Hydrogeologic Investigation of the Ogallala Aquifer in Roger Mills and Beckham Counties, Western Oklahoma

By Mark Belden & Noel I. Osborn

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Cover Photograph: Antelope Hills in Roger Mills County, Oklahoma.

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Introduction

The Ogallala aquifer underlies portions of 10 counties in western Oklahoma. Regionally, it is part of the High Plains aquifer that underlies 174,000 square miles in eight states in the central United States (Figure 1). The study area for this investigation, defined by the outcrop of the Ogallala Formation in Roger Mills and Beckham Counties, covers 428 square miles (Figure 2). The study unit is comprised of the saturated material of the Tertiary-age Ogallala Formation. Well yields average 50 gallons per minute (gpm). Water is used for irrigation, municipal, industrial, household, and livestock purposes.

The purpose of this study is to provide the Oklahoma Water Resources Board (OWRB) with the information needed to allocate the amount of fresh water withdrawn from the Ogallala aquifer in Roger Mills and Beckham Counties in western Oklahoma.

Figure 1. *Location of the High Plains aquifer.*

Physical Setting

Physiography

The study area lies within the central High Plains of the Great Plains Province, where Tertiary-age rocks crop out. The High Plains extends from southern South Dakota to northwestern Texas. It lies between the Rocky Mountains to the west and the Central Lowland to the east. The High Plains is a remnant of a vast plain formed by sediments that were deposited by streams flowing eastward from the Rocky Mountains. Regional uplift forced streams to cut downward and erode the plain. Erosion isolated the plains from the mountains and formed escarpments that typically mark the boundary of the High Plains (Gutentag and others, 1984).

The topography of the study area generally consists of gently sloping hills, which have been developed by erosion of the underlying Tertiary sands. The exception is a series of small buttes in northwestern Roger Mills County known as the Antelope and Twin Hills. The buttes are capped by a layer of medium-grained sandstone, 25 feet thick, which has preserved the upper- most section of the Ogallala Formation (Kitts, 1959). The buttes mark the highest elevation in the study area, with an altitude of more than 2,600 feet above mean sea level. The Antelope and Twin Hills exhibit approximately 100 feet of relief above the surrounding terrain (see front cover for a view of four of the buttes comprising the Antelope Hills). The lowest elevation of the study area is approximately 2,030 feet in northwestern Beckham County.

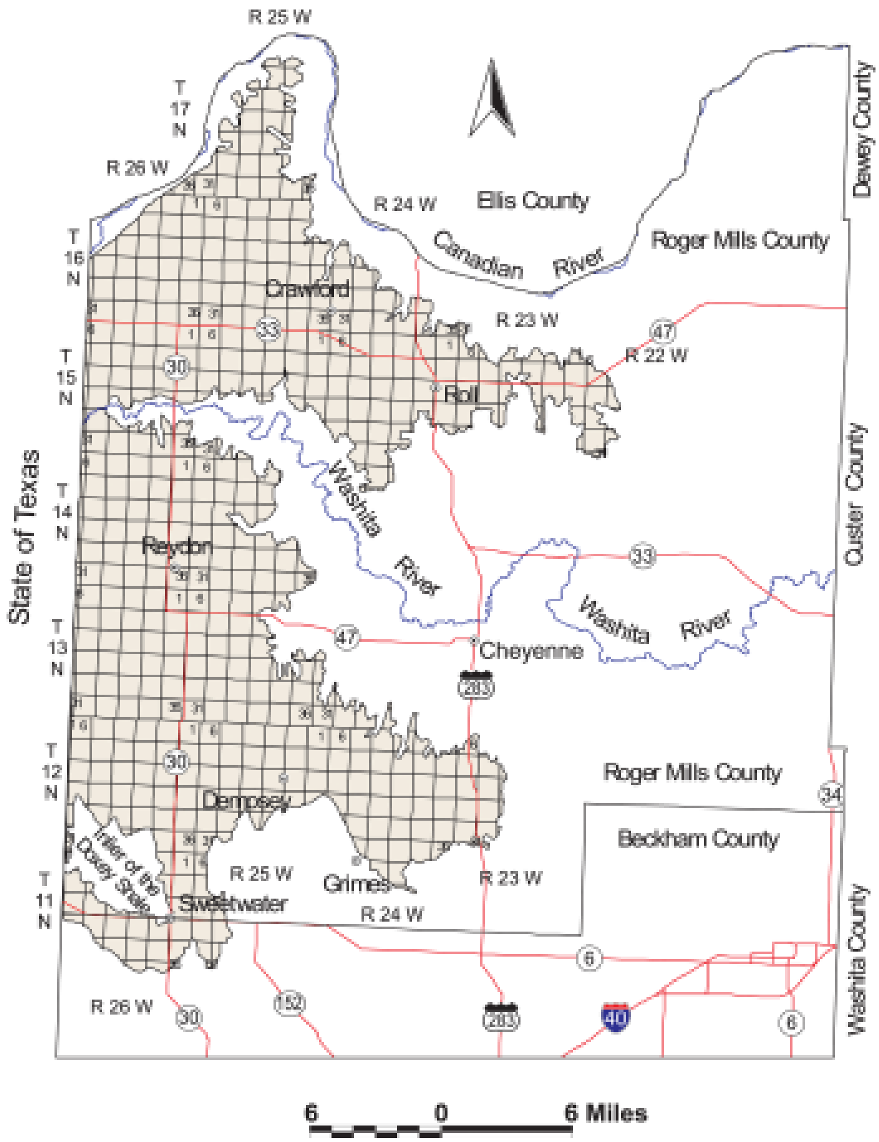

Figure 2*. Location of the Ogallala aquifer in Roger Mills and Beckham Counties, Oklahoma.*

Surface Drainage Features

The Canadian River, Washita River, and North Fork of the Red River drain the northern, central, and southern portions of the study area, respectively. The rivers originate in New Mexico or Texas, and flow eastward into Oklahoma. No significant reservoirs are located within the study area.

