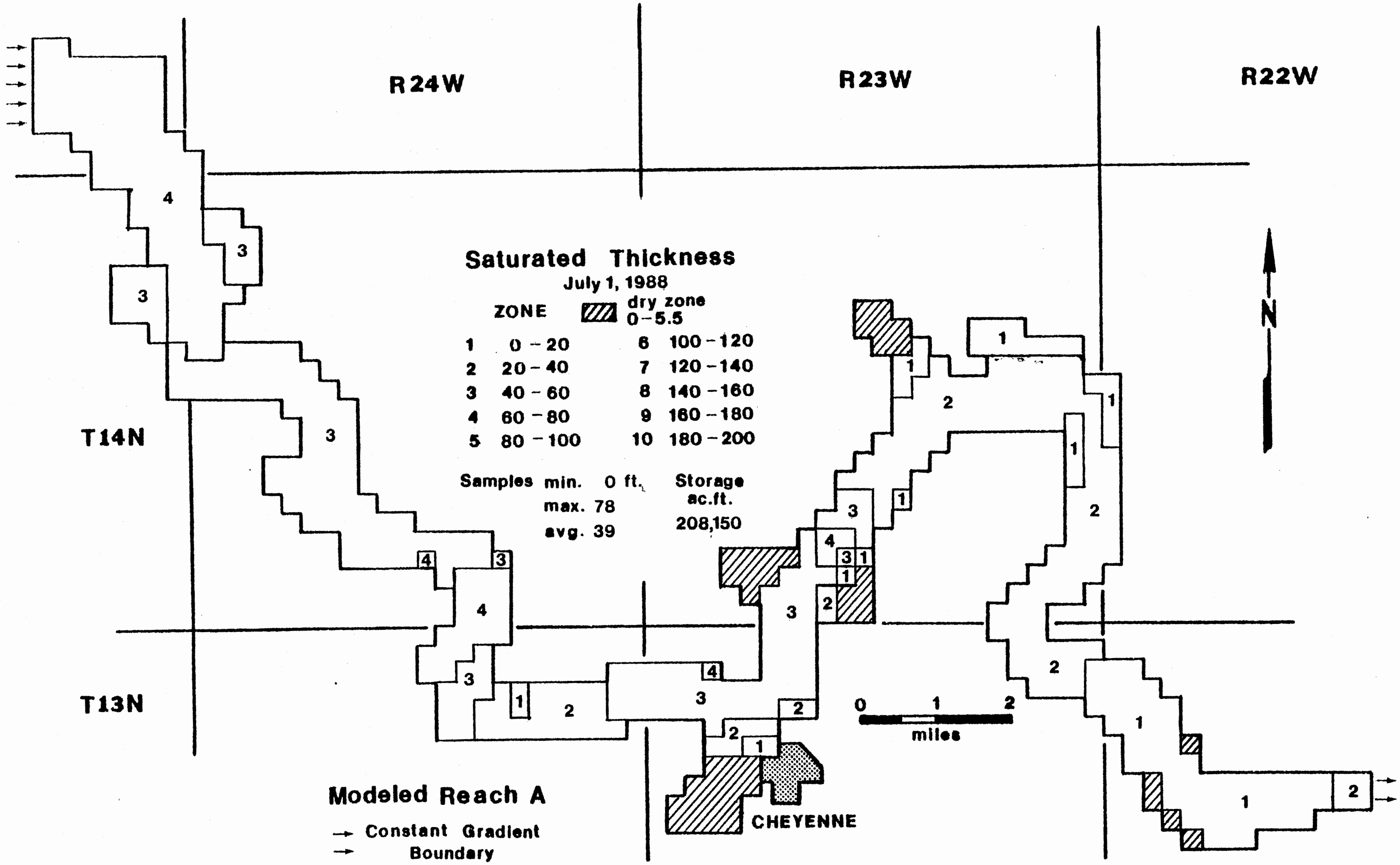

Figure 48. Saturated Thickness, July 1, 1988, Upper Modeled Reach (Part A)

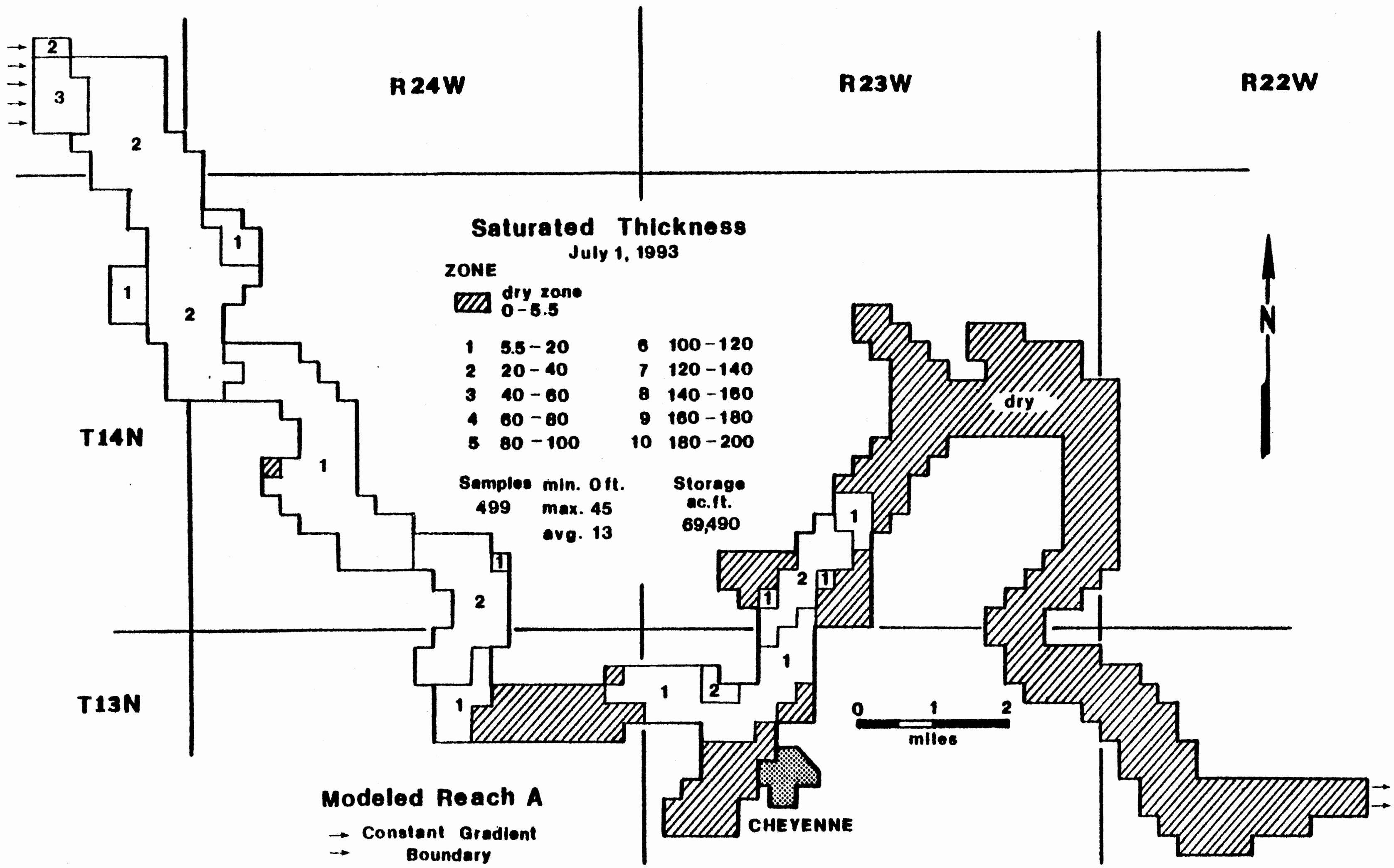

Figure 49. Saturated Thickness, July 1, 1993, Upper Modeled Reach (Part A)

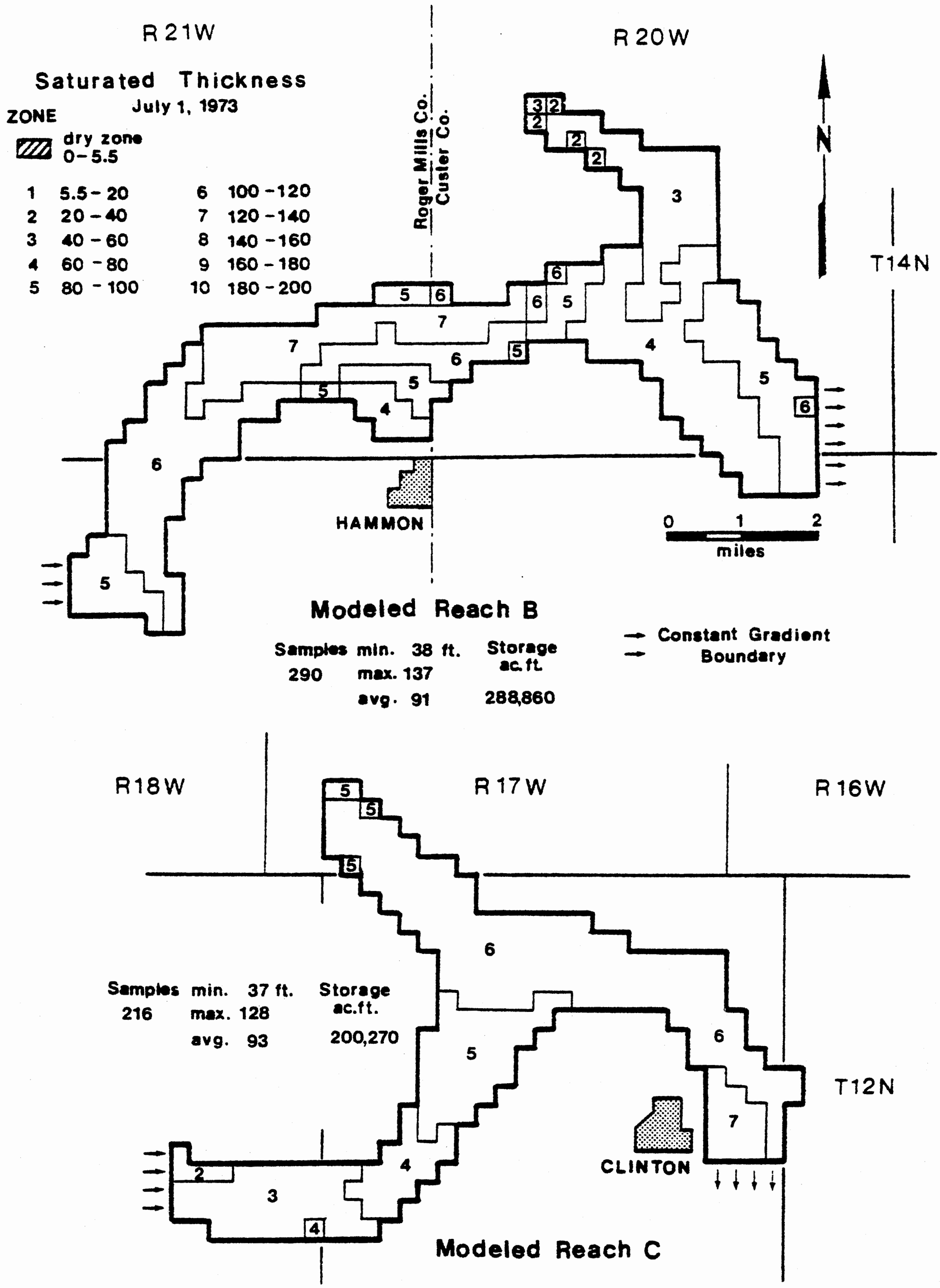

Figure 50. Saturated Thickness, July 1, 1973, Middle and Lower Modeled Reaches (Parts B and C)

