

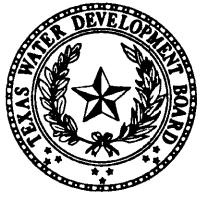
Report 342

Water-Quality Evaluation of the Ogallala Aquifer, Texas

August 1993



Texas Water Development Board



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Water-Quality Evaluation of the Ogallala Aquifer, Texas

by
Janie Hopkins, Geologist

with the cooperation of:
High Plains Underground Water Conservation District No. 1
North Plains Water District
Panhandle Underground Water Conservation District No. 3
Sandy Land Underground Water Conservation District
Permian Basin Underground Water Conservation District

August 1993

Texas Water Development Board

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ABSTRACT

More than 700 representative wells were sampled from 1989 to 1992 with the help of several cooperators throughout the Texas High Plains to assess water quality in the Ogallala aquifer. Cooperators included the High Plains Underground Water Conservation District No. 1, North Plains Water District, Panhandle Underground Water Conservation District No. 3, Sandy Land Underground Water Conservation District, and Permian Basin Underground Water Conservation District. This project fulfills one objective of the Hydrologic Monitoring Section of the Texas Water Development Board (TWDB): to collect and assess water-quality data in each of the nine designated major aquifers in Texas as part of a six-year routine monitoring cycle. Such assessment involves evaluation of recent water-quality data and comparison with previous data.

Certain measurements, including conductivity, pH, and temperature, were taken in the field during sampling. Sampling was conducted in accordance with the methods described in the TWDB *Field Manual for Ground-Water Sampling* (Nordstrom and Beynon, 1991). Samples were analyzed for major cations, anions, and nutrients; and for the first time on an aquifer-wide basis, tests were conducted to determine the presence of minor inorganic elements (metals), pesticides, and radionuclides.

Historically, the concentrations of dissolved solids, chloride, sulfate, and fluoride have exceeded primary Maximum Constituent Levels (MCLs) in numerous wells in the southern part of the study area. Maps illustrating the concentrations and locations, as well as tables listing averages and ranges of these constituents corroborate findings of earlier studies. The average dissolved-solids content of 1,132 milligrams per liter (mg/l) in the south, compared to 366 mg/l in the north, is indicative of the poorer water quality in the south. Twenty-eight percent of samples in the south contained chloride in excess of 300 mg/l, compared to less than one percent in the north; 33 percent of samples in the south contained sulfate in excess of 300 mg/l, compared to less than one percent in the north; and almost 40 percent of wells sampled in the south contained concentrations of fluoride in excess of 4.0 mg/l, compared to three percent in the north. Ogallala ground water is considered very hard, with total hardness, measured as CaCO₃, averaging 421 and 230 mg/l in the southern and northern parts of the study area, respectively.

Selenium was the one minor element found in any significant amount in Ogallala ground water. Although 41 percent of the samples in the southern wells contained selenium in excess of the former MCL of 10 micrograms per liter ($\mu\text{g/l}$), less than three percent contained concentrations in excess of the recently adopted MCL of 50 $\mu\text{g/l}$. Nitrate was the only nutrient of any concern; in the south, 15 percent of the samples contained nitrogen as nitrate in excess of the MCL of 44.3 mg/l compared to less than one percent in the north. Of the 18 organics detected in 11 wells in six southern counties, only three were in excess of their respective MCLs. The 28 wells with excessive radioactivity all contained excess alpha particles, three contained excess beta particles, and two contained excess combined radium.

The water-quality problems determined from this study have been well documented in previous reports published by the TWDB and others. In an effort to quantify the increase or decrease in water quality over time, major cation and anion data from the early '70s were compared with these same data from the recent sampling event. Data from analyses taken during the past 20 years appear to indicate a slight amelioration in water quality in the north compared to a somewhat more significant deterioration in water quality in the south during the same period.

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INTRODUCTION

Purpose

The purpose of this report is to examine the quality of the ground water in the Texas High Plains based principally on analyses of recent samples collected from selected wells completed in the Ogallala aquifer. This project is part of the TWDB water-quality monitoring program which was established to: (1) monitor changes in the quality of ground water in major and minor aquifers over a period of time; and (2) establish, as accurately as possible, the baseline characteristics of the dissolved constituents in ground water occurring naturally in these aquifers throughout the state.

Location and Extent

The study area encompasses approximately 35,450 square miles of the Texas High Plains (Figure 1) and includes the outcrop of the Ogallala Formation from the eastern escarpment westward to the New Mexico border. Figure 1 shows the location of wells sampled in all or parts of the following counties: Andrews, Armstrong, Bailey, Borden, Briscoe, Carson, Castro, Cochran, Crosby, Dallam, Dawson, Deaf Smith, Dickens, Donley, Ector, Floyd, Gaines, Garza, Glasscock, Gray, Hale, Hansford, Hartley, Hemphill, Hockley, Howard, Hutchinson, Lamb, Lipscomb, Lubbock, Lynn, Martin, Midland, Moore, Motley, Ochiltree, Oldham, Parmer, Potter, Randall, Roberts, Sherman, Swisher, Terry, Wheeler, and Yoakum. Excluded are a few minor outliers of the Ogallala east of the escarpment. Amarillo, Lubbock, Pampa, Plainview, Brownfield, and Lamesa are within the study area. Although the entire region south of the Canadian River is generally considered the Southern High Plains, in this report, the region from the Oklahoma border south to Bailey, Lamb, Hale, Floyd, and Motley Counties is considered the northern part of the study area; the remainder of the region south to Winkler, Ector, Midland, and Glasscock Counties is considered the southern.

Topography and Drainage

The High Plains forms a southeast-sloping plateau consisting of a level to gently rolling prairie broken by rivers, creeks, and playas. Large areas within the region have poorly developed drainage systems. Most rainfall drains into playas, or ephemeral lakes, which range from a few feet to 50 feet or more in depth and from a few hundred feet to a mile or more in diameter (Nativ, 1988). Rainfall which does run off the plateau generally drains into the Canadian, Red, Brazos, and Colorado River Basins to the east and southeast.

Soils are red, gray, and black clays, sandy loams, and sands. Soils in the north primarily consist of clay and clay loam, whereas soils in the south mainly consist of sandy loam (Nativ, 1988). Today about one-half of the High Plains remains as grassland. Buffalo grass (*Buchloe dactyloides*) and blue grama (*Bouteloua gracilis*) grow on the clay and clay loam soils. Little bluestem (*Schizachyrium scoparium*), western wheatgrass, Indiangrass, switchgrass, and sand reedgrass are typical flora on sandy loam soils. Invading brushy plants include sand shinnery oak, sand sagebrush, mesquite, and yucca (Dallas Morning News, 1991).