Climate

The study area has a middle-latitude, dry-continental climate with abundant sunshine, moderate precipitation, frequent winds, low humidity, and high evaporation (Gutentag and others, 1984). The average annual precipitation of Roger Mills County (from 1970-2000) is 23.3 inches (Figure 3). The wettest months are May, June, and September, and the driest months are December through February. Average monthly temperatures range from 35° in January to 81° in July, with an average annual temperature of 58° F (Oklahoma Climatological Survey, 1997).

Soils

The Nobscot-Brownfield association occupies a majority of the southern three-fourths of the study area, and the Pratt-Enterprise the northern one-fourth running parallel and adjacent to the Canadian River. The Nobscot-Brownfield association is described as

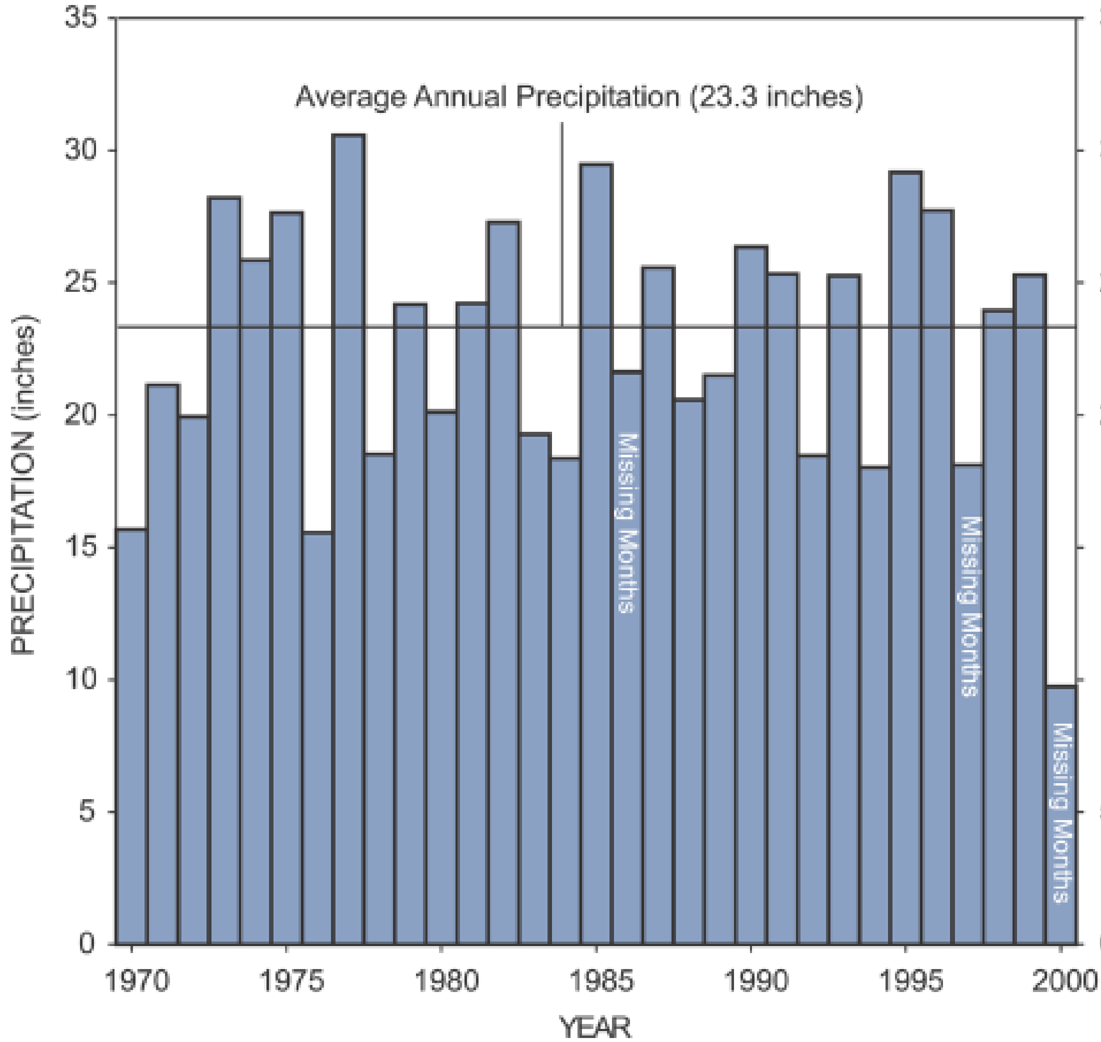

Figure 3. *Graph showing annual precipitation from 1970 to 2000 at Reydon, Oklahoma. Data provided by the Oklahoma Climatological Survey.*

smooth to rolling terrain, with very sandy soils on uplands, and with reddish subsoils. The water-holding capacity of this association is rated as low. Although suitable for cultivation, careful management is needed to maintain fertility and to control wind erosion. The Pratt-Enterprise association is steep to hilly or dune-like, and sandy to moderately sandy. Water-holding capacity of this association is low. Less than 10 percent of its area is suitable for cultivation because of steep slopes. Both associations were formed from sandy eolian materials of Quaternary or Tertiary age (Burgess and others, 1963).