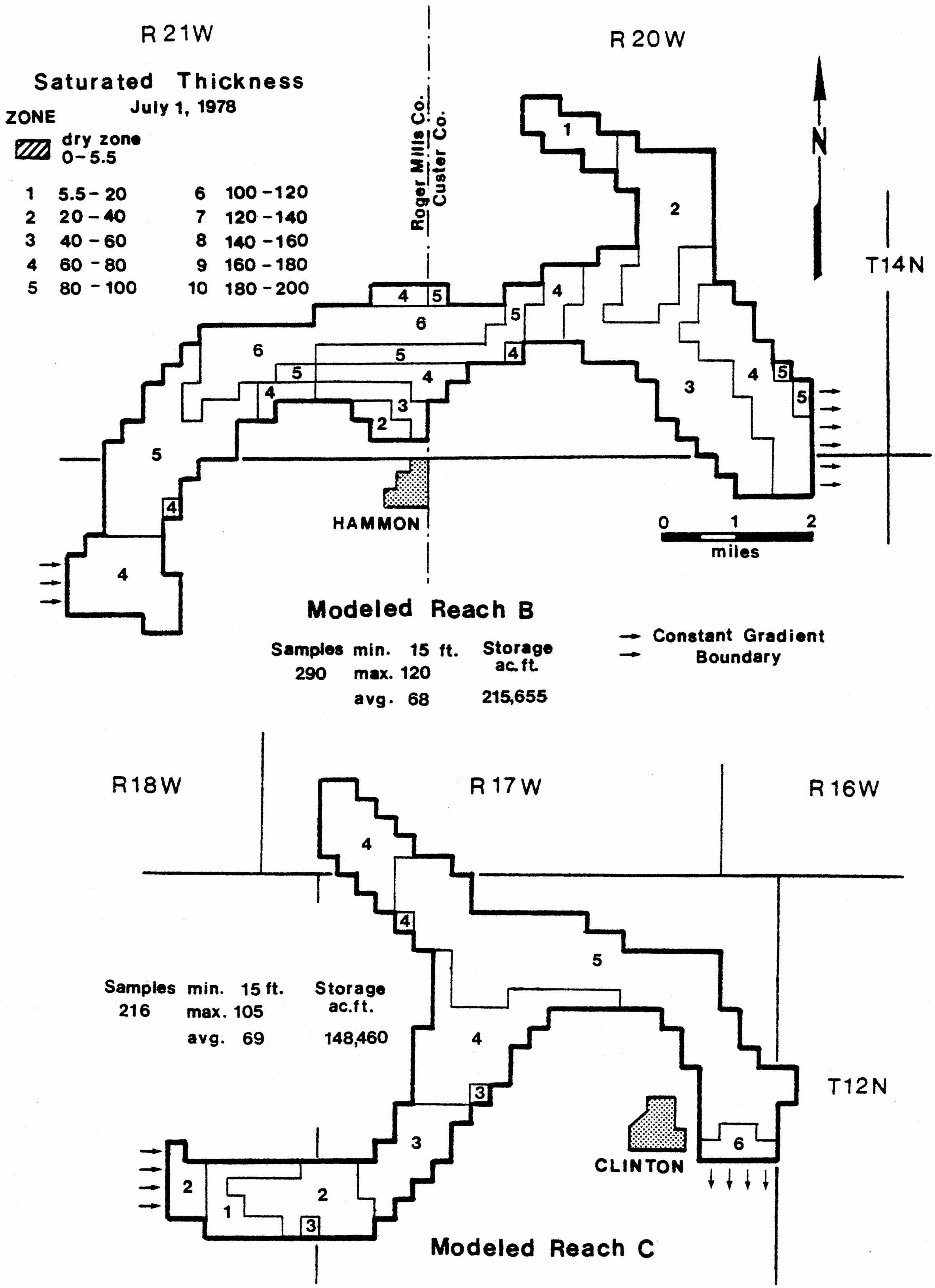

Figure 51. Saturated Thickness, July 1, 1978, Middle and Lower Modeled Reaches (Parts B and C)

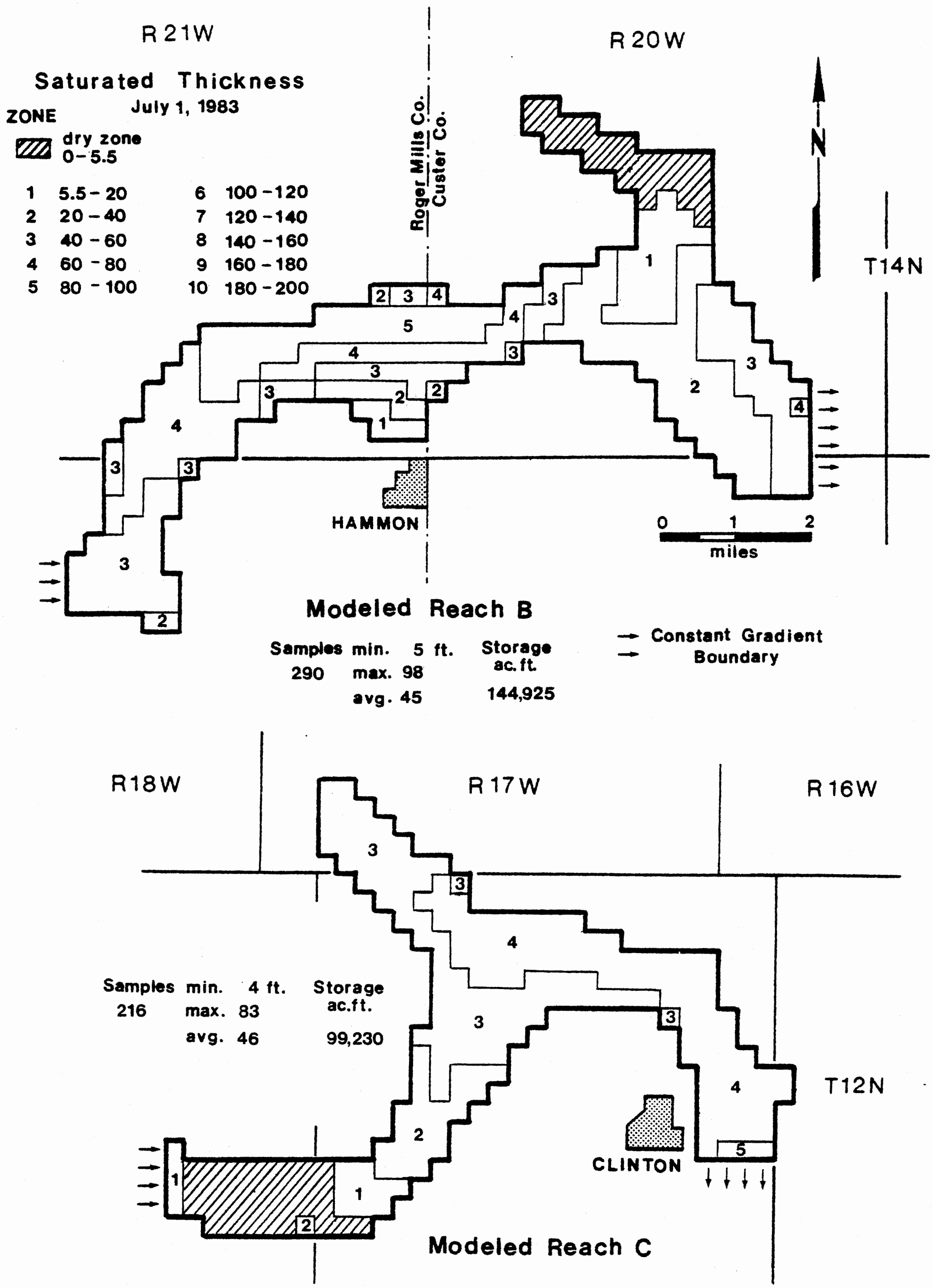

Figure 52. Saturated Thickness, July 1, 1983, Middle and Lower Modeled Reaches (Parts B and C)

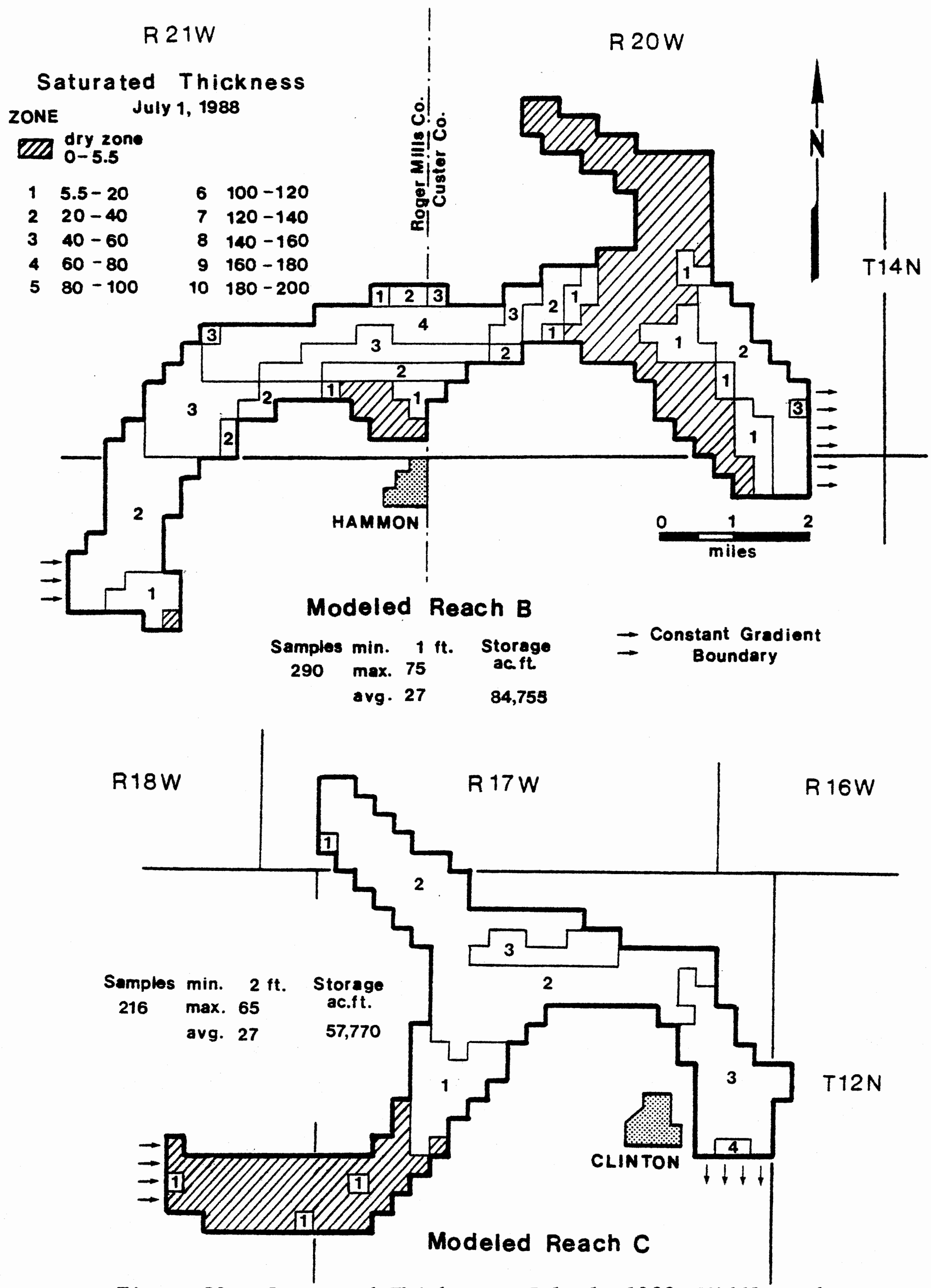

Figure 53. Saturated Thickness, July 1, 1988, Middle and Lower Modeled Reaches (Parts B and C)

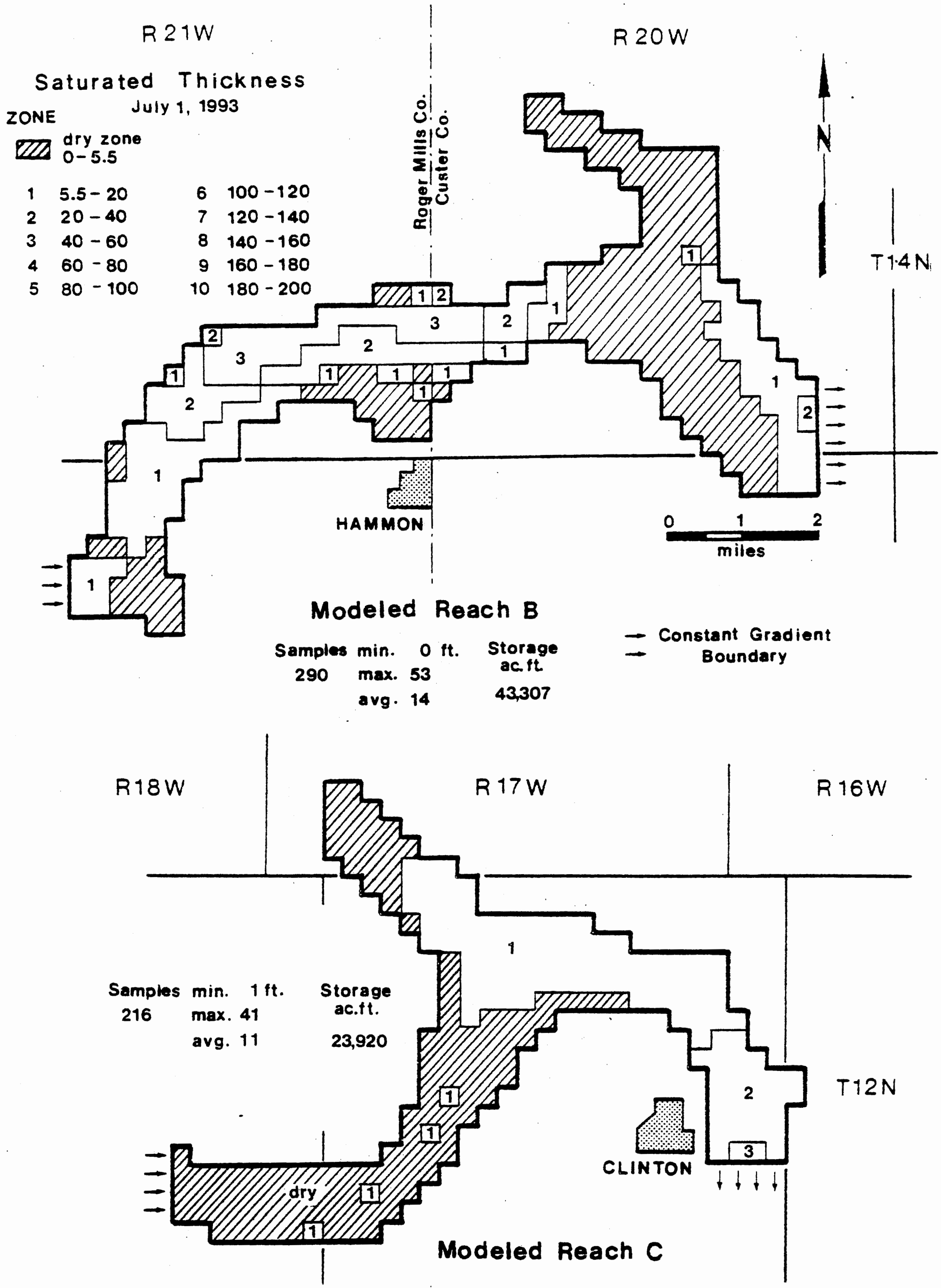

Figure 54. Saturated Thickness, July 1, 1993, Middle and Lower Modeled Reaches (Parts B and C)