Climate

Average annual precipitation ranges from 16 inches in the south to 20 inches in the north. Most precipitation falls during May and September. The mean minimum temperature in January ranges from 21°F in the northern High Plains to 28°F in the southern High Plains. The mean maximum temperature in July ranges from 93°F in the north to 95°F in the south. The semi-arid climate of the High Plains results in an average annual gross lake evaporation rate of 72 to 81 inches, which is three to six times the average annual rainfall (Larkin and Bomar, 1983).

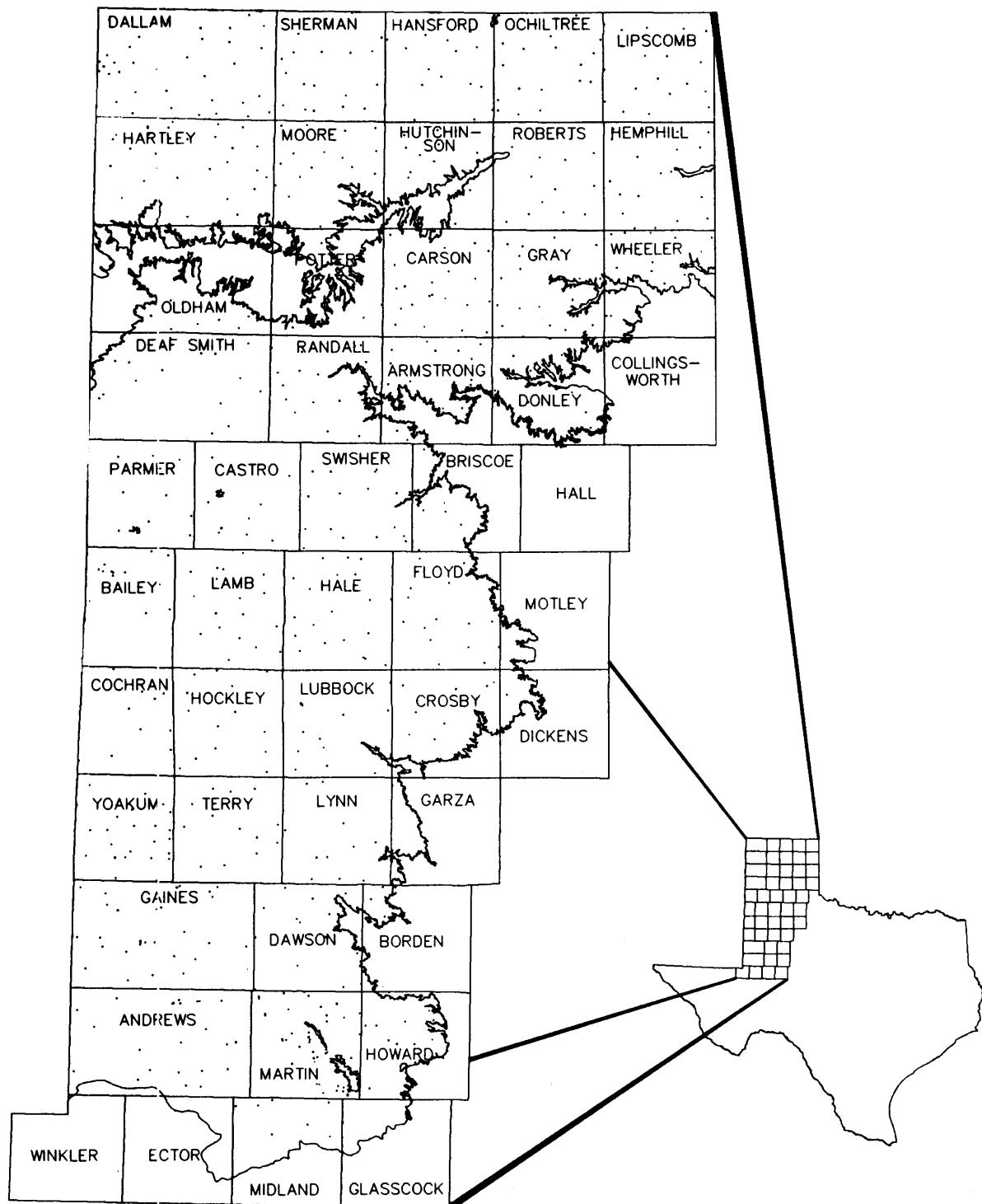


Figure 1. Location of wells in the Ogallala aquifer sampled for water quality, 1989–1992.

Aquifer limits from: TWDB, 1990

Graphics by Steve Gifford

Economy

The overall economy of the area is based on ranching and farming. Farmers irrigate approximately four million acres in the Texas High Plains (TWDB, 1991), and some of the counties with the greatest agricultural production in the state—Gaines, Dawson, Terry, Hale, Castro, Swisher, Deaf Smith, and Parmer—are within the study area. Oil and gas production, petrochemical production, and operation of oilfield-related businesses provide additional revenue to the local economy. Leading oil and gas producing counties in the state include: Midland, Martin, Andrews, Cochran, Ector, Gaines, Hockley, Terry, and Yoakum. Sand, gravel, clay, stone, cement, salt, and sodium sulfate are also mined. Additional industries include feedlot operations, meat packing, food processing, and limited manufacturing of goods such as apparel, glass, metals, furniture, fertilizer, irrigation equipment, and electronic and telecommunication equipment.

Acknowledgments

The TWDB appreciates the cooperation of the property owners for supplying information about their wells and allowing access to their property to sample water. TWDB Engineering Technicians Dennis Jones, John Asensio, Robbie Ozment, Ron Mohr, Eddie Zapata, Lennie Winkleman, and Doug Coker sampled the Ogallala.

Thanks go to Texas Tech University for analyzing samples in several High Plains counties. In addition, special acknowledgment goes to: the High Plains Underground Water Conservation District No. 1 for supplying technicians to assist in the collection of samples (analyzed by Texas Tech University); the North Plains Water District for assisting in the collection of samples; the Panhandle Groundwater Conservation District No. 3 and the Sandy Land Underground Water Conservation District for securing landowners' permission to sample wells; and the Permian Basin Underground Water Conservation District for providing water-quality data from their sampling project performed in conjunction with the Texas Water Commission.