Land Use and Population

Land use in the study area is predominantly agriculture. In 1997, 95 percent of the land was designated as farmland. Seventy-seven percent of the farmland was in pasture and 23 percent was in crops, with alfalfa and wheat accounting for 96 percent of the harvested cropland. Approximately three percent of the cropland (4,600 acres) was irrigated (Agricultural Census of Roger Mills County, 1997).

A portion of the study area underlies the Black Kettle National Grassland. The preserve, which encompasses more than 30,000 acres, was purchased during the 1930s by the U.S. Department of the Interior in an effort to return some of the badly eroded land of the Dust Bowl to its natural state. The U.S. Department of Agriculture Forest Service administers the preserve under a policy of sustainable multiple uses. The intermingled public and private lands are managed to promote development of grasslands and for outdoor recreation, livestock forage, and wildlife (U.S. Department of Agriculture Forest Service, 1999).

No major urban areas are present within the study area. Reydon is the only incorporated town, with a population less than 3,000. Unincorporated communities within the study area include Crawford, Dempsey, Roll, and Sweetwater.

Between 1990 and 2000, the population of Roger Mills County declined by approximately 17 percent, from 4,147 to 3,436 (U.S. Census Bureau, 2001). This represents the largest decline of population for any county in the state between the two censuses. During this same time, the population of the study area decreased from about 1,300 to 1,100.

Geology

The study area lies along and mostly north of the axis of the Anadarko Basin. This major structural feature is comprised of up to 38,000 feet of carbonates, shales, sandstones, and evaporites of Cambrian to Permian age. The regional dip varies from 10 to 100 feet per mile towards the axis of the Anadarko Basin (Carr and Bergman, 1976).

Geologic units of relevance for this study include those that are in physical contact with the Ogallala Formation at the surface or closely underlie it in the subsurface. These formations range in age from Permian to Quaternary and are listed in Table 1. The surficial geology is shown in Figure 4. The map is modified from Cederstrand (1996), and the stratigraphic nomenclature is modified from Carr and Bergman (1976).

Permian-age rocks directly underlie the Tertiary-age Ogallala Formation in Roger Mills and Beckham Counties. The geologic units are the Marlow Formation, Rush Springs Formation, Cloud Chief Formation, Doxey Shale, and Elk City Sandstone. These units consist of shales, mudstones, siltstones, and sandstones with some thin beds of gypsum, anhydrite, limestone, and dolomite. The rocks in these units are readily identified by their orange to brick-red colors, and are commonly referred to as “redbeds”. The Permian-age rocks yield small amounts of poor quality water.

The Permian surface is uneven due to erosion and possible salt dissolution. Considerable salt dissolution in the redbeds probably occurred during deposition of the Ogallala Formation, resulting in collapse features (Gustavson and others, 1980). Figure 5 is a map showing the altitude of the top of the Permian-age rocks. The map was prepared using lithologic descriptions from drillers’ logs of more than 200 wells.

Unconformably overlying the Permian-age rocks is the Ogallala Formation of Tertiary age. The Ogallala Formation is composed of sediments eroded from the ancestral Rocky Mountains by streams and wind. The dominant mode of deposition was by braided streams that coalesced to form broad alluvial fans (Gutentag and others, 1984). The Ogallala Formation consists of semi-consolidated layers of sand, silt, clay, and gravel that are poorly to moderately cemented by calcium carbonate. The sediments are generally light tan, gray, or white in color. Layers of calcium carbonate, or caliche, are common, particularly near the surface (Hart and others, 1976; Havens and Christenson, 1984).

Thickness of the Ogallala Formation is controlled by the topography and salt dissolution in the underlying Permian-age rocks. Where the Permian surface was topographically high, the Ogallala Formation tends to be thin, and where the Permian surface was topographically low, the Ogallala tends to be thicker. The Ogallala Formation is also thicker overlying

Table 1. *Stratigraphic column of the study area*

SYSTEM	SERIES	GROUP	FORMATION	MEMBER
Quaternary	Holocene			Alluvium
	Pleistocene			Terrace Deposits
Tertiary	Miocene		Ogallala Formation	
Permian				
			Elk City Sandstone	
			Doxey Shale	
			Cloud Chief Formation	
		Whitehorse	Rush Springs Formation	
			Marlow Formation	