APPENDIX F

PERMEABILITY MAPS, UPPER, MIDDLE, AND LOWER

MODELED REACHES

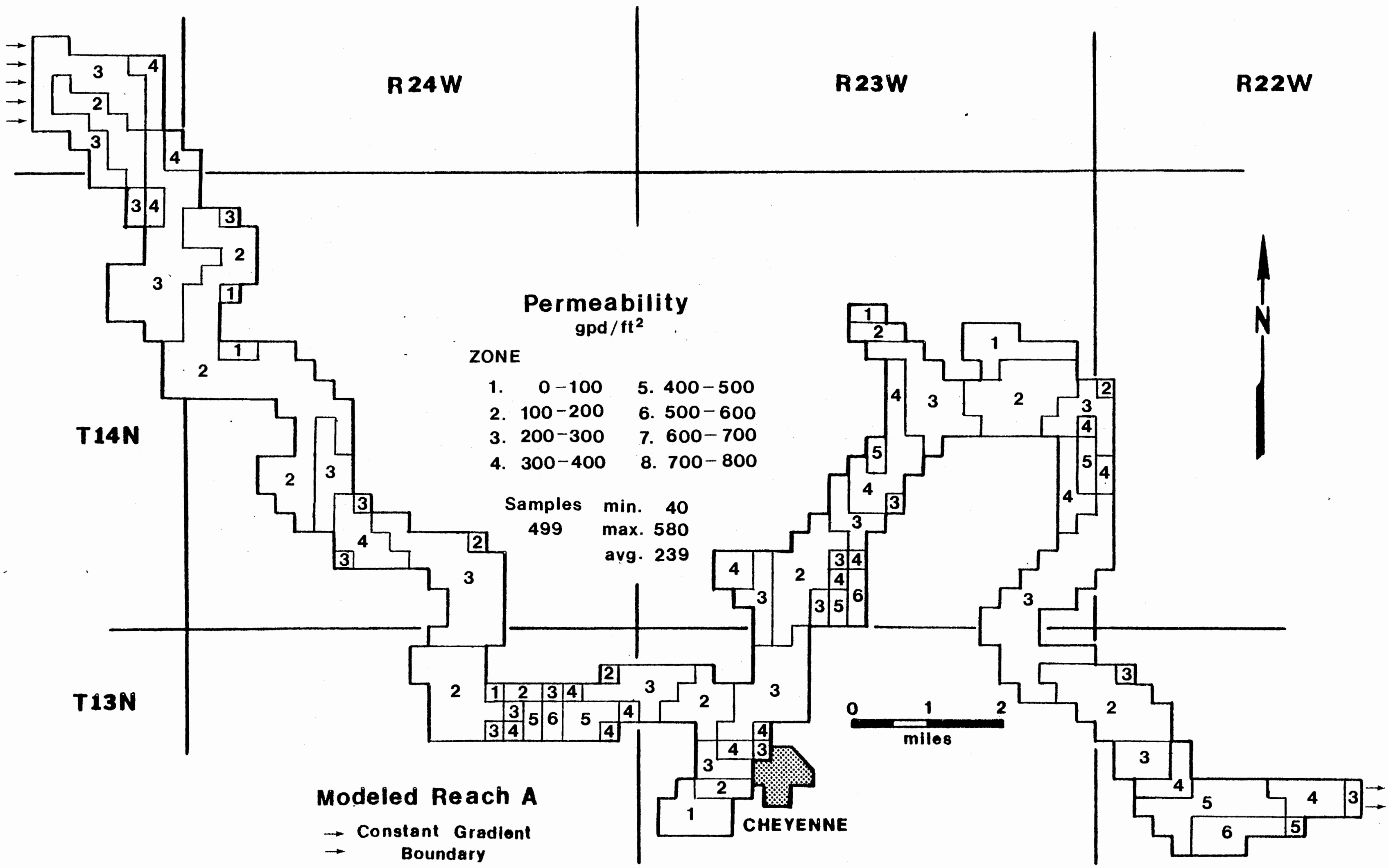

Figure 55. Permeability Map, Upper Modeled Reach (Part A)

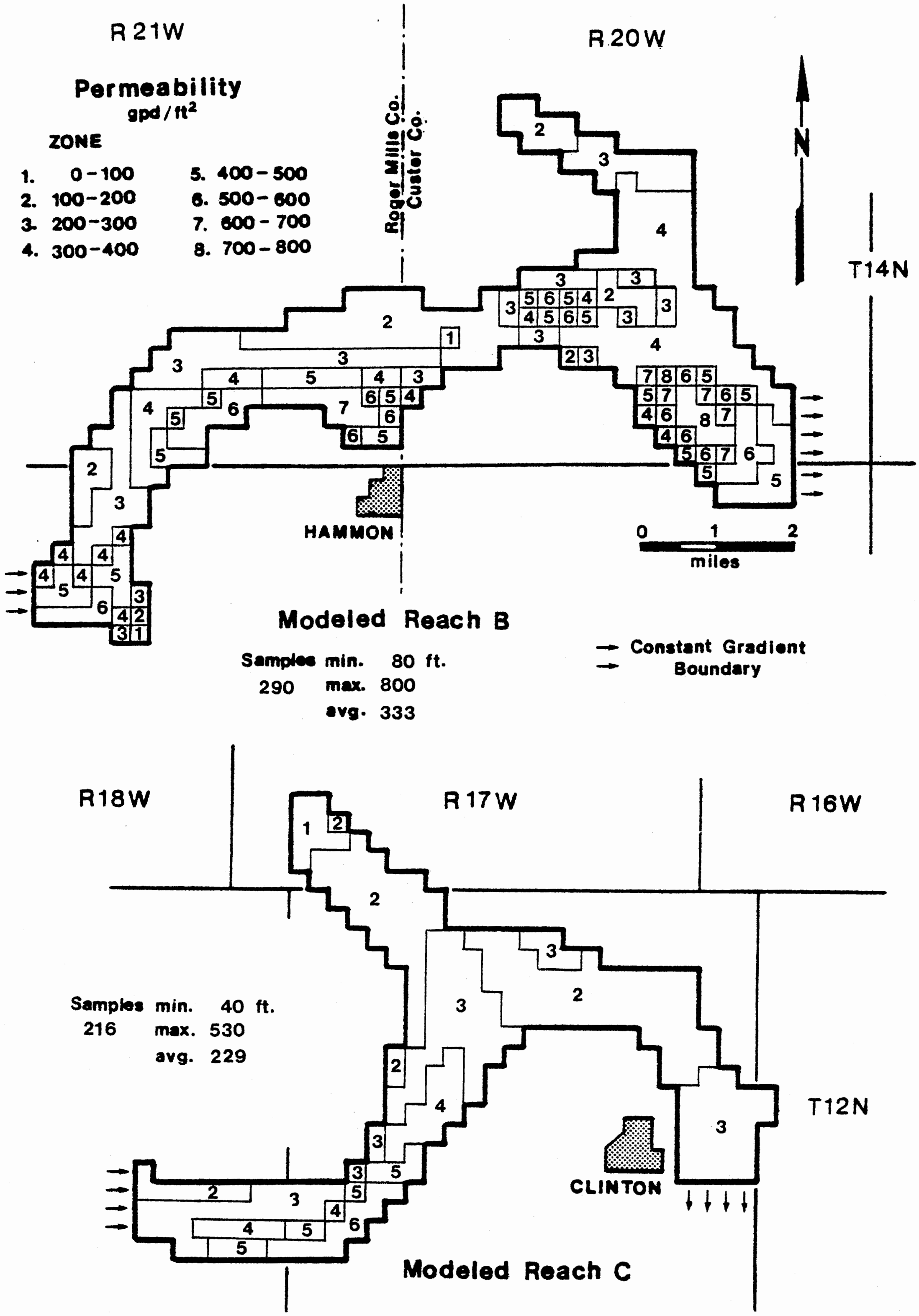

Figure 56. Permeability Map, Middle and Lower Modeled Reaches (Parts B and C)

APPENDIX G

TRANSMISSIVITY MAPS, JULY 1, 1973, AND JULY 1, 1993, FOR THE UPPER, MIDDLE, AND LOWER MODELED REACHES

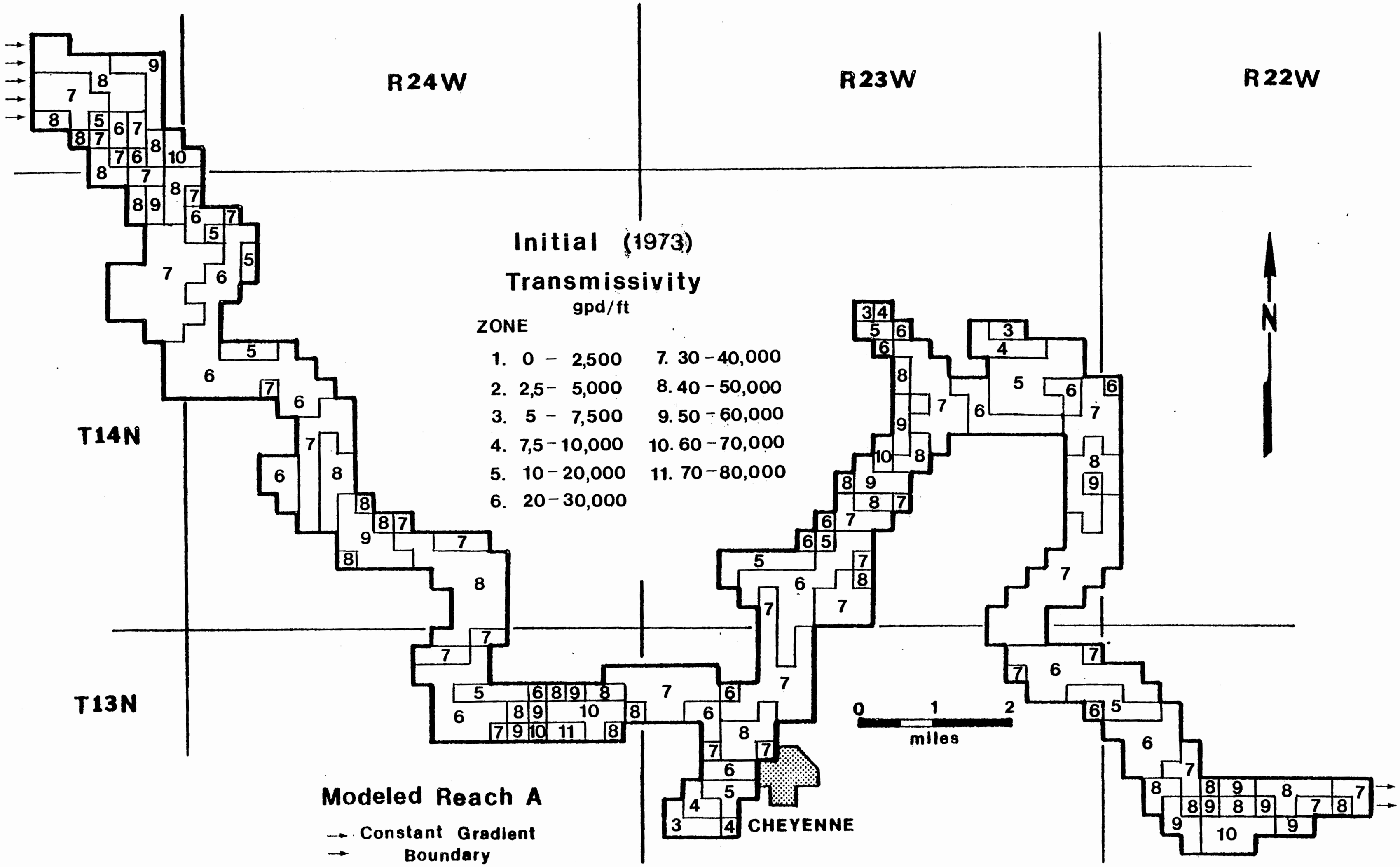

Figure 57. Transmissivity, July 1, 1973, Upper Modeled Reach (Part A)