Appreciation is also extended to geologists Phillip Nordstrom and John Ashworth of the TWDB, and Don McReynolds of the High Plains Underground Water Conservation District No. 1 who shared their knowledge and expertise on the Ogallala and its associated water-quality problems. TWDB Interactive Graphics Technician Steve Gifford created report graphics.

GEOHYDROLOGY

Geologic Framework

Cretaceous Trinity and Tertiary Ogallala sediments were deposited in pre-existing erosional valleys incised into Triassic Dockum and Permian strata. The Ogallala unconformably overlies rocks of Cretaceous, Triassic, and Permian ages. Quaternary sediments cover the Ogallala across most of the region. Figure 2 illustrates locations of the geologic units in unconformable contact with the overlying Ogallala.

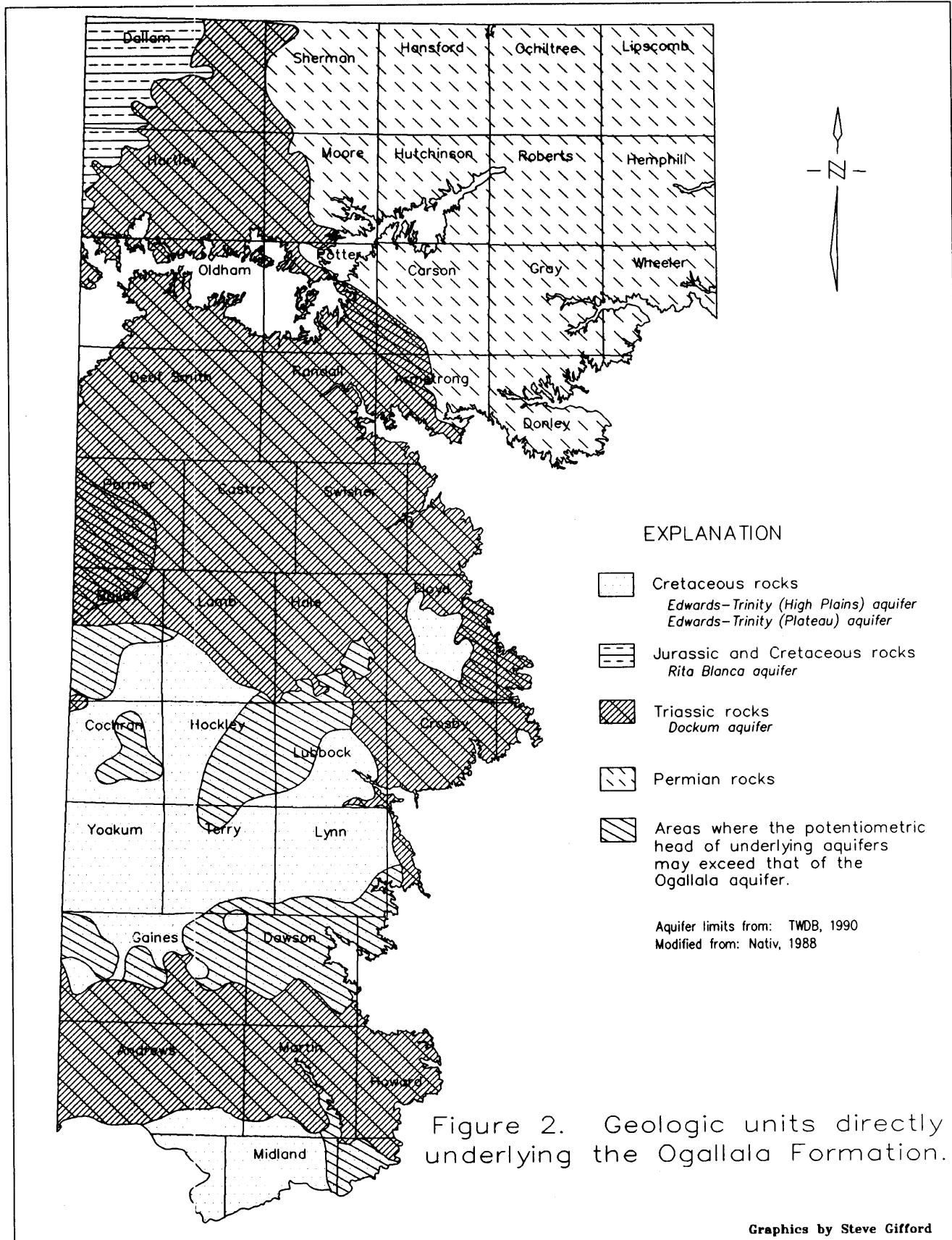
Permian rocks underlie the entire Texas Panhandle. The Ogallala Formation directly overlies Permian rocks (mainly Whitehorse Group and Blaine Formation) in all or parts of Sherman, Hansford, Ochiltree, and Lipscomb Counties in the north to Armstrong and Donley Counties in the south (Fig. 2). Beneath these rocks are Permian evaporites and other Paleozoic rocks.

The Triassic Dockum Group, underlying the Ogallala throughout much of the High Plains (Fig. 2), is composed of sandstone, siltstone, mudstone, and shale originally deposited in fluvial and lacustrine environments (McKee and others, 1959; McGowen and others, 1979). These continental sediments, deposited in the Permian Basin, generally dip toward a central axis of each subbasin. Jurassic formations—the Exeter Sandstone and interbedded shales and sandstones of the Morrison Formation—underlie Cretaceous rocks or the Tertiary Ogallala in parts of Dallam and Hartley Counties (Christian, 1989).

Lower Cretaceous (Comanchean Series) strata are composed of sandstone, limestone, and shale formations belonging to the Trinity, Fredericksburg, and Washita Groups. These formations unconformably overlie the Triassic Dockum Group and occur in two separate subcrops within the study area (Fig. 2). Aquifers associated with these two subcrops are the Edwards-Trinity (High Plains) aquifer, extending from Bailey and Lamb Counties south to Gaines and Dawson Counties, and the Edwards-Trinity (Plateau) aquifer underlying the southernmost extent of the Ogallala in Ector, Midland, and Glasscock Counties. The Edwards-Trinity (High Plains) aquifer is the erosional remnant of a larger Cretaceous deposit of unknown size which was continuous with the Edwards-Trinity (Plateau). The basal Antlers Formation of the Trinity Group is composed mostly of sand and sandstone. The Fredericksburg Group includes the interbedded sands, marls, limestones, and shales of the Walnut, Comanche Peak, Edwards, and Kiamichi Formations. The Washita Group, represented by the Duck Creek Formation, is comprised of shale with interbedded limestones and sandstones. In the study area, the Edwards-Trinity (Plateau) aquifer consists of sands and sandstones of the Antlers Formation.