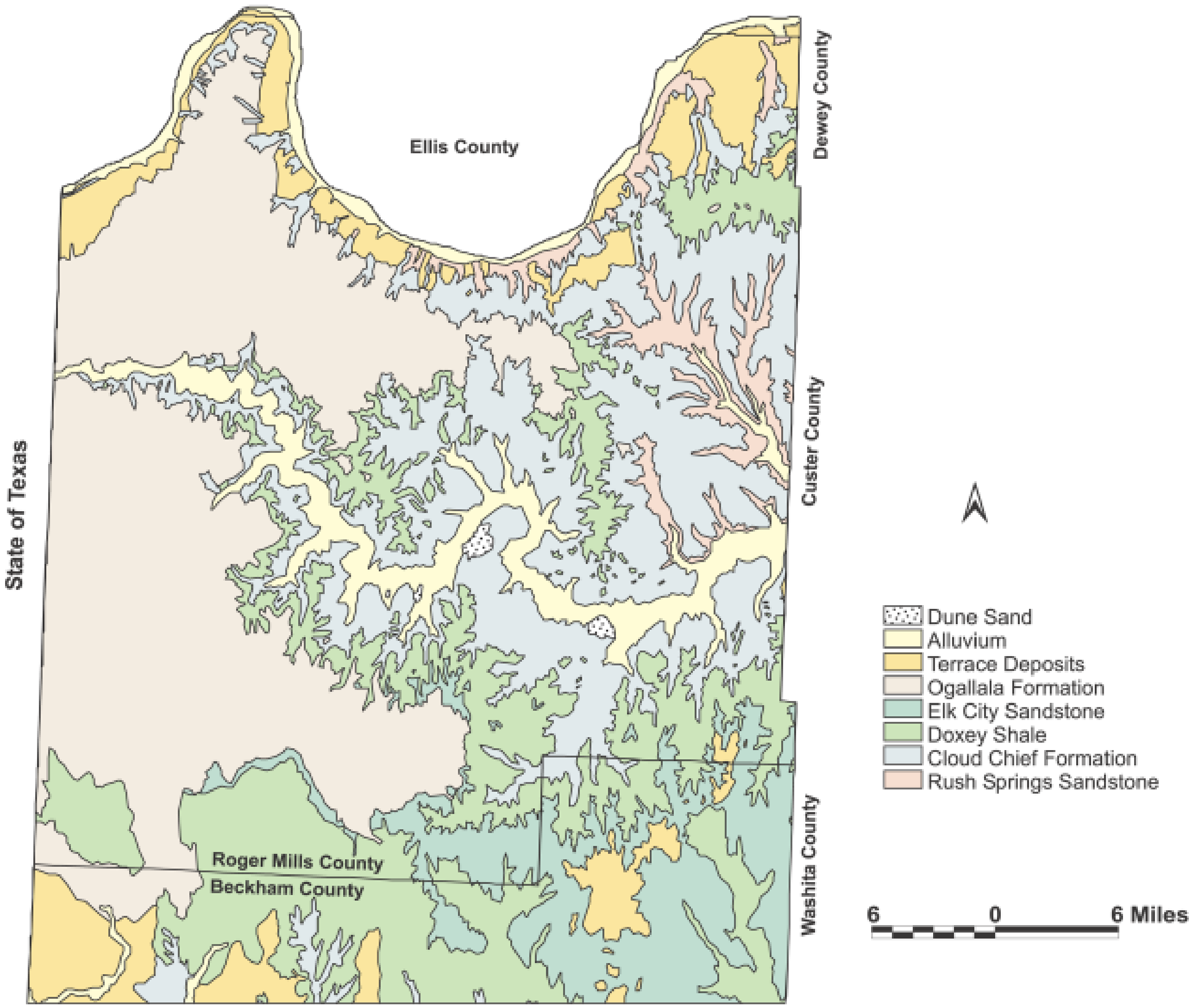

Figure 4. *Surficial geology of the study area.*

collapse features formed by salt dissolution. In the Oklahoma Panhandle, the Ogallala Formation can be as thick as 650 feet (Hart and others, 1976). In the study area, the Ogallala Formation thins eastward from a maximum thickness of about 320 feet.

Quaternary-age alluvium and terrace deposits are associated with the rivers. The sediments consist of stream-laid deposits of sand, silt, clay, and gravel ranging from 0 to 120 feet thick (Carr and Bergman, 1976).

Hydrology

Regional Setting

The High Plains aquifer extends from southern South Dakota to the southern portion of the Texas Panhandle. Approximately 20 percent of the irrigated land in the United States is in the High Plains, and 30 percent of all groundwater used for irrigation is pumped from this aquifer (Gutentag and others, 1984). The High Plains aquifer consists mainly of hydrologically connected geologic units of late Tertiary and Quaternary age (Gutentag and others, 1984). Within Oklahoma, this aquifer consists primarily of the saturated material of the Ogallala Formation, and is referred to as the Ogallala aquifer.

Recharge and Discharge

Natural recharge to the aquifer occurs primarily as infiltration of precipitation. Recharge also occurs as seepage in streams, subsurface inflow from the

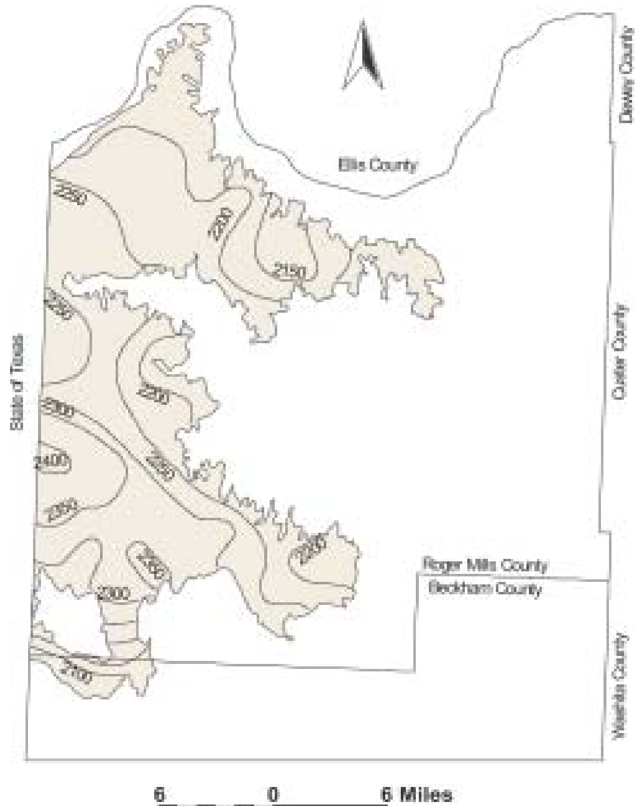

Figure 5. Altitude of the top of the Permian-age rocks (base of the Ogallala aquifer) in Roger Mills and Beckham Counties. Contour interval is 50 feet.

High Plains aquifer in Texas, and irrigation return flows. It is possible that some recharge is received from the underlying Permian formations (Luckey and Becker, 1999).