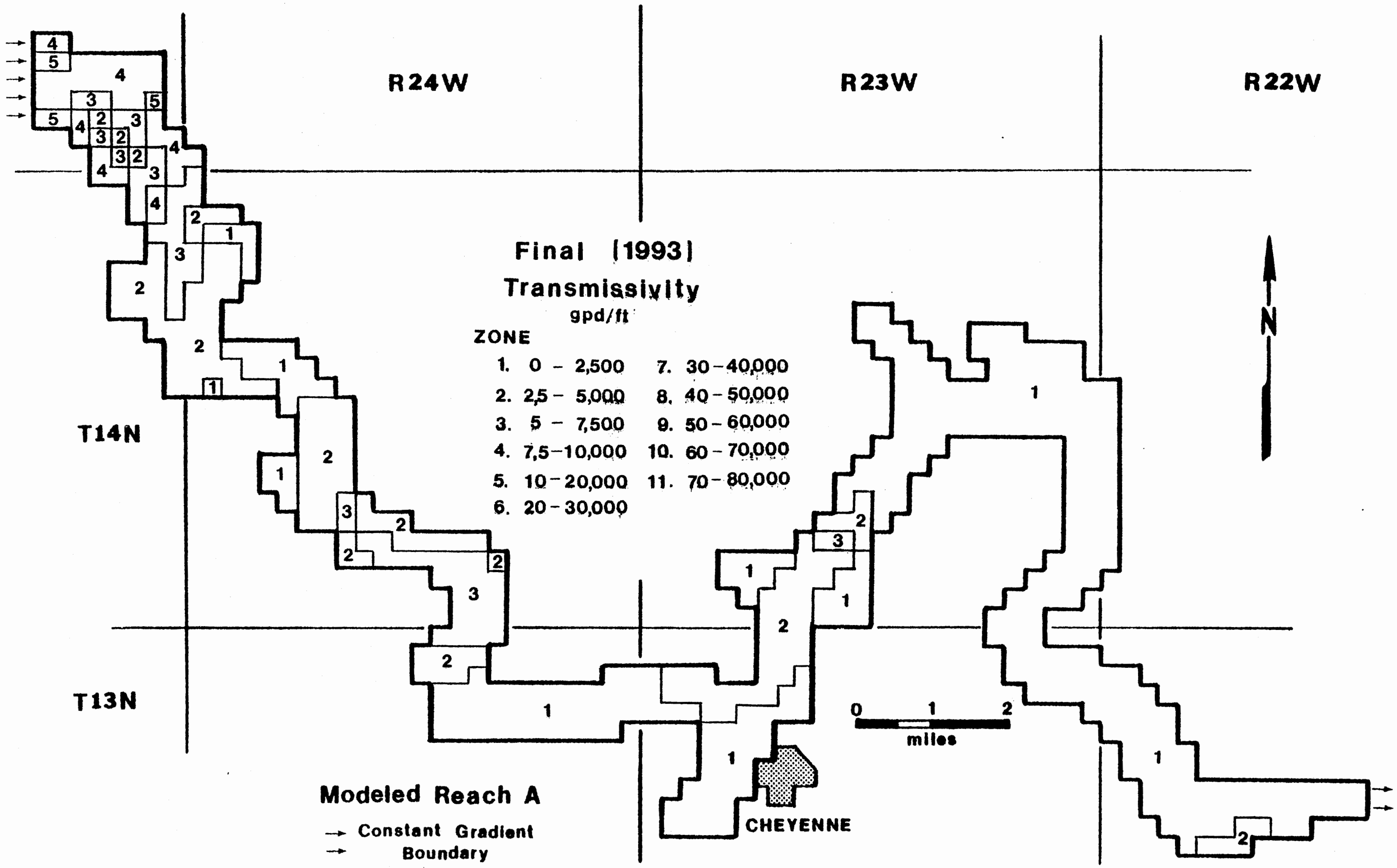

Figure 58. Transmissivity, July 1, 1993, Upper Modeled Reach (Part A)

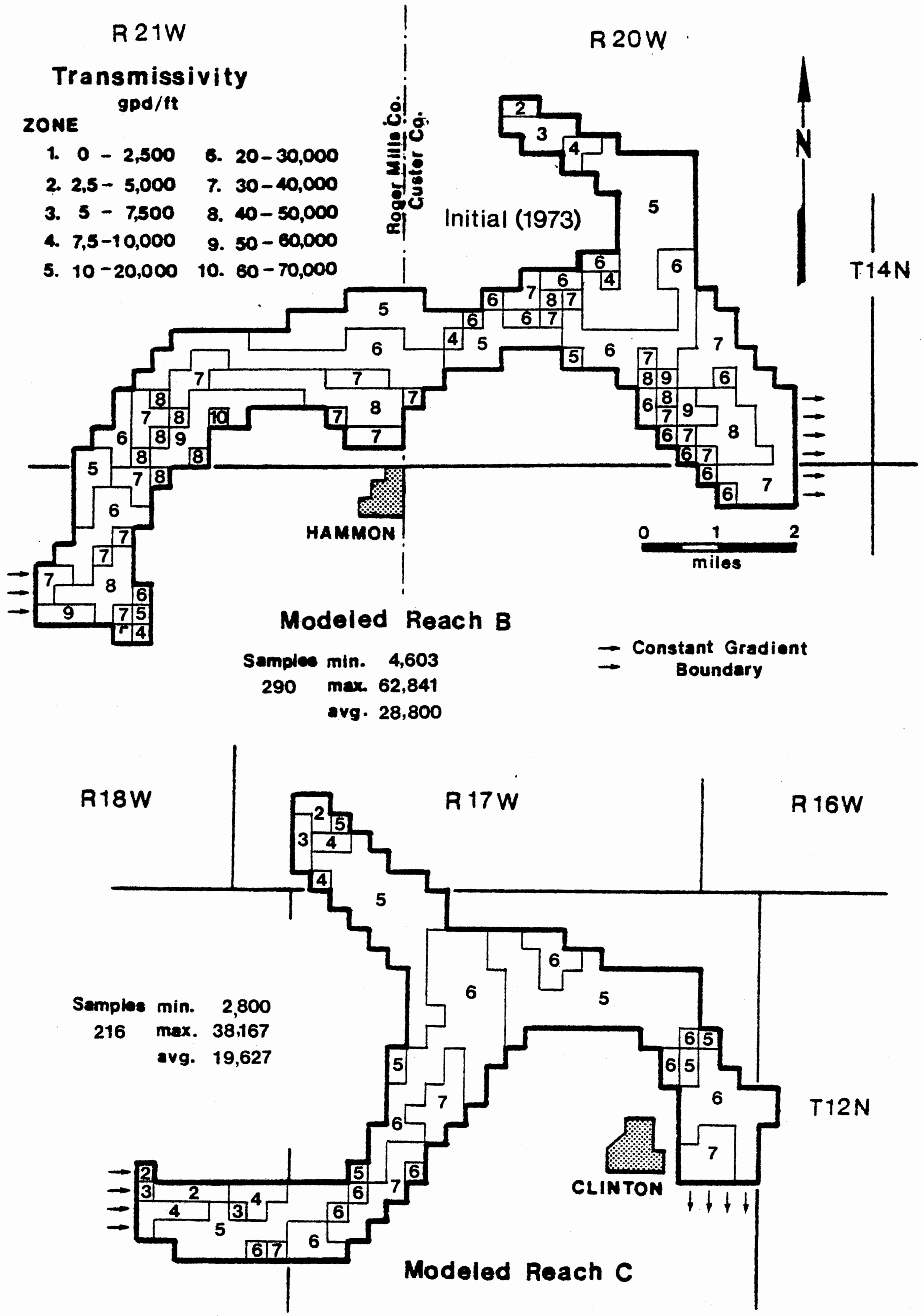

Figure 59. Transmissivity, July 1, 1973, Middle and Lower Modeled Reaches (Parts B and C)

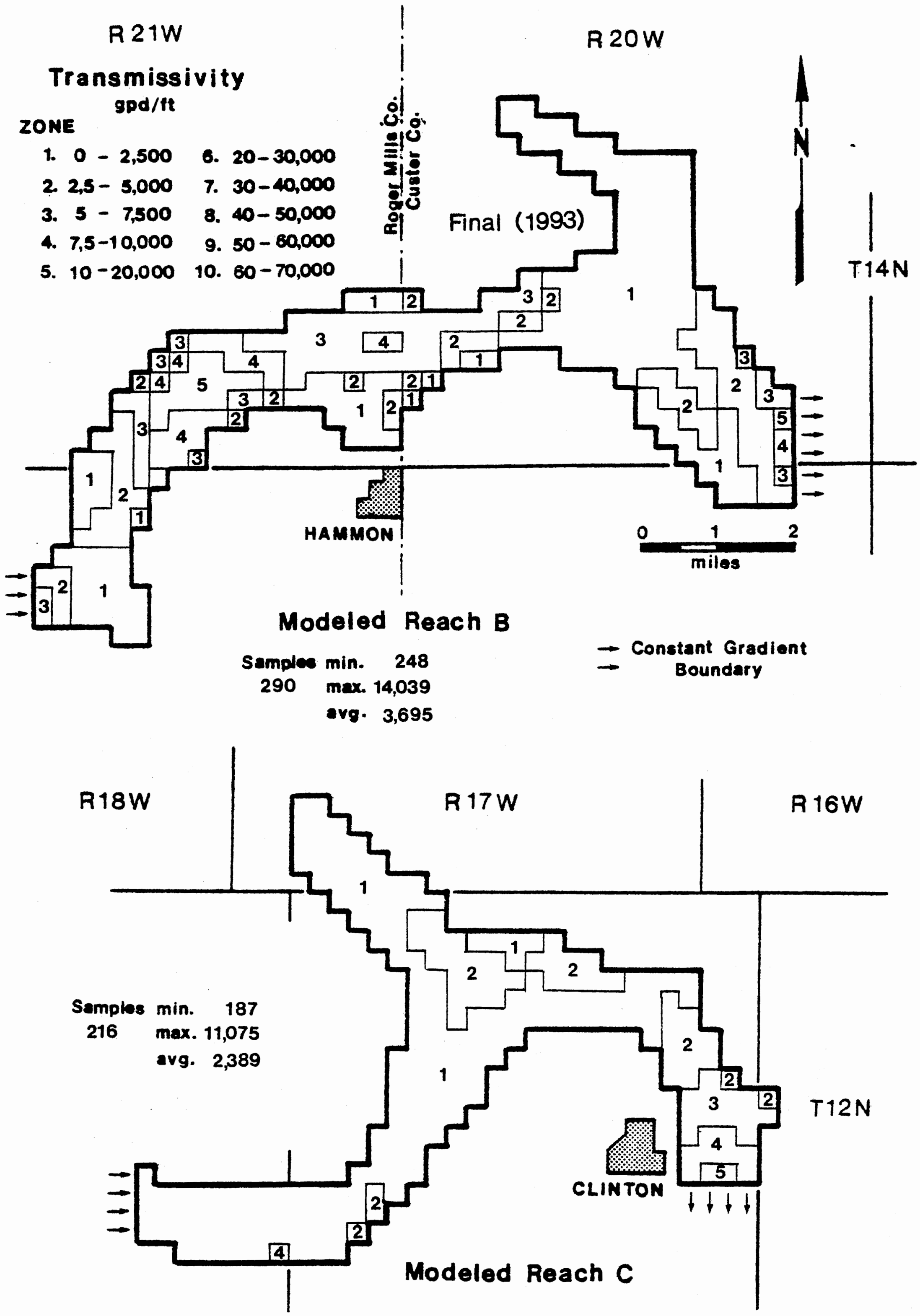

Figure 60. Transmissivity, July 1, 1993, Middle and Lower Modeled Reaches (Parts B and C)

APPENDIX H

WATER DEPTH, JULY 1, 1973, AND JULY 1, 1993, FOR THE UPPER, MIDDLE, AND LOWER MODELED REACHES

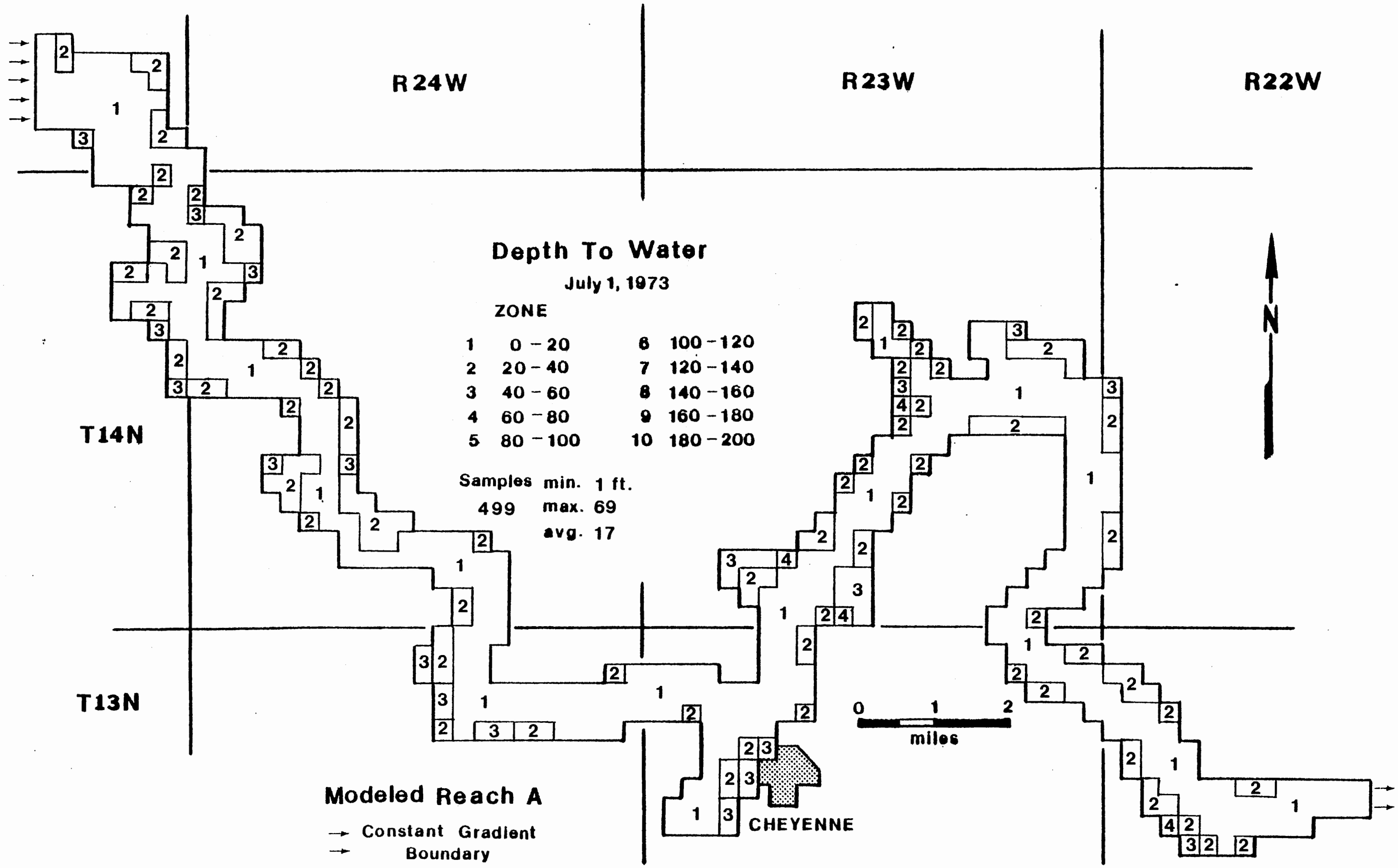

Figure 61. Water Depth, July 1, 1973, Upper Modeled Reach (Part A)