The Tertiary Ogallala Formation is composed of coarse-grained fluvial deposits grading upward into thick sequences of fine-grained eolian sands and clays. Seni (1980) described a depositional model of Ogallala and Quaternary sediments as a series of coalescing, humid-type alluvial fans. Gustavson and Holliday (1985) and Gustavson and Winkler (1987) refined the alluvial fan model to include finer eolian sediments deposited in upland areas and above the fluvial deposits, indicative of a change in the palaeoenvironment.

A resistant layer of caliche, or the "caprock," occurs at or near the top of the Ogallala. Caliche is an authigenic accumulation of calcium carbonate which results from soil-forming processes, precipitation from ground water, or a combination of both. Several layers of caliche exist beneath the northern High Plains, while in the southern High Plains the number of layers and their cumulative thickness decreases (Reeves, 1970; Rics, 1981; Knowles and others, 1984).



Quaternary sediments are eolian, fluvial, and lacustrine in origin. The Blackwater Draw Formation is the most widespread unit and covers the Ogallala to a depth of up to 80 feet. Alluvial silts, sands, and gravels occur along streams and riverbeds. Silts and clays line the bottoms of the playa lakes.

Source and Occurrence

One source of ground water in the study area is the direct infiltration of precipitation into the Ogallala outcrop or Quaternary deposits overlying the Ogallala. This is generally the most significant natural source of recharge; however, sustained regular rainfall in this area is uncommon and evaporation rates are high. Still, a small amount percolates downward under the force of gravity to the zone of saturation, or that portion in the rock where all of the voids contain water, particularly during the winter months when plant growth and evaporation rates are low. Because of its high porosity and permeability, the Ogallala Formation is an excellent aquifer rock capable of yielding large quantities of water.

Water may also enter the aquifer from indirect infiltration of precipitation through surface streams and playas on the outcrop, through interformational leakage, and return flow of irrigation water. Whereas recharge from streams, most of which flow intermittently, is not considered to be substantial, significant and rapid recharge may occur as focused percolation from playa lakes (Nativ, 1988). Nativ and Riggio (1990) concluded that "the most likely method of ground-water recharge is focused percolation of partly evaporated playa-lake water," based on slightly enriched values of oxygen and hydrogen isotopes found in Ogallala ground water and on the results of a tritium tracer study suggesting fast recharge rates.

Recharge also occurs by upward leakage from underlying formations. As the Ogallala exists under water-table conditions, movement of ground water follows the slope of the surface. Normal hydraulic head causes most Ogallala water to continue to move downdip and downward into older formations. However, changes in hydraulic pressure between the Ogallala and Cretaceous, Triassic, or Permian rocks will cause ground water to migrate upward from these deeper, older rocks into the Ogallala wherever permeable contacts are available. Although data are limited, areas identified on the subcrop map in Figure 2, modified from Nativ (1988), illustrate locations covering parts of several counties in the southern High Plains where potentiometric head is greater in formations underlying the Ogallala.

Discharge from the Ogallala occurs naturally into springs, mostly along the eastern escarpment. Where water levels in the Ogallala are higher than the potentiometric surfaces of either Cretaceous or the Triassic aquifers (Fig. 2), and where permeable sections of either exist in contact with the Ogallala, discharge may also occur into these formations (Nativ, 1988). Such downward leakage to deeper Permian formations is considered less likely because of the low permeability of these older units.

Artificial discharge through pumping wells accounts for the most significant amounts of discharge. Extensive pumpage in much of the High Plains has altered the water-table elevation: water levels have declined significantly, especially in heavily irrigated areas where annual pumpage volume may be as much as ten times that of annual recharge (Nativ, 1988). Natural springs have slowed or stopped flowing altogether, and interformational leakage between the aquifer and underlying aquifers containing more highly-mineralized water with higher potentiometric head has caused the water quality to deteriorate.

WATER QUALITY

The chemical character of ground water mirrors the mineral composition of the rocks through which it has passed, unless contaminants have been added to the recharging water. As water moves through its environment, its solvent power dissolves some of the minerals from the surrounding rocks. Concentrations of the various dissolved mineral constituents depend on the solubility of the minerals in the formation, the length of time the water is in contact with the rock, and the concentration of carbon dioxide present within the water. Additionally, dissolved mineral concentrations generally increase with depth and temperature. Neutralizing or removing the unwanted constituents is usually difficult and can be very costly.

Municipal, industrial, or irrigation wells provide the most representative water samples. Because of their constant pumping and high yield, these wells draw water from a large area of the aquifer which usually ensures a representative sample. Figure 1 shows the location of wells sampled for water-quality analyses for this study.

Sampling Procedures

TWDB personnel follow certain procedures to obtain water samples for analysis that are representative of the true hydrochemical character of the aquifer. These procedures are described in the TWDB *Field Manual for Ground Water Sampling* (Nordstrom and Beynon, 1991). Prior to collection of a ground-water sample, the well must first be purged: a sufficient volume of ground water stored in the well must be removed before sampling. Furthermore, the sample should be collected near the wellhead before the water has gone through pressure tanks, water softener, or other treatment. Temperature, pH, and specific conductance are monitored until the readings stabilize if a well is being actively pumped, after which time the well may be sampled. It is essential to obtain accurate field measurements within minutes of withdrawing a water sample from the well, not only because it is an indication of well stabilization, but also because the conductivity could change significantly with time. Standby, new, or little-used wells may require a day or more of pumping before the water is of constant quality (Wood, 1976).

Upon arrival at the wellsite, temperature, specific conductance (using a VWR conductivity meter), and pH (using a Beckman pH meter) were monitored at five-minute intervals until the readings stabilized. Additionally, field measurements of total alkalinity and Eh (using a pH meter with an Eh diode) were made, then water samples were collected according to the TWDB *Field Manual for Ground Water Sampling* (Nordstrom and Beynon, 1991). All samples except those collected for pesticides (organics) were filtered through a 0.45 μm nonmetallic filter into a one-liter polyethylene bottle and placed on ice. Samples collected for determination of dissolved anion and cation/metal content were delivered to the Texas Department of Health (TDH) laboratory or the Texas Tech University Laboratory if collected within the boundary of the High Plains Underground Water Conservation District No. 1, and analyses were completed within 28 days. Samples collected for nutrient content were analyzed within seven days, and those collected for radioactivity within six months by the TDH laboratory. Unfiltered water samples collected for pesticide content were analyzed within seven days by the TDH laboratory.