Luckey and Becker (1999) used a groundwater flow model to determine the rate of recharge from precipitation in the Ogallala aquifer, north of the Canadian River. The simulated rate of recharge ranged from 0.06 inches/year to 0.90 inches/year, averaging 0.18 inches/year. Areas overlain by sand dunes or very sandy soil had greater recharge (4.0 percent of precipitation) than other areas (0.37 percent of precipitation). Areas cultivated for dry-land crops also had greater recharge (3.9 percent of precipitation). The groundwater flow model did not include the study unit, which lies south of the Canadian River. Because the soils overlying the study unit are generally sandy with a high infiltration rate, it is reasonable to assume that the rate of recharge in the study unit is similar to the simulated rate in the greater recharge areas identified in the model (about 0.90 inches/year).

Groundwater discharges naturally from the aquifer to streams and springs, to evapotranspiration where the water table is shallow, and to adjoining formations. Groundwater in the study unit discharges to the Washita River, to streams and springs, to the terrace and alluvium deposits of the North Fork of the Red River and the Canadian River, and to Permian formations. Water is artificially discharged from wells.

Groundwater Flow and Water-Level Fluctuations

The 2000 water table surface of the aquifer is shown in Figure 6 and is based on a network of 17 wells that were measured by the OWRB in March 2000. The map indicates that the average hydraulic gradient, or slope, of the water table was about 20 feet per mile. The average depth to water was 39 feet.

Groundwater flows perpendicular to water-level contours, from high to low elevations. As illustrated in Figure 6, groundwater flow through the study unit is generally in an easterly direction, but local variations occur due to the effects of topography and the presence of streams. A groundwater divide, which approximates a topographic divide, occurs between the Washita and Canadian Rivers. Groundwater north of the divide generally flows north-northeast toward the Canadian River, and groundwater south of the divide flows south-southeast toward the Washita River. Another groundwater divide occurs between the Washita and North Fork of the Red River.

Water levels in the aquifer fluctuate in response to recharge from precipitation and discharge from well pumping. Representative hydrographs depicting annual water-level change in the study unit are shown in Figure 7. Groundwater levels in the study unit have been rising over the last twenty years at an average rate of about 0.4 foot per year. Similar increases in water levels have been observed in both bedrock and alluvium and terrace deposits across the state. Over the last 20 years, most of the state's aquifers exhibited rising water levels (Belden, 1999). One notable exception is the Ogallala aquifer in the Panhandle, which is being depleted from pumping at a greater rate than it is replenished from precipitation (Belden, 1999; Luckey and Becker, 1999).

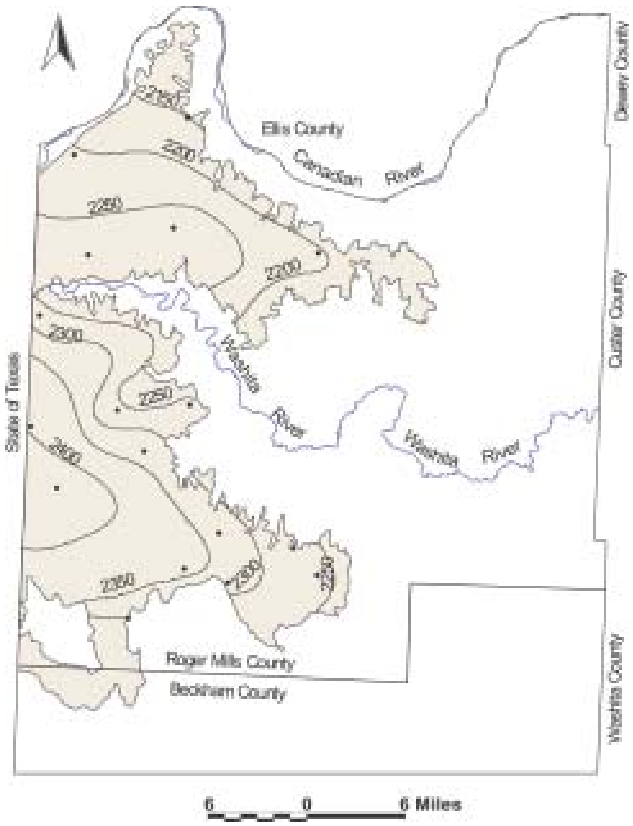

Figure 6. Altitude of the 2000 water table surface of the Ogallala aquifer in Roger Mills and Beckham Counties. Contour interval is 50 feet.

Hydrologic Characteristics

Saturated thickness was determined by subtracting the altitude of the aquifer base from the altitude of the water table surface. In March 2000, the study unit had a maximum saturated thickness of about 250 feet and an average saturated thickness of about 60 feet.

Hydraulic conductivity of the study unit is estimated to range from 10 to 122 ft/day. Gutentag and others (1984) used the lithology descriptions reported on well drillers' logs to estimate hydraulic conductivity in the study unit to range from 25 to 100 ft/day. Havens and Christenson (1984) used a regional groundwater flow model to determine hydraulic conductivity in the eastern portion of the Oklahoma High Plains aquifer to be 19.3 ft/day. Luckey and Becker (1999) used a regional groundwater flow model to determine hydraulic conductivity in the portion of the Oklahoma High Plains aquifer that lies north of the Canadian River. Simulated hydraulic conductivity ranged from 10 to 122 ft/day, and averaged 33 ft/day.

Specific yield, the ability of the aquifer to store and release water, is estimated to range between 0.04 and 0.30, and to average 0.15. Gutentag and others (1984) estimated specific yield in the study unit ranged from 0.10 to 0.30. Havens and Christenson (1984) used a specific yield of 0.147 to simulate groundwater flow in the Oklahoma High Plains aquifer. Luckey and Becker (1999), using a groundwater flow model, determined the specific yield for the Oklahoma High Plains aquifer north of the Canadian River ranged from 0.04 to 0.27, and averaged 0.16.