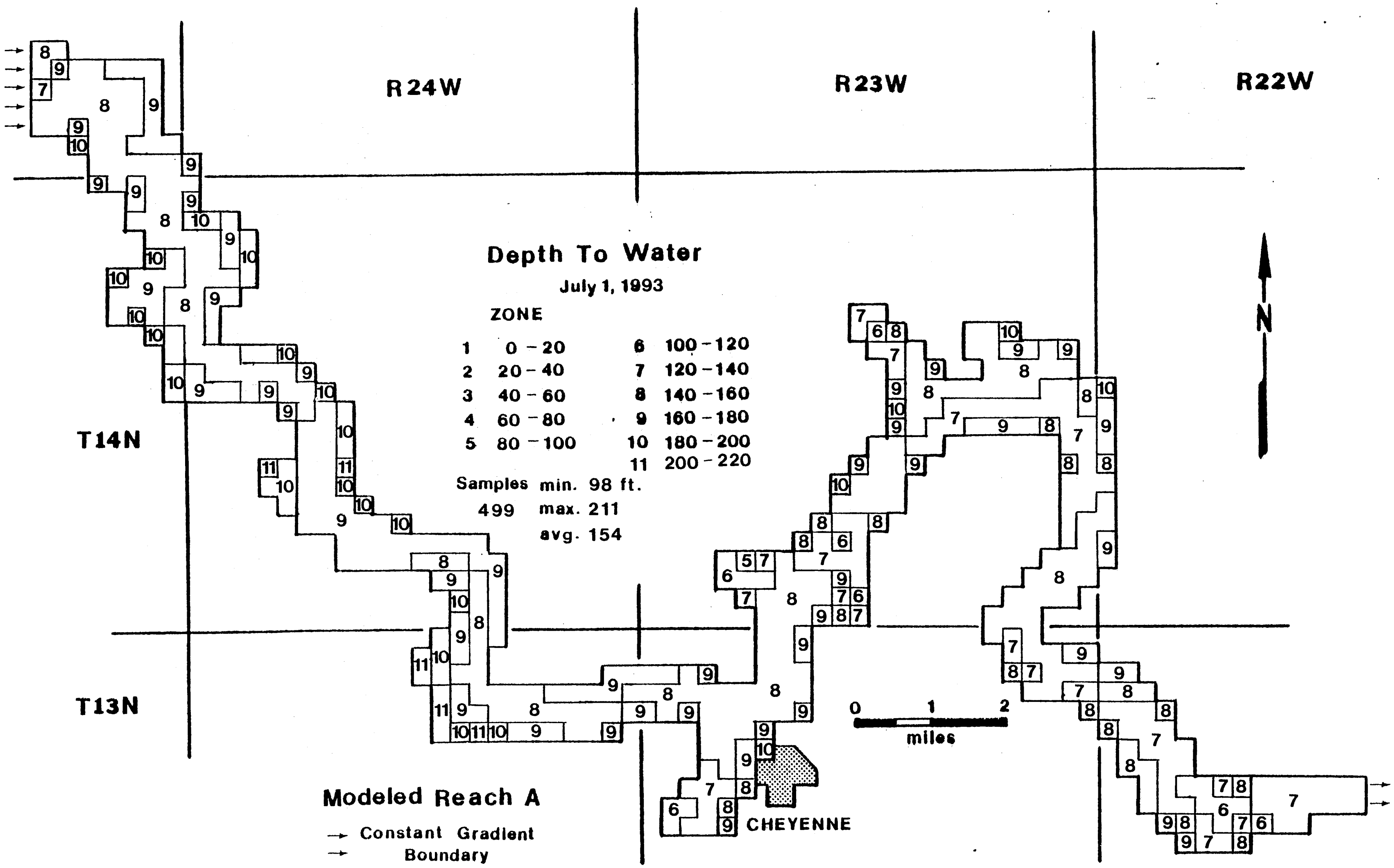

Figure 62. Water Depth, July 1, 1993, Upper Modeled Reach (Part A)

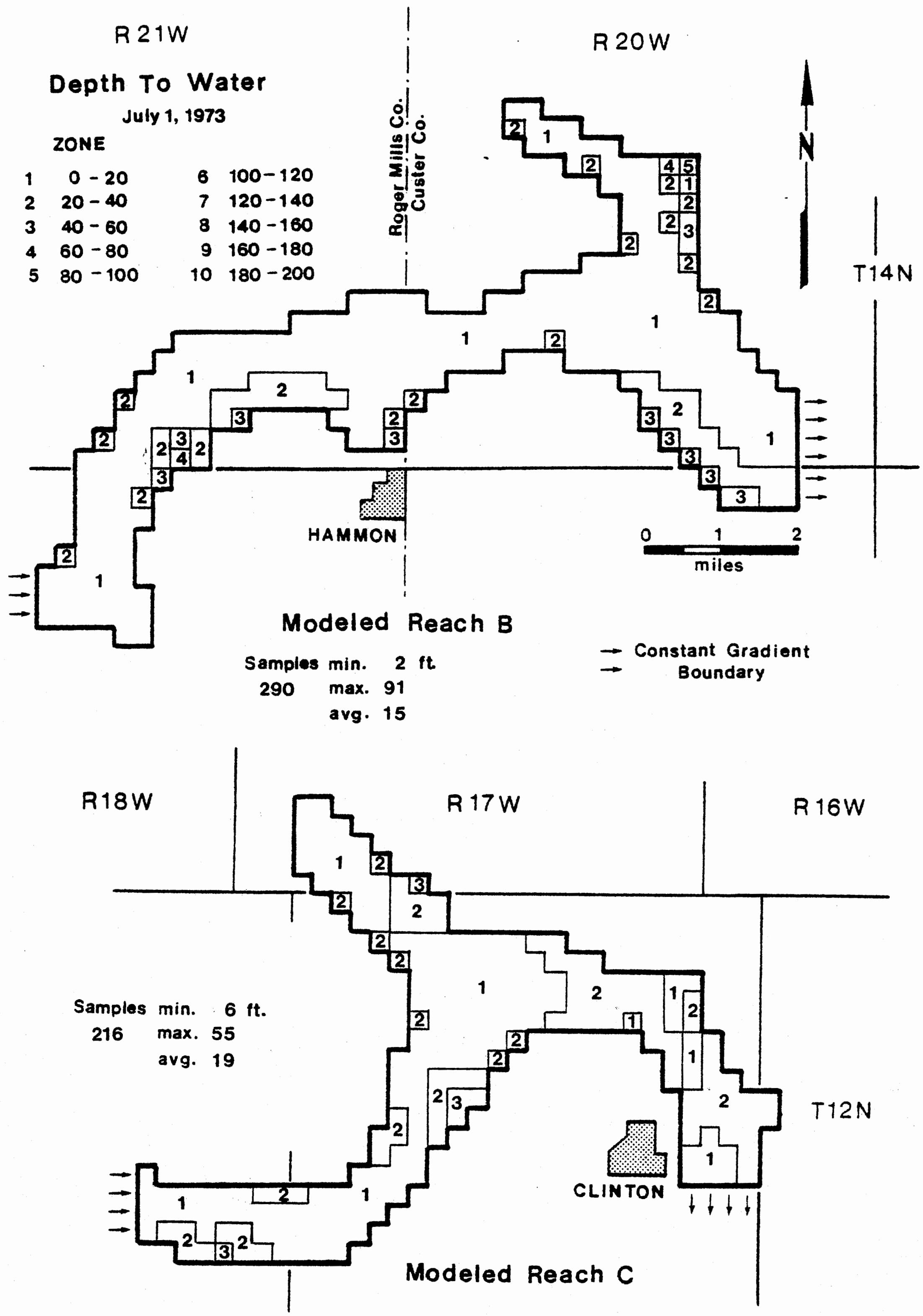

Figure 63. Water Depth, July 1, 1973, Middle and Lower Modeled Reaches (Parts B and C)

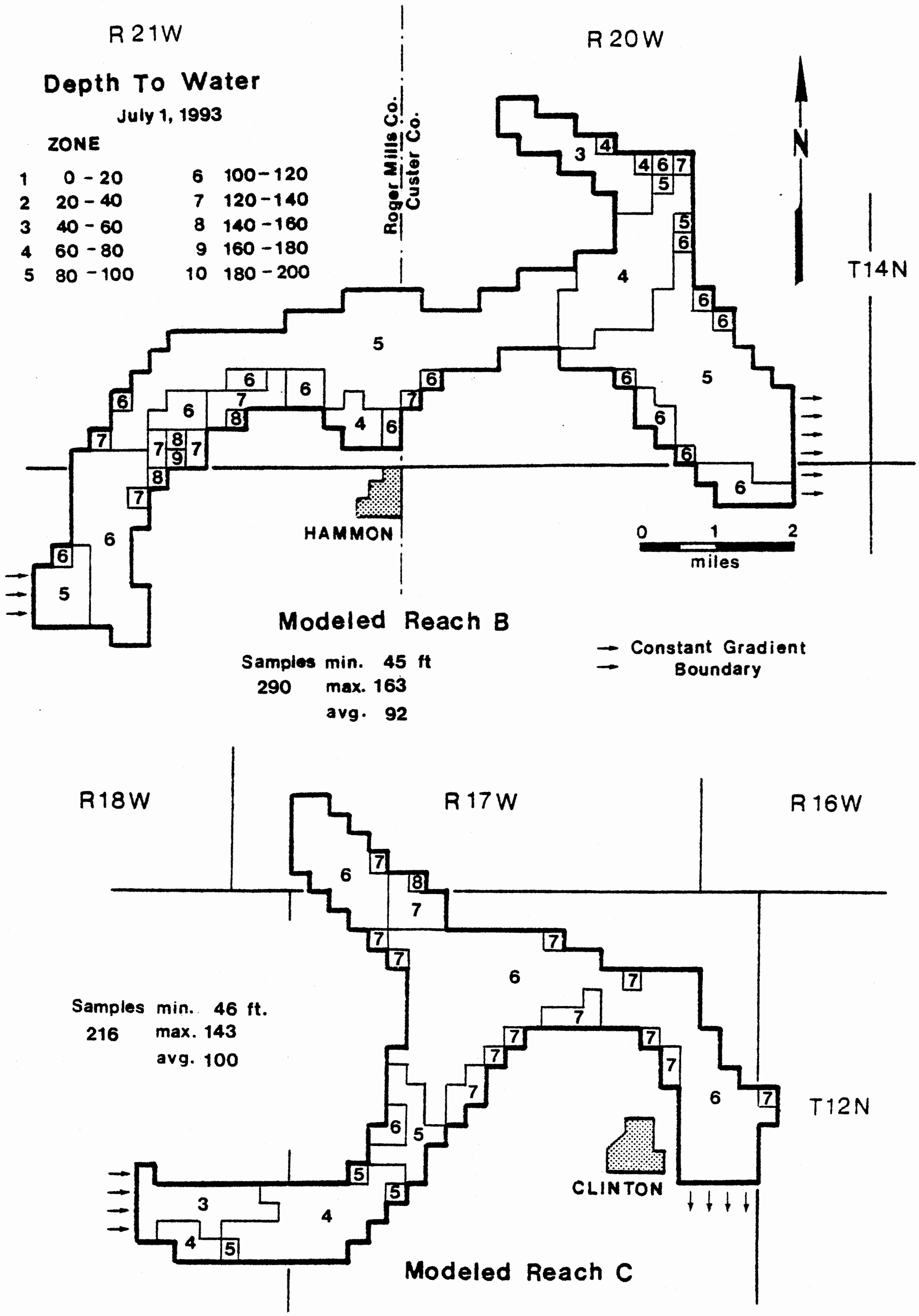

Figure 64. Water Depth, July 1, 1993, Middle and Lower Modeled Reaches (Parts B and C)