Table 1 lists analytical methods and detection limits for dissolved anions, cations/metals, nutrients, and radioactive species. Table 2 lists analytical methods and detection limits for the organic chemicals.

Table 1. Detection limits and analytical methods for dissolved constituents, nutrients, and radioactive species.

Dissolved Anions			
Constituent	Symbol	Detection Limit	Method
Boron	B	0.01 mg/l	Method 404A
Bromide	Br	0.01 mg/l	Method 405
Chloride	Cl	1 mg/l	EPA Method 325.2
Fluoride	F	0.1 mg/l	EPA Method 325.2
Iodide	I	0.01 mg/l	Method 415A
Silica	SiO ₂	1 mg/l	Method 425E
Sulfate	SO ₄	2 mg/l	EPA Method 375.2

Unless otherwise specified, "Method" refers to Standard Methods for the Examination of Water and Wastewater (ACHPA, 1985).

Dissolved Cations/Metals			
Constituent	Symbol	Detection Limit	Method
Aluminum	Al	50 µg/l	ICP
Arsenic	As	10 µg/l	GFAA
Barium	Ba	10 µg/l	ICP
Cadmium	Cd	10 µg/l	FAAS
Calcium	Ca	1 mg/l	ICP
Chromium	Cr	20 µg/l	ICP
Copper	Cu	20 µg/l	ICP
Iron	Fe	20 µg/l	ICP
Lead	Pb	50 µg/l	FAAS
Magnesium	Mg	1 mg/l	FAAS
Manganese	Mn	20 µg/l	ICP
Mercury	Hg	0.2 µg/l	CVAAS
Molybdenum	Mo	20 µg/l	ICP
Potassium	K	1 mg/l	ICP
Selenium	Se	2 µg/l	Fluorometric
Silver	Ag	10 µg/l	FAAS
Sodium	Na	1 mg/l	ICP
Strontium	Sr	200 µg/l	ICP
Vanadium	V	20 µg/l	ICP
Zinc	Zn	20 µg/l	ICP

ICP- Induction Coupled Plasma, EPA Method 200.7
GFAA- Graphite Furnace AA, EPA Method 206.2
FAAS- Flame AA, EPA Method 213.1 (Cd), 239.1 (Pb), 272.1 (Ag)
CVAAS- Cold Vapor AA, EPA Method 245.1
Fluorometric, DAN Method, AOAC Method 25.157

Nutrients			
Constituent	Symbol	Detection Limit	Method
Ammonia	NH ₃ (N)	0.02 mg/l	EPA Method 350.1
Kjeldahl	N	0.1 mg/l	EPA Method 351.2
Nitrate	NO ₃ (N)	0.01 mg/l	EPA Method 353.2
Nitrite	NO ₂ (N)	0.002 mg/l	EPA Method 353.2
Orthophosphate	PO ₄ (P)	0.01 mg/l	EPA Method 365.1

Radioactivity			
Constituent	Symbol	Detection Limit	Method
Gross Alpha	-	2.0 pCi/l	EPA Method 900.0
Gross Beta	-	4.0 pCi/l	EPA Method 900.0
Radium-226	Ra ²²⁶	0.2 pCi/l	EPA Method 903.1
Radium-228	Ra ²²⁸	1.0 pCi/l	EPA Method 904.0

Table 2. Detection limits for organic constituents.

Organic Compound	Detection Limit ($\mu\text{g/l}$)
Aldrin	0.20
α -BHC	0.03
β -BHC	0.03
δ -BHC	0.03
Banvel	5.0
Chlordane (cis)	0.02
Chlordane (trans)	0.02
Chloropyrifos	0.6
Dacthal	0.05
Dicamba	1.0
Dieldrin	0.10
Dursban	0.60
DDD	0.30
DDE	0.20
DDT	0.30
Endrin	0.2
Endosulfan I	0.2
Endosulfan II	0.2
Endosulfan Sulfate	0.2
Hexachlorobenzene	0.02
Heptachlor	0.02
Heptachlor Epoxide	0.06
Lindane	0.03
Malathion	0.40
Methoxychlor	0.50
Mirex	0.50
Methyl Parathion	0.25
Ethyl Parathion	0.25
PCBs (araclors)	1.0
Pentachlorophenol	2.0
Picloram	3.0
Silvex	5.0
Toxaphene	5.0
Treflan	0.06
2,4-D	20.0
2,4,5-T	5.0

Discussions of field measurements are followed by the results of analyses in each major chemical group: dissolved inorganic constituents, nutrients, pesticides, and radioactivity. The range and average of constituents determined by laboratory analyses are discussed and/or data are depicted in map form where appropriate. The TWDB analyzed Ogallala ground water for pesticides and radioactivity for the first time during this project.

The Texas Water Commission (TWC) has set the primary and secondary maximum concentration levels (MCLs) for specific constituents in water used for human consumption. Table 3 lists standards adopted in January 1993 by the TWC. Areas in which key constituents are in excess of MCLs are illustrated in maps contained in the following sections.

Table 3. Drinking water standards for selected inorganic constituents and radioactive species as set by the Texas Water Commission.

Primary Constituent Levels		
Constituent	Symbol	MCL
Arsenic	As	0.05 mg/l
Barium	Ba	2.0 mg/l
Cadmium	Cd	0.005 mg/l
Chromium	Cr	0.10 mg/l
Fluoride	F	4.0 mg/l
Lead	Pb	0.015 mg/l
Mercury	Hg	0.002 mg/l
Nitrate (as N)	NO ₃ (N)	10.0 mg/l
Selenium	Se	0.05 mg/l
Gross Alpha	—	15 pCi/l
Gross Beta	—	50 pCi/l
Radium	Ra ²²⁶ + Ra ²²⁸	20 pCi/l

Secondary Constituent Levels		
Constituent	Symbol	MCL
Chloride	Cl	300 mg/l
Copper	Cu	1.0 mg/l
Fluoride	F	2.0 mg/l
Iron	Fe	0.3 mg/l
Manganese	Mn	0.05 mg/l
pH		≥7.0
Silver	Ag	0.10 mg/l
Sulfate	SO ₄	300 mg/l
Dissolved Solids	TDS	1,000 mg/l
Zinc	Zn	5.0 mg/l
Radon 222	Rn ²²²	300 pCi/l

FIELD MEASUREMENTS

The average ground-water temperature of the Ogallala water samples was 20°C. Secondary drinking water standards indicate that pH should be greater than 7.0 units because acidic water (less than 7.0) will act as a solvent to release metal ions to the water. Thirty-two samples had a pH less than 7.0, but the average pH of all analyses was 7.4 units.