Groundwater Use

At the time of this study, about 500 drillers' logs of water wells in the study unit were on file at the OWRB. Approximately half of these wells were drilled for household use, and half were drilled for irrigation, municipal, industrial, or oil and gas drilling purposes. Wells yield from less than 5 gpm in some household wells to as much as 800 gpm in higher-capacity irrigation wells, and average 50 gpm.

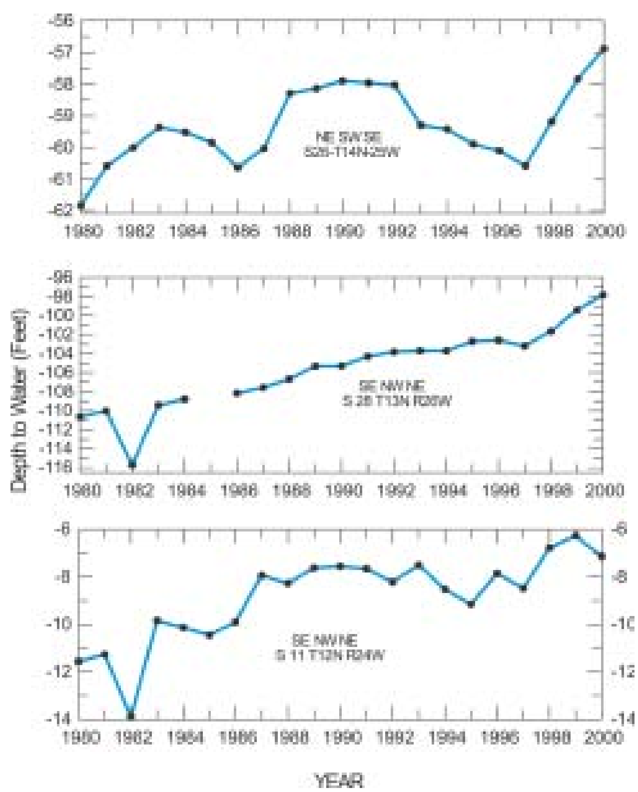

Figure 7. Hydrographs of three wells in the Ogallala aquifer in Roger Mills County.

Water use records on file at the OWRB indicate that water from the study unit is withdrawn primarily for irrigation (41 percent in 1999), municipal (38 percent), and industrial (21 percent) purposes. The Town of Reydon and Roger Mills Rural Water District Number 2 provide drinking water for public water supply systems. Water withdrawals are not reported for household use. Total groundwater withdrawals remained relatively consistent from 1980 to 1999. Permit holders reported 878 acre-feet of withdrawals in 1980 and 762 acre-feet of withdrawals in 1999.

Water Quality

The chemical composition of the High Plains aquifer is variable, ranging from calcium bicarbonate to sodium bicarbonate. Generally, water containing less than 250 mg/L dissolved solids is a calcium bicarbonate type derived from the solution of calcium carbonate cementing the sands and gravels. As the concentration of dissolved solids increases from 250 to 500 mg/L, concentrations of sodium and sulfate increase, and the type becomes sodium bicarbonate. Water with dissolved solids exceeding 500 mg/L is mixed, with calcium, sodium, sulfate, and chloride as the most common ions. The source of these saline waters is the dissolution of gypsum (calcium sulfate) and halite (sodium chloride) deposits in the underlying Permian-age rocks. Concentrations of dissolved solids in the vicinity of the study unit generally range from 250 to 500 mg/L, and concentrations of sodium generally range from 25 to 50 mg/L (Krothe and others, 1982).

As part of a statewide monitoring program, the OWRB collected 25 groundwater samples from 10 water wells in the study unit between 1984 and 1992 (Figure 8). Chemical analyses are listed in Table 2. Not listed in Table 2 are arsenic, cadmium, chromium, lead, manganese, silver, and selenium because the concentrations of these constituents were all below the detection limit. Summary statistics of the analyses are listed in Table 3. For those wells that were sampled more than one year, an average value was calculated for each of the constituents before generating the descriptive statistics. For those constituents with values below the detection limit, only the minimum and maximum concentrations are listed.

The summary statistics indicate total dissolved solids (TDS) concentrations ranged from 232 to 1,084 mg/L, with a median of 411 mg/L. Calcium concentrations ranged from 56 to 172 mg/L. Sodium concentrations ranged from 17 to 109 mg/L, chloride concentrations ranged from <10 to 309 mg/L, and sulfate concentrations ranged from <20 to 180 mg/L.

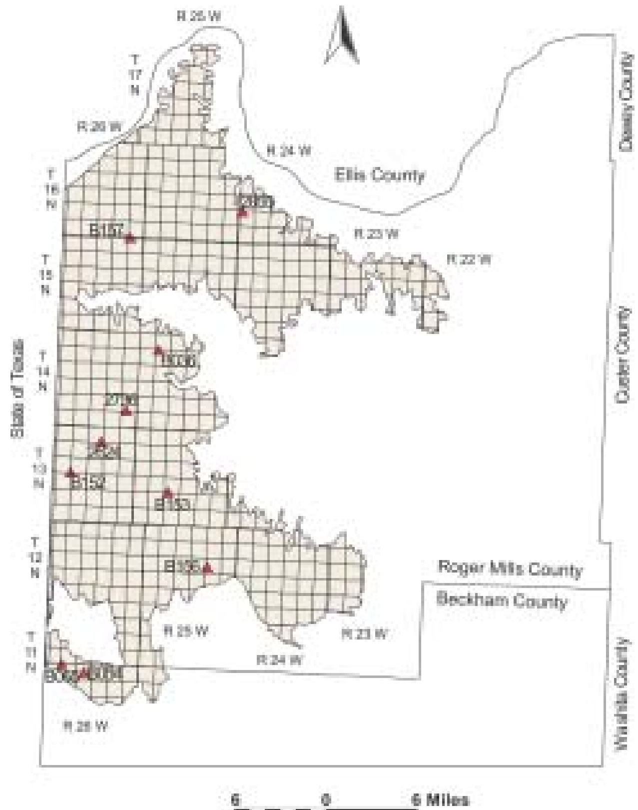

Figure 8*. Location of wells completed in the Ogallala aquifer that were sampled by the OWRB between 1984 and 1992.*