APPENDIX I

DISTRIBUTION OF PRIOR APPROPRIATIVE RIGHTS FOR THE UPPER, MIDDLE, AND LOWER MODELED REACHES

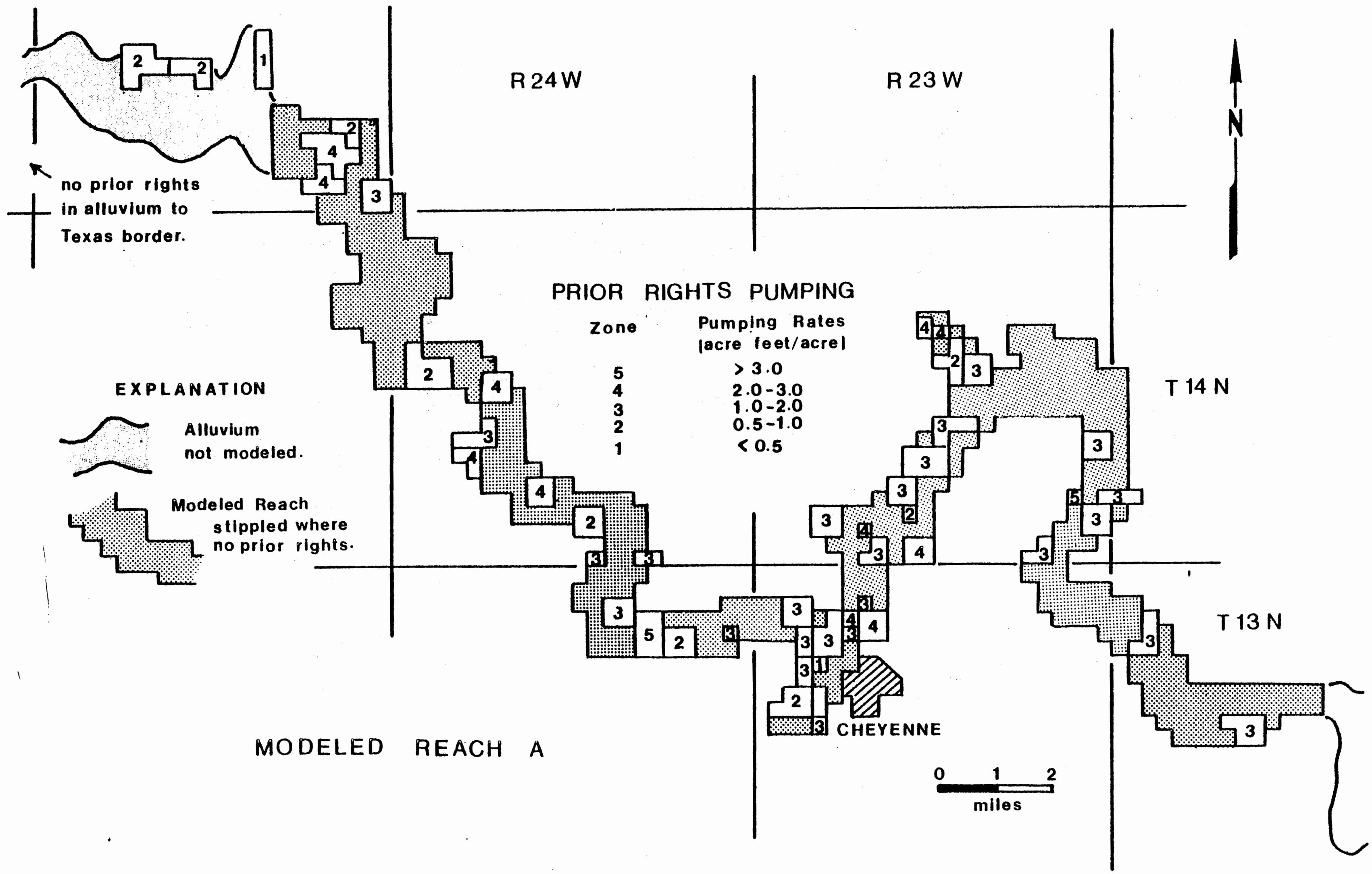

Figure 65. Distribution of Prior Rights Pumping, Upper Modeled Reach (Part A) and Adjacent Areas

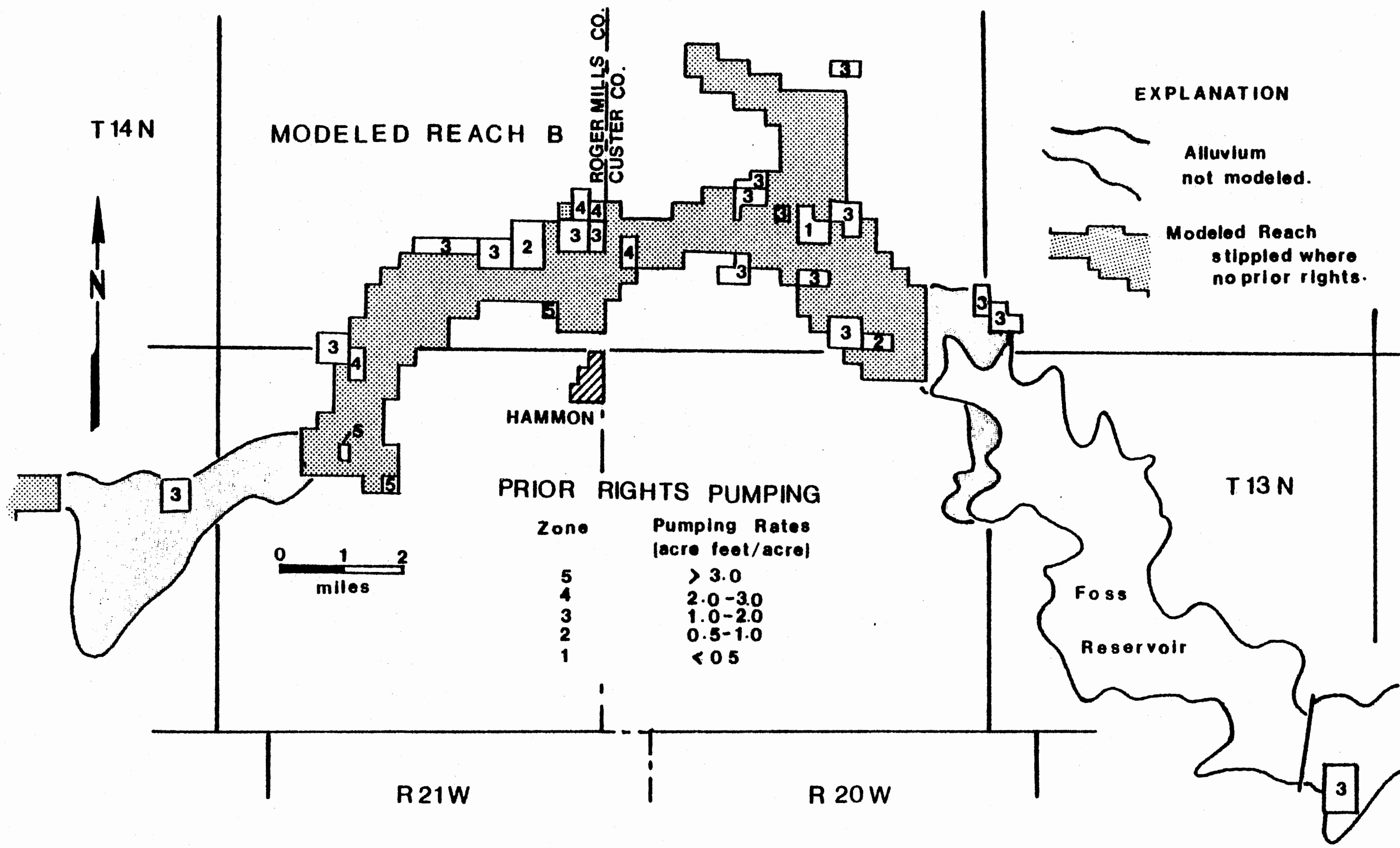

Figure 66. Distribution of Prior Rights Pumping, Middle Modeled Reach (Part B) and Adjacent Areas

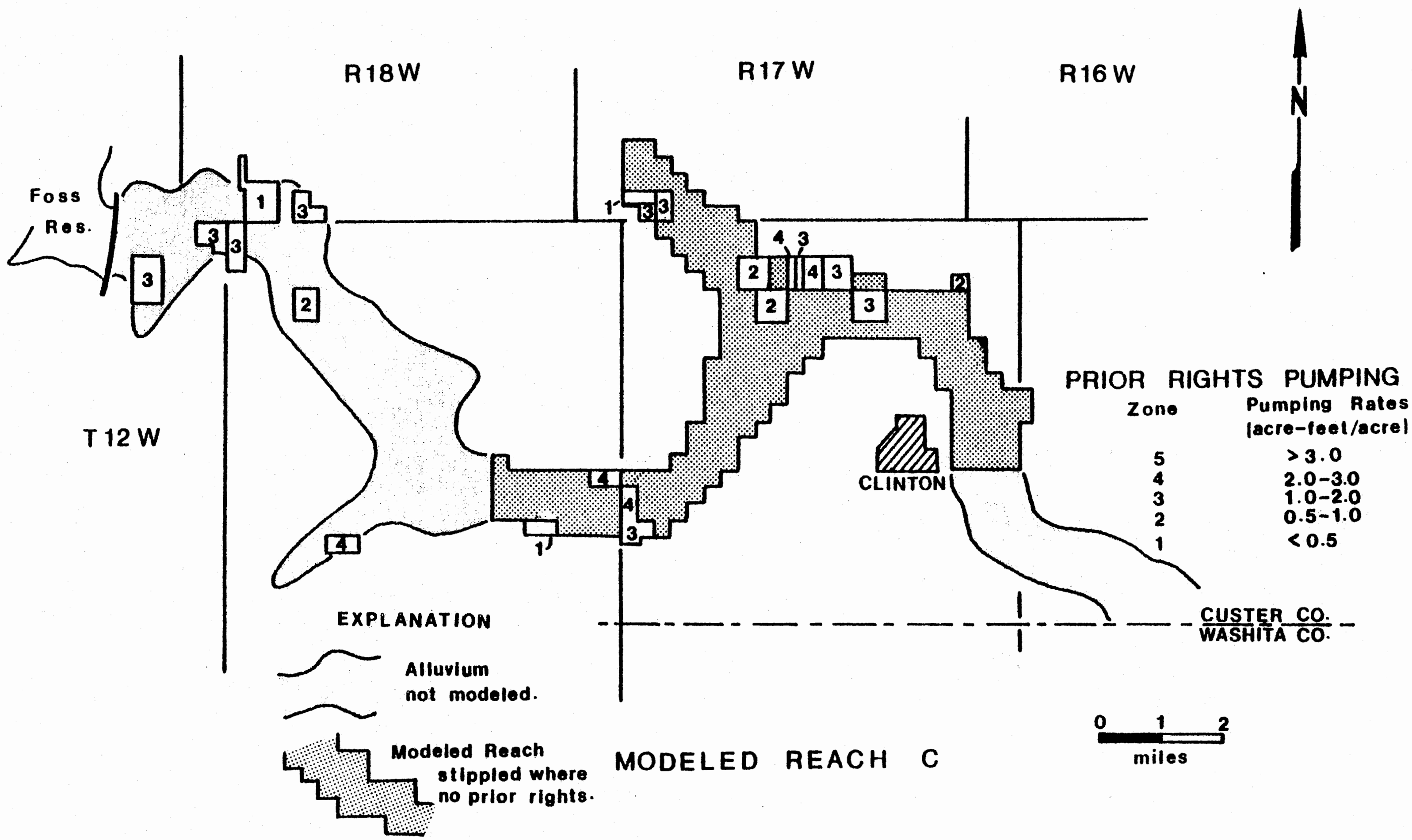

Figure 67. Distribution of Prior Rights Pumping, Lower Modeled Reach (Part C) and Adjacent Areas

APPENDIX J

MASS BALANCE OF PRIOR APPROPRIATIVE PUMPING FROM JULY 1, 1973, TO JULY 1, 1993, FOR THE UPPER, MIDDLE, AND LOWER MODELED REACHES

TABLE VII

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

	Average Annual (acre feet)		Twenty Year Total (acre feet)	
	Inflow	Outflow	Inflow	Outflow
Recharge	4990		99,798	
Pumpage		-8209		-164,181
River Leakage	.9	-1277	18	-25,547
Subsurface Flow	508	-221	10,150	-4,423
Evapotranspiration		-44		-871
TOTALS	5498	-9751	109,966	-195,022
Net Storage		-4253		-85,056

Total Prior Rights for Upper Modeled Reach (1973) = 9658 a.f.
or 0.48 ac ft/ac

TABLE VIII

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

	Average Annual (acre feet)		Twenty Year Total (acre feet)	
	Inflow	Outflow	Inflow	Outflow
Recharge	3093		61,863	
Pumpage		-2911		-58,207
River Leakage	1.15	-823	23	-16,463
Subsurface Flow	260	-425	5,198	-8,507
Evapotranspiration				-0
TOTALS	3354	-4159	67,085	-83,177
Net Storage		-805		-16,092

Total Prior Rights for Middle Modeled Reach (1973) = 3792 a.f. or .33 ac ft/ac.