As a measure of the ionized salts, specific conductance gives an indication of the concentration of total ions dissolved in the ground water. The average specific conductance was 585 μmhos in the north where it ranged from 293 to 2,920 μmhos , and 756 μmhos in the south where it ranged from 250 to 13,524 μmhos , in agreement with other indications of poorer water quality in the area.

Two types of alkalinity were tested in each well: phenolphthalein alkalinity as CaCO_3 , from which carbonate is calculated, and total alkalinity as CaCO_3 , from which bicarbonate is calculated. Both were tested according to the TWDB procedures for alkalinity determination (Nordstrom and Beynon, 1991). Since the pH of all samples was less than 8.3, phenol alkalinity was zero and, therefore, no carbonate ions were present. The average total alkalinity in the north as determined in the field was 215 mg/l (range: 56 - 365 mg/l) as CaCO_3 , compared to the average in the south of 246 mg/l (range: 142 - 920 mg/l). Average bicarbonate ion concentration, calculated from mean total alkalinity, was 263 mg/l in the north and 300 mg/l in the south.

The measured Eh ranged from -239.7 to +540.3 mV and averaged +139.4 mV in the north and +108.1 mV in the south. Ogallala waters are oxidizing, as ground waters commonly are in aquifers with good circulation rates (relatively high permeabilities) and little organic matter.

DISSOLVED INORGANIC CONSTITUENTS

Most of the water samples collected from wells in the northern part of the Texas High Plains met drinking water standards for dissolved inorganic constituents. However, numerous wells in the southern part had constituents in excess of the primary MCLs. These included:

Dissolved Solids

The main factor which limits or determines the use of ground water is its dissolved-solids content. These solids are primarily mineral constituents dissolved from the host rock. The Texas Groundwater Protection Committee has adopted a ground-water classification system defined by four classes based on quality as determined by dissolved-solids content. Table 4 describes the classes. Water containing more than 1,000 mg/l should not be used for drinking if other, less mineralized supplies are available or unless some kind of water treatment or filter system is used.

Table 4. Ground-water classification system.

Class	Quality*	Examples of Use
Fresh	0 - 1000	Drinking and all other uses
Slightly Saline	>1,000 - 3,000	Drinking if fresh unavailable; for livestock, irrigation, and industrial use
Moderately Saline	>3,000 - 10,000	Industrial, mineral extraction, oil and gas production; potential/future drinking and limited livestock watering and irrigation if fresh or slightly saline water is unavailable
Very Saline to Brine	>10,000	Mineral extraction, oil and gas production

* Concentration range of total dissolved solids in mg/l

Table 5 lists average concentrations and ranges of dissolved solids and other inorganic constituents from the Ogallala sampled from 1989 through 1992. The higher average dissolved solids content of 1,132 mg/l (and extreme range of 319 to 6,642 mg/l) for the southern half of the study area in comparison to the northern half is reflected on the map in Figure 3. Here contours indicate areas in which the predominant range of dissolved solids is greater than 1,000 mg/l, between 3,000 and 10,000 mg/l, and greater than 10,000 mg/l.

The maps in Figures 3, 4, 5, 6, 8, and 9 were constructed using all available data in the files of the TWDB and include analyses dating back as far as 1963. Data from the recent sampling event (1989-1992) were the major determinants of contour positions, particularly from wells with multiple sampling events in which recent data could more accurately delineate an increase or decrease in the amount of dissolved solids or other constituents. Historical data were more influential in those areas where 1989 - 1992 data were not available. The numerous data points that appear outside of contoured areas indicate locations of wells with anomalously high concentrations of dissolved constituents; these wells are typically surrounded by wells with lower concentrations. By contrast, discussions of averages and ranges listed in Tables 5, 6, and 7 only refer to data collected during the recent sampling event.