Samples from well B153 had exceptionally high TDS concentrations, averaging 1,084 mg/L. Samples from this well also had high average concentrations of chloride (309 mg/L), sodium (109 mg/L), and sulfate (159 mg/L). Possible sources of these constituents include the underlying Permian formations or oil field brine.

Average nitrate concentrations for the 10 wells ranged from less than 2 to more than 13 mg/L, with a median concentration of 6 mg/L. Nitrate concentrations in groundwater under natural conditions are usually less than 2 mg/L (Mueller and others, 1995). When nitrate concentrations exceed 2 mg/L, non-natural sources are suspected. These sources include nitrogen-based fertilizers, septic systems, animal feedlots, animal waste lagoons, manure applied to

__Table 2__. Concentrations (mg/L) of chemical constituents in water samples collected by the OWRB

Site ID	Year	Hardness	Alkalinity	Bicarbonate	TDS	Calcium	Magnesium	Sodium	Nitrate	Chloride	Fluoride	Sulfate	Barium	Zinc	Iron
2624	1987	296	215	262	553	91	11	64	9.5	90	0.42	62	0.131	0.018	<0.01
2624	1988	160	258	315	560	90	13	73	13.1	98	0.36	62	0.145	0.011	0.024
2624	1989	200	200	244	562	91	11	82	11.3	64	0.44	92	0.141	0.010	0.226
2624	1990	279	230	280	596	94	11	69	2.0	87	0.38	45	0.139	0.022	0.223
2736	1984	245	319	388	544	73	16	93	9.0	36	0.99	49	<0.20	0.036	<0.01
2736	1985	247	312	380	508	68	15	103	10.5	33	0.96	42	0.32	0.004	<0.01
2736	1986	216	315	384	503	66	15	101	6.9	29	1.09	52	0.145	<0.005	0.024
2736	1987	255	317	386	507	65	16	82	8.4	28	1.05	49	0.145	<0.005	0.044
2736	1988	120	301	367	464	61	14	76	10.9	28	0.88	43	0.115	0.023	0.034
2736	1989	163	240	293	473	65	15	72	8.3	10	0.87	63	0.115	0.016	0.015
2736	1990	312	226	276	550	99	14	42	0.7	95	0.36	48	0.215	<0.005	0.042
2736	1991	245	308	376	521	61	15	81	4.2	33	0.41	42	0.136	<0.005	0.014
2855	1990	215	214	261	448	72	8	22	11.0	<10	0.40	27	0.406	0.089	0.034
2855	1991	241	198	241	325	63	6	16	5.2	<10	0.84	<20	0.349	0.005	0.020
2855	1992	251	211	257	337	74	6	14	7.1	<10	0.43	<20	0.434	0.031	0.935
B152	1984	257	271	330	455	68	12	22	3.5	48	<0.10	26	—	—	<0.01
B152	1985	303	249	304	450	124	15	46	5.8	69	0.21	<20	0.51	0.057	0.12
B153	1984	644	252	307	1112	150	67	114	5.7	318	<0.10	167	—	—	<0.01
B153	1985	695	248	302	1056	193	59	103	8.4	299	0.19	150	0.26	0.048	<0.01
B156	1984	239	245	299	346	88	6	54	5.0	11	0.21	<20	—	—	<0.01
B157	1984	182	204	249	258	59	10	19	1.3	10	0.26	<20	0.35	—	<0.01
B157	1985	189	198	242	249	53	11	21	2.1	<10	0.29	<20	0.43	0.0238	<0.01
B036	1985	217	209	255	267	93	12	29	1.8	<10	0.37	<20	0.67	0.66	8.10
B054	1984	386	182	222	622	86	42	43	13.1	31	0.50	180	<0.2	0.317	2.86
B065	1985	157	144	176	232	61	13	30	3.4	10	0.18	<20	<0.2	0.016	<0.01

land, municipal sewage effluent, industrial wastewater, and barnyards.

Groundwater from the study unit is generally good for drinking water. However, samples from some wells exceeded primary and secondary drinking-water standards established by the U.S. Environmental Protection Agency for nitrate, TDS, and chloride. Primary drinking-water standards are established for chemical constituents that may have an adverse effect upon human health when present at excessive levels. Six of the 25 samples, representing four wells, exceeded the primary standard of 10 mg/L for nitrate. Secondary drinking-water standards present no health hazard, but affect the taste, smell, and appearance of the water, or can damage components of the water system. Thirteen of the 25 samples, representing 4 wells, exceeded the secondary standard of 500 mg/L for TDS, and two samples from one well exceeded the secondary standard of 250 mg/L for chloride.

Pollution from natural sources could occur if the potentiometric head in the underlying Permian formations is greater than that of the overlying Ogallala Formation. Pumping in the Ogallala aquifer could induce upward movement of saline water that exists in the underlying Permian formations.