TABLE IX

MASS BALANCE OF PRIOR APPROPRIATIVE PUMPING FROM
JULY 1, 1973, TO JULY 1, 1993
(Lower Reach C)

	Average Annual (acre feet)		Twenty Year Total (acre feet)	
	Inflow	Outflow	Inflow	Outflow
Recharge	2407		48,142	
Pumpage		-1488		-29,762
River Leakage	0.25	-977	5	-19,546
Subsurface Flow	55	-171.6	1,092	-3,432
Evapotranspiration		0		0
TOTALS	2462	-2636	49,238	-52,721
Net Storage		174		-3,483

Total Prior Rights for Lower Modeled Reach (1973) = 1819 a.f.
or 0.21 ac ft/ac.

APPENDIX K

PRIOR APPROPRIATIVE ONLY WATER-TABLE MAPS,

JULY 1, 1993, FOR THE UPPER, MIDDLE,

AND LOWER MODELED REACHES

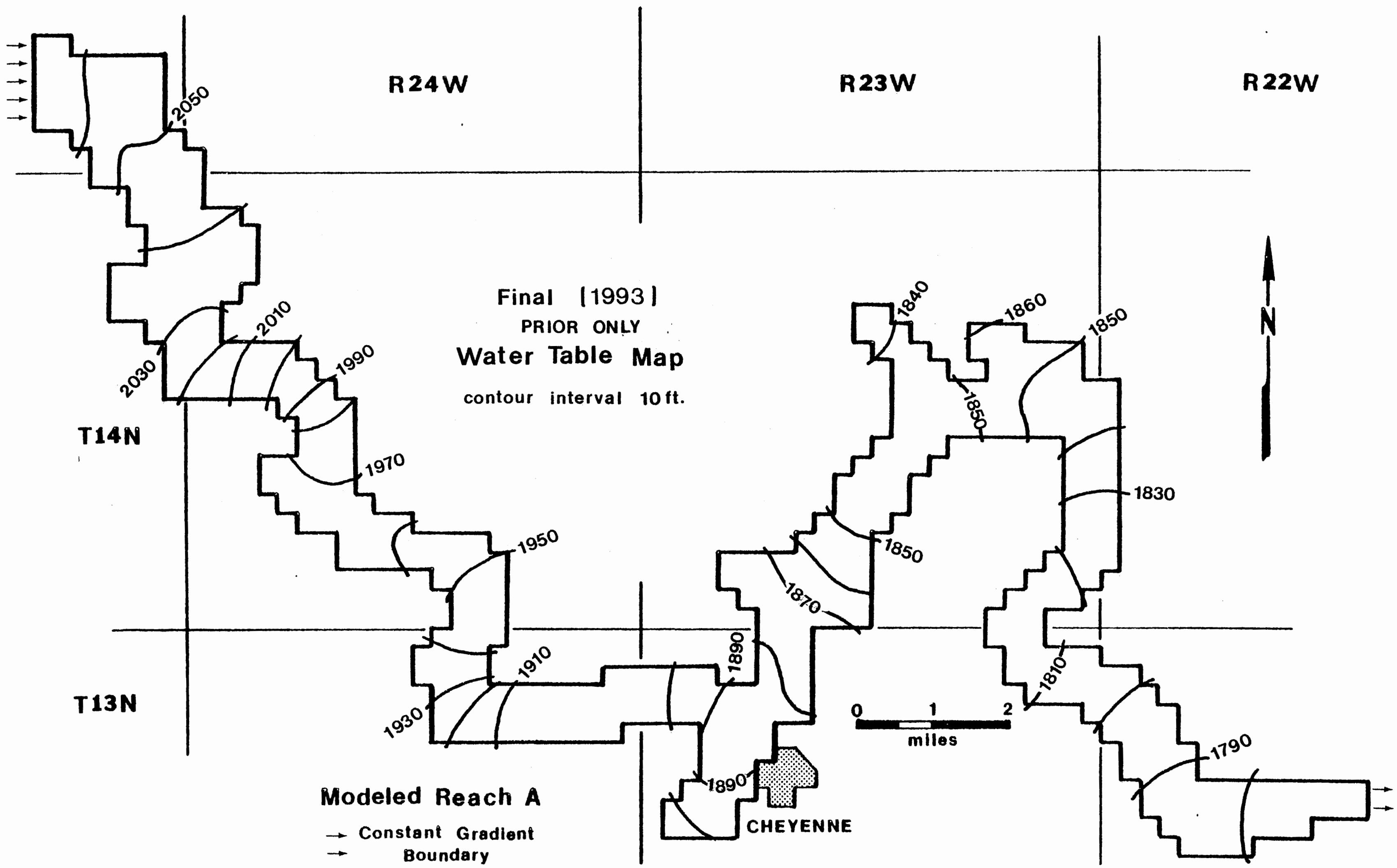

Figure 66. Prior Rights Pumping Water Table Map, July 1, 1993, Upper Modeled Reach (Part A)

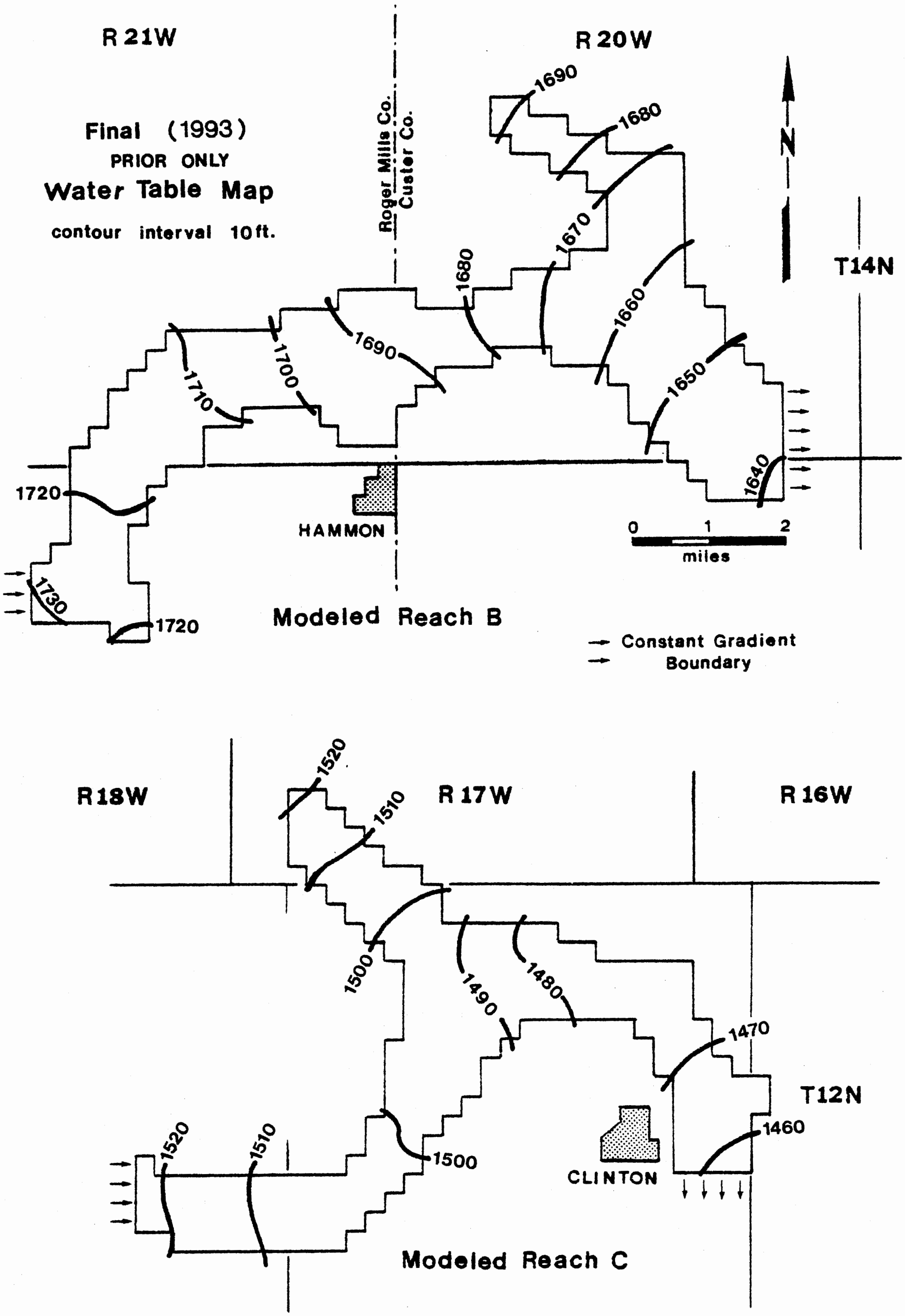

Figure 69. Prior Rights Pumping Water Table Map, July 1, 1993, Middle and Lower Modeled Reaches (Parts B and C)

APPENDIX L

COMPUTER-GENERATED MAP OUTPUT WITH CORRESPONDING COMPLETED ZONED MAP

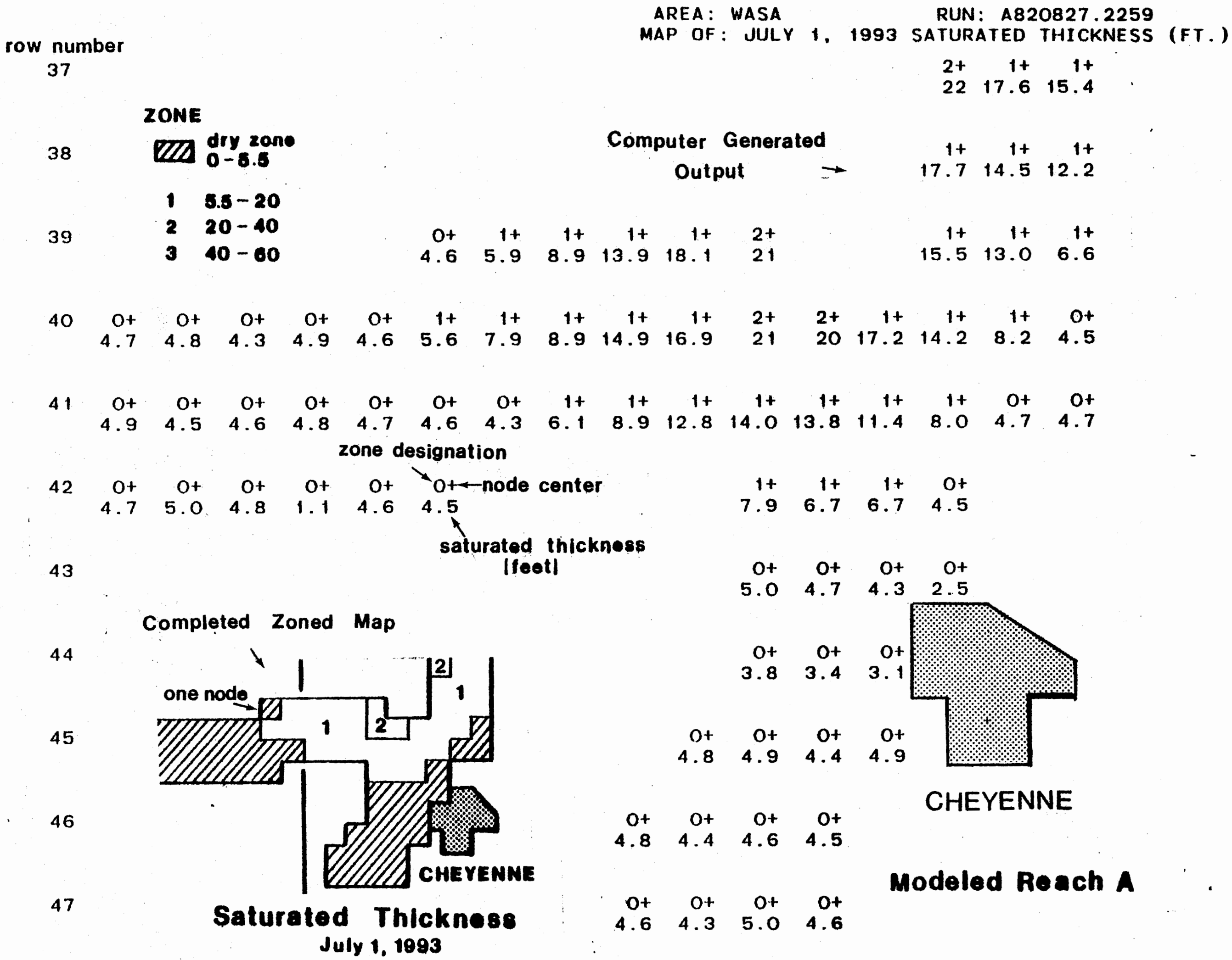

Figure 70. Example of Computer-generated Map Output With the Corresponding Completed Zoned Map Showing Saturated Thickness, 1993, for Part of Modeled Reach A

APPENDIX M

PROCEDURE FOR COMPLETING 20-YEAR GROUND-WATER BUDGET

Procedure to complete 20-year ground-water budget "plumbing diagram" for a modeled area:

Obtain 20-year mass balance for prior and allocation runs. Make a table as shown in Table X. Table X is completed as an example for Modeled Reach A. Figure 37 is the water budget diagram for Modeled Reach A. Figure 71 is the example water budget diagram with the boxes numbered for use with the completion following procedure. Computer-generated statistics and the allocation mass balance for the upper modeled reach that were used in completing this example water budget are shown in Figures 72 and 73, respectively.