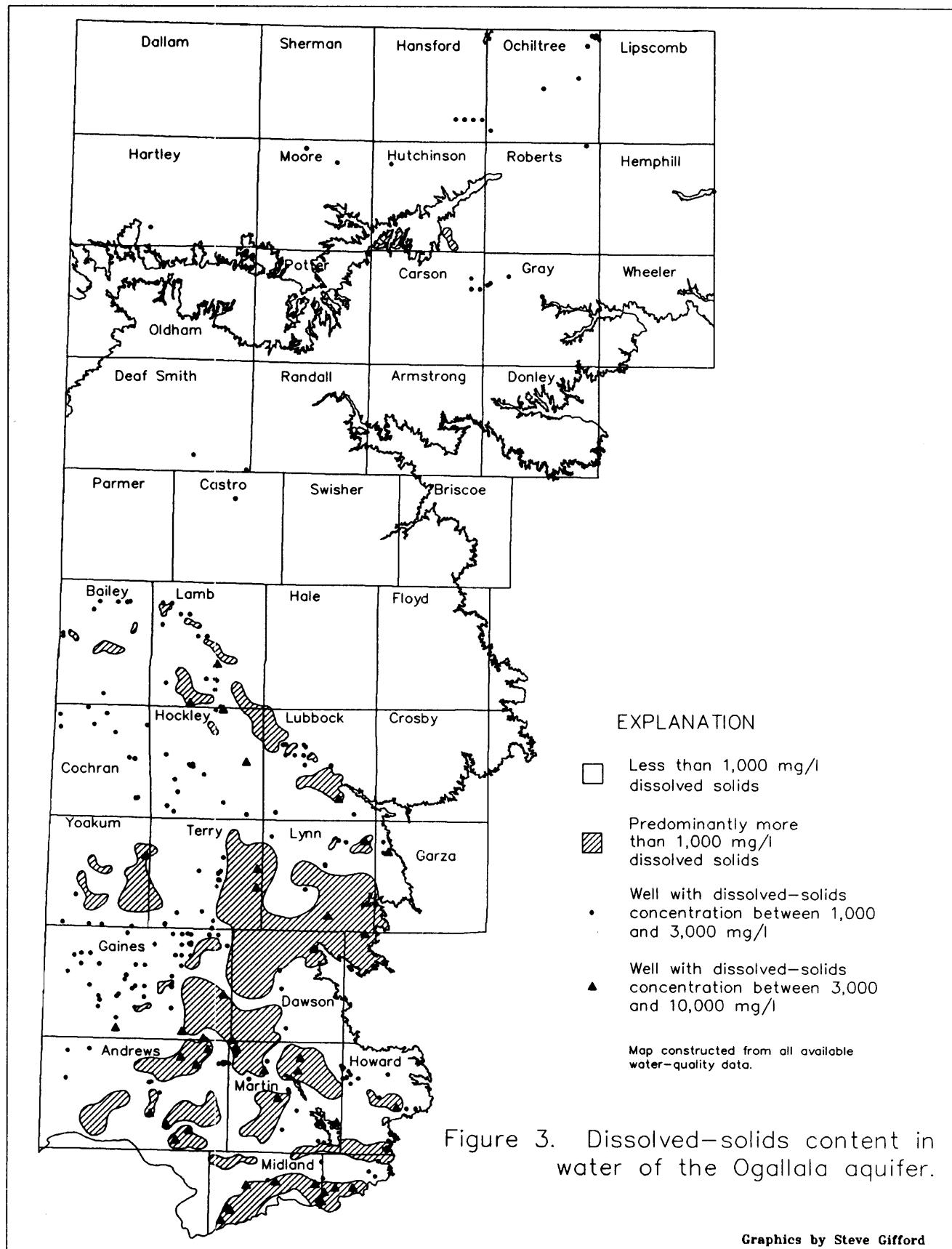


Table 5. Major anions and cations in ground water of the Ogallala aquifer.

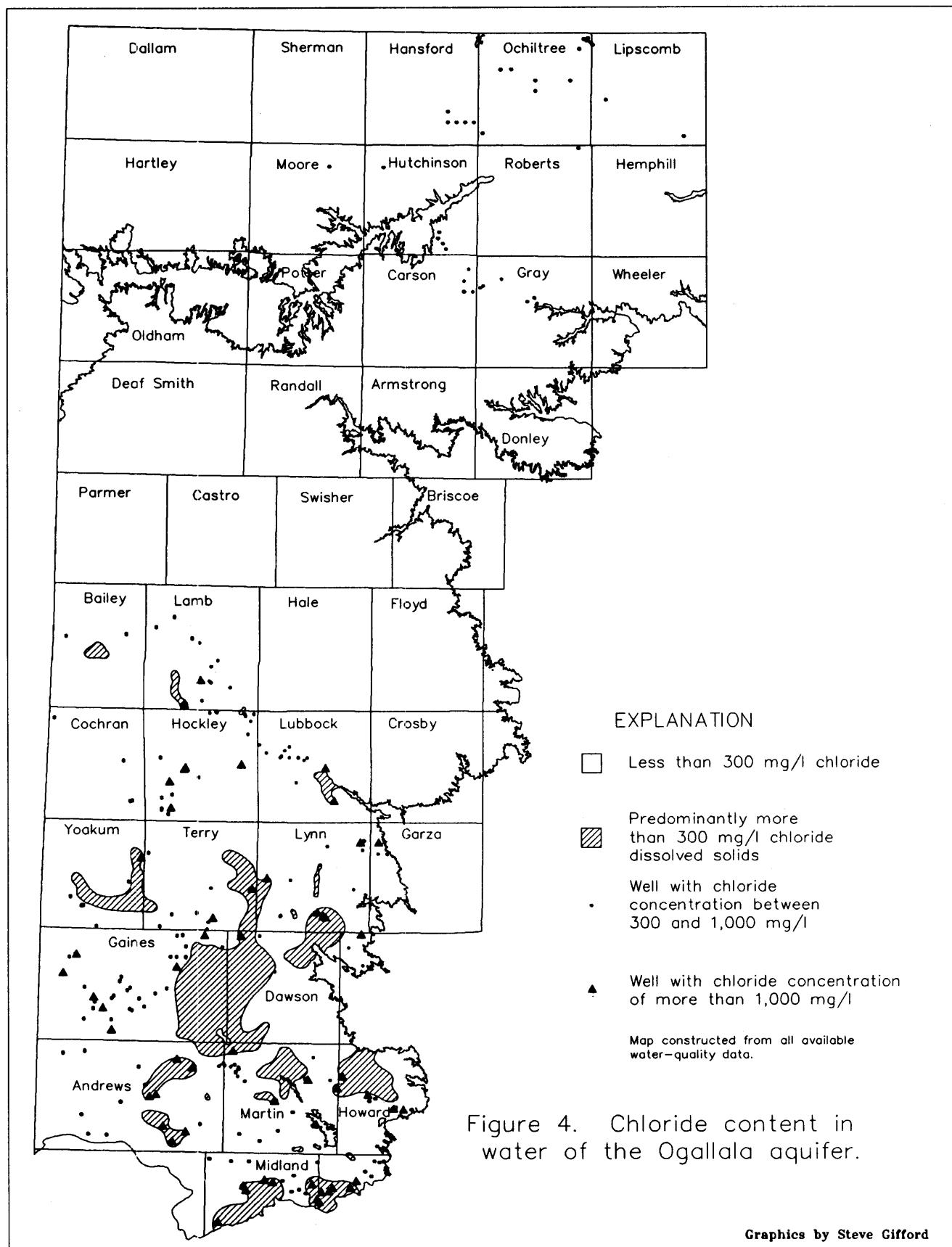
Parameter	Range	Average	Range	Average
	North	North	South	South
Silica (mg/l)	18 - 74	35	17 - 91	51
Calcium (mg/l)	16 - 562	49	26 - 573	104
Magnesium (mg/l)	2 - 131	26	9.5 - 524	78
Potassium (mg/l)	0.7 - 14	6.1	3 - 78	14.2
Sodium (mg/l)	3.6 - 261	36	13 - 1,340	156
Strontium (mg/l)	<2 - 13.5	1.2	0.4 - 91.6	4.2
Bicarbonate (mg/l)	68 - 445	263	173 - 1,123	298
Sulfate (mg/l)	3 - 1,882	46	19 - 2,262	285
Chloride (mg/l)	1 - 583	29	6 - 3,069	256
Fluoride (mg/l)	<0.1 - 5	1.6	0.2 - 12.1	3.5
Dissolved solids (mg/l)	98 - 2,732	366	319 - 6,642	1,132
Hardness-Calcium Carbonate (mg/l)	98 - 1,956	230	151 - 3,585	421