__Table 3__. Descriptive statistics, based on average concentrations (mg/L) in 10 wells, for water samples collected by the OWRB between 1984 and 1992

	Hardness	Alkalinity	Bicarbonate	TDS	Calcium	Magnesium	Sodium	Nitrate	Chloride	Fluoride	Sulfate	Barium	Zinc	Iron
Minimum	157	144	176	232	56	6	17	1.7	<10	<0.10	<20	<0.20	<0.005	<0.01
25th Percentile	219	203	248	287	70	11	29	3.7						
Median	235	218	266	411	87	13	39	6.0						
75th Percentile	270	249	304	553	92	15	68	7.7						
Maximum	670	292	356	1084	172	63	109	13.1	309	0.83	180	0.67	0.66	8.1

Summary

The Ogallala aquifer encompasses 428 square miles in Roger Mills and Beckham Counties. The study unit consists of the saturated portion of the Tertiary-age Ogallala Formation, which is composed primarily of sands and gravels. The Ogallala Formation is underlain by Permian-age rocks, which yield small amounts of poor quality water.

Wells completed in the aquifer yield an average of 50 gpm and supply water for irrigation, municipal, industrial, household, and livestock purposes. In 1999, permit holders reported 762 acre-feet withdrawals from the study unit.

A water table map was constructed using 17 static water level measurements collected in March 2000. The average depth to water was 39 feet, and the average slope of the water table was 20 feet per mile. In contrast to the Oklahoma Panhandle, where groundwater levels are declining, groundwater levels in the study area have been rising over the last twenty years.

Natural recharge to the aquifer occurs primarily as infiltration of precipitation. The rate of recharge to the study unit is estimated to be about 0.90 inches per year. Based on previous studies, hydraulic conductivity is estimated to range from 10 to 122 ft/day. Specific yield is estimated to range from 0.04 to 0.30 and average 0.15. In March 2000, the study unit had a maximum saturated thickness of 250 feet and an average saturated thickness of about 60 feet.

The chemical composition of the Ogallala aquifer is variable, ranging from calcium bicarbonate to sodium bicarbonate. Water samples collected from 10 wells in the study area had total dissolved solids concentrations ranging from 232 to 1,084 mg/L, with a median of 411 mg/L. The most common ions were calcium, sodium, sulfate, and chloride. Although groundwater from the study unit is generally good for drinking water, some samples exceeded primary and secondary drinking-water standards. Six of 25 samples, representing four wells, exceeded the primary standard of 10 mg/L for nitrate.

Pollution from natural sources could occur if the potentiometric head in the underlying Permian formations is greater than that of the overlying Ogallala Formation. Pumping in the Ogallala aquifer could induce upward movement of saline water that exists in the underlying Permian formations.

References

Agricultural Census of Roger Mills County, 1997: http://govinfo.library.orst.edu/cgi-bin/ag-list?01-129.okc.

Belden, M.H., 1999, Groundwater Level Changes in Oklahoma (1978-1998): Oklahoma Water Resources Board Technical Report 99-4, 73 p.

Burgess, D.L., Nichols, J.D., and Henson, O.G., 1963, Soil Survey of Roger Mills County, Oklahoma: U.S. Department of Agriculture, series 1959, no. 29, p. 1-11.

Carr, J.E. and Bergman, D.L., 1976, Reconnaissance of the Water Resources of the Clinton Quadrangle, West-Central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 5, 4 Sheets.

Cederstrand, J.R., 1996, Digital Geologic Map of Clinton Quadrangle, West-Central Oklahoma: U.S. Geological Survey Open-File Report 96-373, based on a scale of 1:250,000, 2 diskettes.

Gustavson, T.C., Finley, R.J., and McGillis, K.A., 1980, Regional Dissolution of Permian Salt in the Anadarko, Dalhart, and Palo Duro Basins of the Texas Panhandle: University of Texas, Bureau of Economic Geology Report of Investigations no. 106, 40 p.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 63 p.

Hart, D.L., Jr., Hoffman, G.L., and Geomaat, R.L., 1976, Geohydrology of the Oklahoma Panhandle, Beaver, Cimarron and Texas Counties: U.S. Geological Survey Water Resources Investigation 25-75, 62 p.

Havens, J.S. and Christenson, S.C., 1984, Numerical Simulation of the High Plains Regional Aquifer, Northwestern Oklahoma: U.S. Geological Survey Water-Resources Investigation 83-4269, 27 p.

Kitts, D.B., 1959, Cenozoic Geology of Northern Roger Mills County: Oklahoma Geological Survey, Circular 48, 1 plate, 48 p.

Krothe, N.C., Oliver, J. W., and Weeks, J. B., 1982, Dissolved Solids and Sodium in Water from the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-658, scale 1:2,500,000, 2 sheets.

Luckey, R.L. and Becker, M.F., 1999, Hydrogeology, Water Use, and Simulation of Flow in the High Plains Aquifer in Northwestern Oklahoma, Southeastern Colorado, Southwestern Kansas, Northeastern New Mexico, and Northwestern Texas: U.S. Geological Survey Water-Resources Investigation 99-4104, 62 p.

Mueller, D.K., Hamilton, P.S., Helsel, D.R., Hitt, K.J., and Ruddy, B.C., 1995, Nutrients in Ground Water and Surface Water of the United States—An Analysis of Data Through 1992: U.S. Geological Survey Water-Resources Investigations Report 95-4031, 74 p.

Oklahoma Climatological Survey, 1997, Data and Products: http://climate.ocs.ou.edu/.

U.S. Census Bureau, 2001, Census 2000 Redistricting Data: http://census.gov/population/cen2000phc-t4/tab01.txt.

U.S. Department of Agriculture Forest Service, 1999, The National Grasslands Story: http://www.fs.fed.us/grasslands.