Water Budget Completion Procedure

Fill in the water budget diagram for modeled area as follows:

Δ = 1973-1993; values from column Δ are used in the 20-year budget.

Box 1-5 values are taken from program statistics
Box 6 is Box 5 minus actual river surface area
Box 7 is annual irrigation allocation
Box 8 is Box 7 x return flow rate (Box 10)
Box 9 is Box 7 - Box 8
Box 10 is the assigned return flow rate
Box 11 is the average rainfall rate in inches/year
Box 12 is (Box 11 ÷ 12) x 20 years x total area (Box 5)
Box 13 is (Box 14 x 12 ÷ 20) ÷ total area (Box 5)
Box 14 value taken from mass balance (e.g., Table X)
Box 15 is Box 13 ÷ Box 11
Box 16 is Box 11 - Box 13
Box 17 is Box 12 - Box 14
Box 18 is allocation ΔE.T. from mass balance (e.g., Table X)
Box 19 is (Box 18 x 12 ÷ 20) ÷ Box 5
Box 20 through 23 are from mass balance (e.g., Table X)
Box 24 is allocation Δ pumping from mass balance (e.g., Table X)
Each Box 25 is the corresponding Box above ÷ 20
Each Box 26 is the corresponding Box 25 ÷ Box 5
Box 27 is Box 28 - Box 24
Box 28 is Box 24 ÷ (1 - return flow rate)
Box 29 is prior Δ pumping from mass balance (e.g., Table X)
Box 30 is Box 31 - Box 29
Box 31 is Box 29 ÷ Box 29 ÷ (1 - return flow rate)
Box 32 is Box 24 - Box 29

Box 33 is Box 27 - Box 30
Box 34 is Box 28 - Box 31
Box 35 is final storage, 1993, for modeled area taken from program statistics
Box 36 is initial storage, 1973, for modeled area taken from program statistics
Box 37 is final storage + effective pumping, or Box 35 + Box 24
Box 38 is Box 37 + Box 27
Box 39 is Box 24 ÷ Box 37
Box 40 is Box 29 ÷ Box 37
Box 41 is Box 32 ÷ Box 37
Box 42 through 45 are taken from program statistics

TABLE X

EXAMPLE MASS BALANCE
(Values for Modeled Reach A used as an example)

	Allocation			Prior		
	1973 Time Step 3 0.08 years	1993 Time Step 3 20.08 years	Δ	1973 Time Step 3 0.08 years	1993 Time Step 3 20.08 years	Δ
OUTFLOW						
Pumping	-2,052	-850,874	-848,822	2,052	-166,233	-164,181
Leakage	-134	-153	-19	-134	-25,681	-25,547
Gradient	-18	-2,587	-2,569	-18	-4,441	-4,423
E. T.	-18	-21	-3	-18	-889	-871
TOTAL →	-2,223	-853,635	-851,412	-2,223	-197,245	-195,022
INFLOW						
Leakage	0	49	49	0	18	18
Gradient	47	6,740	6,693	47	10,197	10,150
Recharge	416	100,214	99,798	416	100,214	99,798
TOTAL →	463	107,002	106,539	463	110,429	109,966
NET	-1,760	-746,633	-744,873	-1,760	-86,816	-85,056

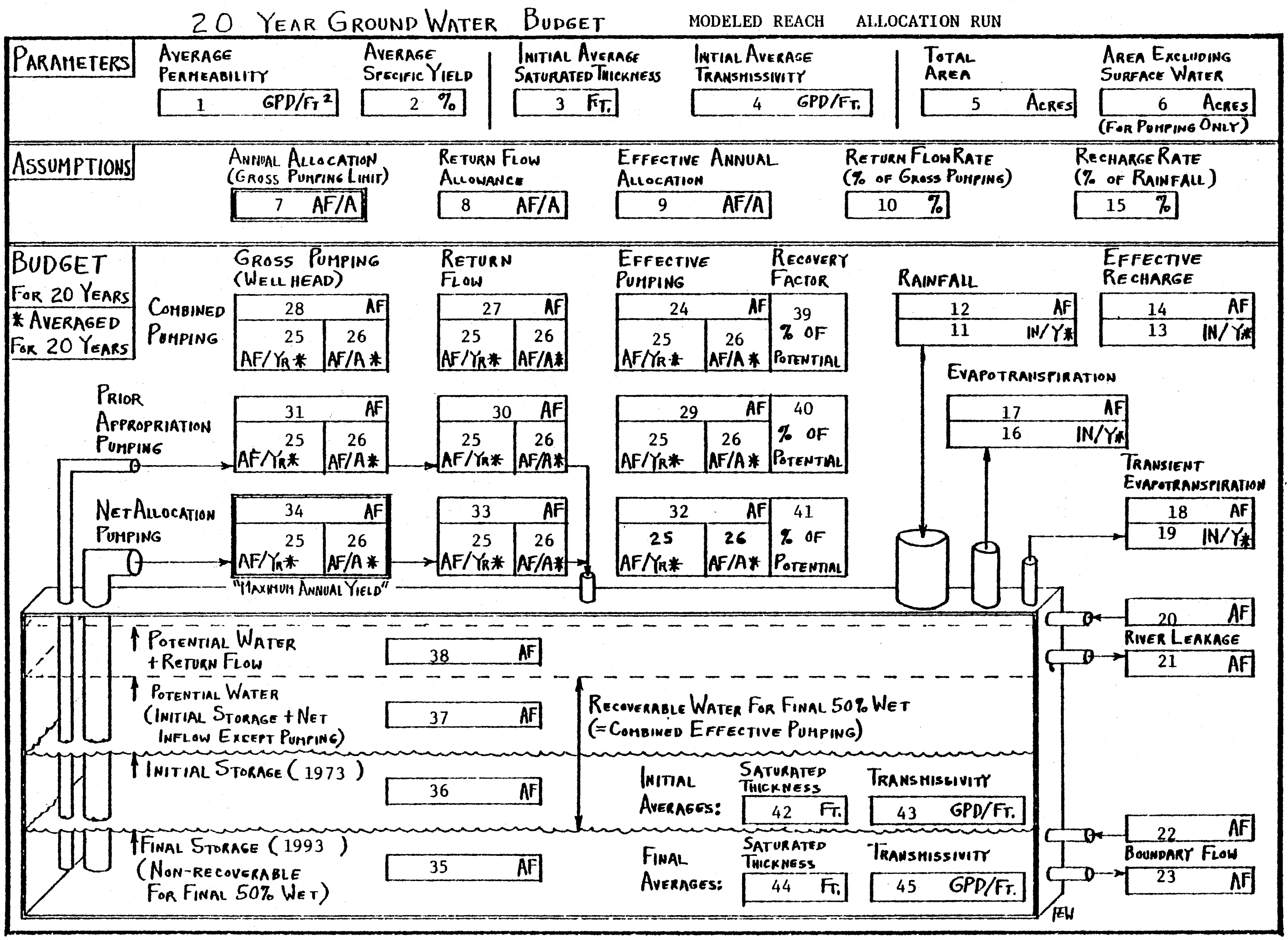

Figure 71. Example Water Budget Diagram

AREA: WASA
RUN: A820827.2259
NODE AREA: 40 ACRES
PUMPING PERIOD: 0.33 (FRACTION OF YEAR)
RETURN FLOW RATE: 15 PERCENT
NET PUMPING RATE: 85 PERCENT

JULY 1, 1973:	NON-RIVER	RIVER	STUDY AREA	BOUNDARY	ALL NODES	
NUMBER OF NODES:	372	127	499	13	512	
NUMBER OF DRY NODES:						
PERCENT DRY:						PERCENT
AREA:	14880	5080	19960	520	20480	ACRE
PERMEABILITY:	235	251	239	217	239	GPD/FT2
SPECIFIC YIELD:	26.6	26.6	26.6	26.6	26.6	PERCENT
SATURATED THICKNESS:	149	154	150	152	150	FEET
RECHARGE:	3.00	3.00	3.00	0.00	2.92	IN/YR
TOTAL PUMPING:	17850	6778	24628	0	24628	AF/YR
STORED WATER:	589834	208448	798282	21046	819327	AF

DATA FROM:
A820827.2259 ALLOC=2.70AF/A; RATE=250GPD*.075; M=330; RIVER+1; RECH 3

AREA: WASA
RUN: A820827.2259
NODE AREA: 40 ACRES
PUMPING PERIOD: 0.33 (FRACTION OF YEAR)
RETURN FLOW RATE: 15 PERCENT
NET PUMPING RATE: 85 PERCENT

JULY 1, 1993:	NON-RIVER	RIVER	STUDY AREA	BOUNDARY	ALL NODES	
NUMBER OF NODES:	372	127	499	13	512	
NUMBER OF DRY NODES:	194	55	249		249	
PERCENT DRY:	52.2	43.3	49.9		48.6	PERCENT
AREA:	14880	5080	19960	520	20480	ACRE
PERMEABILITY:	235	251	239	217	239	GPD/FT2
SPECIFIC YIELD:	26.6	26.6	26.6	26.6	26.6	PERCENT
SATURATED THICKNESS:	12	15	13	32	14	FEET
RECHARGE:	3.00	3.00	3.00	0.00	2.92	IN/YR
TOTAL PUMPING:	102979	35284	138263	0	138263	AF/YR
STORED WATER:	49206	20283	69489	4473	73962	AF
CHANGE IN STORAGE:	-540628	-188164	-728793	-16572	-745365	AF

	GROSS PUMPING	RETURN FLOW	NET PUMPING	
MAXIMUM ALLOCATION:	2.70	0.40	2.29	AF/A

DATA FROM:
A820827.2259 ALLOC=2.70AF/A; RATE=250GPD*.075; M=330; RIVER+1; RECH 3

Figure 72. Computer-generated Statistics From the 20-Year Allocation Pumping Simulation for the Upper Modeled Reach (Part A)

Time step no. 3
Pumping dur. 0.08 yr.

M A S S   B A L A N C E

TYPE OF FLOW	CURRENT RATE (ACRE FT/YR) INFLOW	OUTFLOW	CUMULATIVE (ACRE FT) INFLOW	OUTFLOW
PUMPING	0.	-24987.	0.	-2052.
LEAKAGE	0.	-2627.	0.	-134.
CONSTANT FLUX	572.	-225.	47.	-18.
EVAPOTRANS.		-225.		-18.
RECHARGE	5063.	0.	416.	0.
TOTAL	5635.	-28063.	463.	-2223.
NET INFLOW	-22428.		-1760.	
STORAGE INCR.	-22428.		-1760.	
ERROR	0.		0.	
PERCENT ERROR	0.00%		0.00%	

0 DRY NODES.

MAXIMUM CHANGE IN HEAD FOR THIS TIME STEP = 1.056

SUM OF THE ABSOLUTE VALUE OF HEAD CHANGES FOR EACH ITERATION:

98.83 1.329 .6616E-01

Time step no. 3
Pumping dur. 20.08 yr.

M A S S   B A L A N C E

TYPE OF FLOW	CURRENT RATE (ACRE FT/YR) INFLOW	OUTFLOW	CUMULATIVE (ACRE FT) INFLOW	OUTFLOW
PUMPING	0.	-74882.	0.	-850874.
LEAKAGE	0.	0.	49.	-153.
CONSTANT FLUX	128.	-42.	6740.	-2587.
EVAPOTRANS.		0.		-21.
RECHARGE	5063.	0.	100214.	0.
TOTAL	5191.	-74924.	107002.	-853635.
NET INFLOW	-69733.		-746633.	
STORAGE INCR.	-69732.		-746607.	
ERROR	-1.		-26.	
PERCENT ERROR	-0.03%		-0.02%	

0 DRY NODES.

MAXIMUM CHANGE IN HEAD FOR THIS TIME STEP = 0.703

SUM OF THE ABSOLUTE VALUE OF HEAD CHANGES FOR EACH ITERATION:

190.0 .1685

Figure 73. Computer-generated Mass Balance From the 20-Year Allocation Pumping Simulation for the Upper Modeled Reach (Part A)

VITA

Mark Raymond Schipper

Candidate for the Degree of

Master of Science

Thesis: A GROUND WATER MANAGEMENT MODEL FOR THE WASHITA RIVER ALLUVIAL AQUIFER IN ROGER MILLS AND CUSTER COUNTIES, OKLAHOMA

Major Field: Geology

Biographical:

Personal Data: Born in Dayton, Ohio, June 9, 1953, the son of Mr. and Mrs. Raymond J. Schipper.

Education: Graduated from Chaminade High School, Dayton, Ohio, in June, 1971; received Bachelor of Science degree from Ohio State University, Columbus, in May, 1975, with a major in Geology; completed requirements for the Master of Science degree at Oklahoma State University, Stillwater, Oklahoma, in May, 1983.

Professional Experience: Exploration geologist, Continental Oil Company, Uranium Exploration, Albuquerque, New Mexico, 1977; Staff Hydrologist, Geohydrology Associates, Albuquerque, 1977-1980; Research Assistant, Oklahoma State University, 1981-1982.