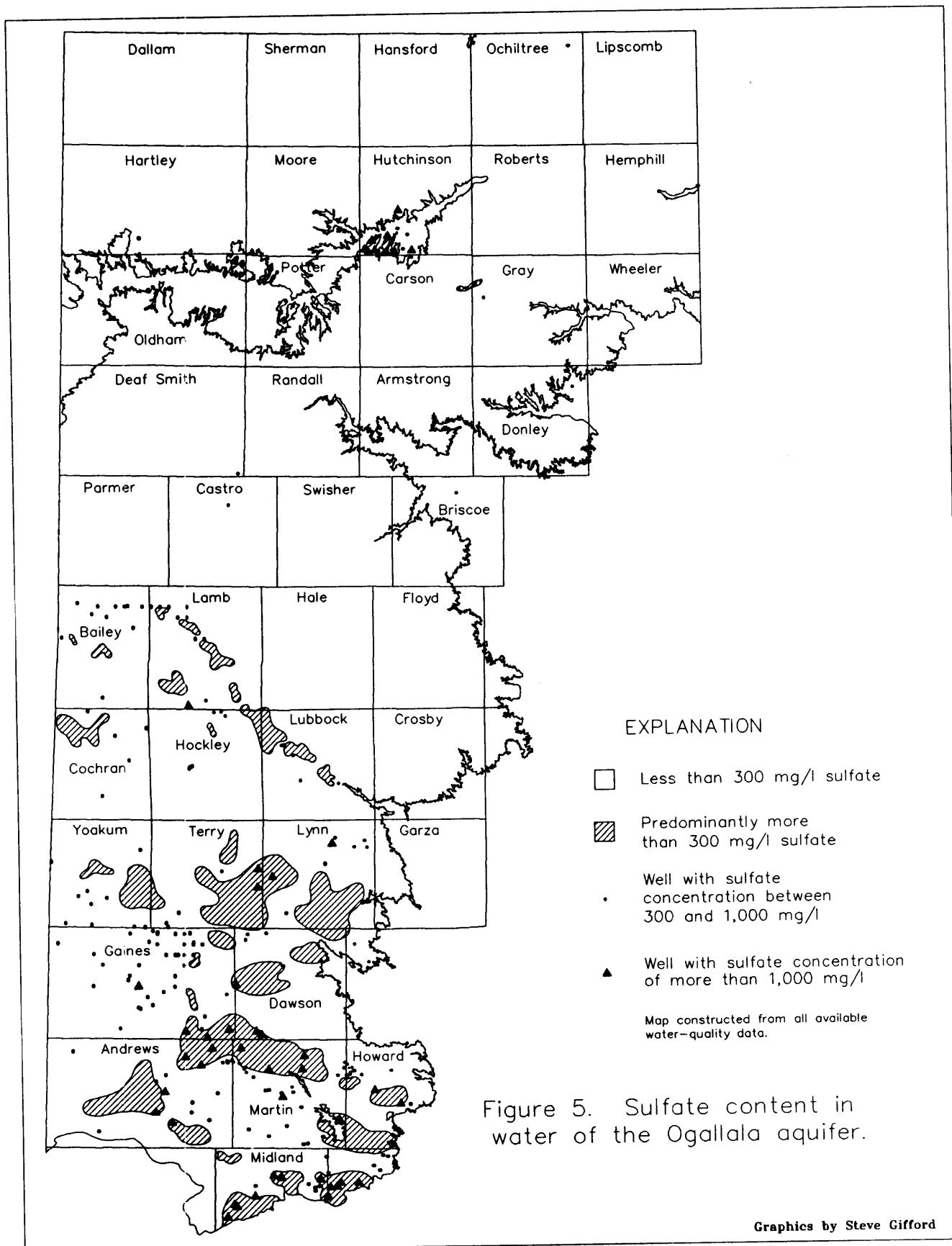
Chloride

Chloride is naturally dissolved from rocks and soils. It can also be introduced into ground water by human activities, as it is present in sewage, oil-field brines, industrial brines, and seawater (which may contaminate fresh-water aquifers in areas of heavy pumpage). In large amounts in combination with sodium, chloride gives a salty taste to drinking water and can increase the corrosiveness of the water. As with dissolved-solids content in the Ogallala, the chloride content was higher in the south than in the north, averaging 29 and 256 mg/l respectively. Twenty-eight percent of samples contained chloride in excess of the secondary drinking standard of 300 mg/l in the south compared to less than one percent in the north. Areas in which chloride content was higher than 300 mg/l are depicted on the map in Figure 4. Numerous isolated occurrences of well water with chloride analyses in excess of 300 mg/l or even 1,000 mg/l exist outside of these contours; wells with dissolved-solids concentrations greater than 10,000 mg/l assumed to be contaminated, however, were not included in this or any other map of dissolved constituents.

Sulfate

Sulfate is naturally formed by the dissolution of sulfur from rocks and soils containing sulfur compounds such as gypsum and iron sulfide. In large amounts, sulfate in combination with other ions gives a bitter taste to drinking water. Figure 5 illustrates areas, mostly in the south, where 33 percent of the wells (94 samples) contained sulfate in excess of the secondary MCL of 300 mg/l, and highlights individual wells with values greater than 1,000 mg/l. Only one well sampled in the north contained more than 300 mg/l of sulfate.





Fluoride

Fluoride within the Ogallala is formed as naturally occurring volcanic-ash deposits or sands and gravels containing fluoride-rich minerals in the formation are leached (Gutentag and others, 1984). Although a certain amount of fluoride (of at least 0.8 mg/l, maximum benefits at 3.0 mg/l) sharply reduces the incidence of dental carries formation, long-term intake of fluoride in concentrations higher than 4 mg/l may cause mottling of the teeth and asymptomatic osteosclerosis (De Zuane, 1990). In the northern part of the study area, the average concentration was 1.6 mg/l; only 10 of 367 samples contained concentrations greater than 4.0 mg/l, and 99 contained between 2.0 and 4.0 mg/l. In the south, however, the average concentration was 3.5 mg/l; 112 of 281 samples contained concentrations greater than 4.0 mg/l, and 115 ranged between 2.0 and 4.0 mg/l. Fluoride concentrations greater than 4.0 mg/l are contoured in the map in Figure 6.

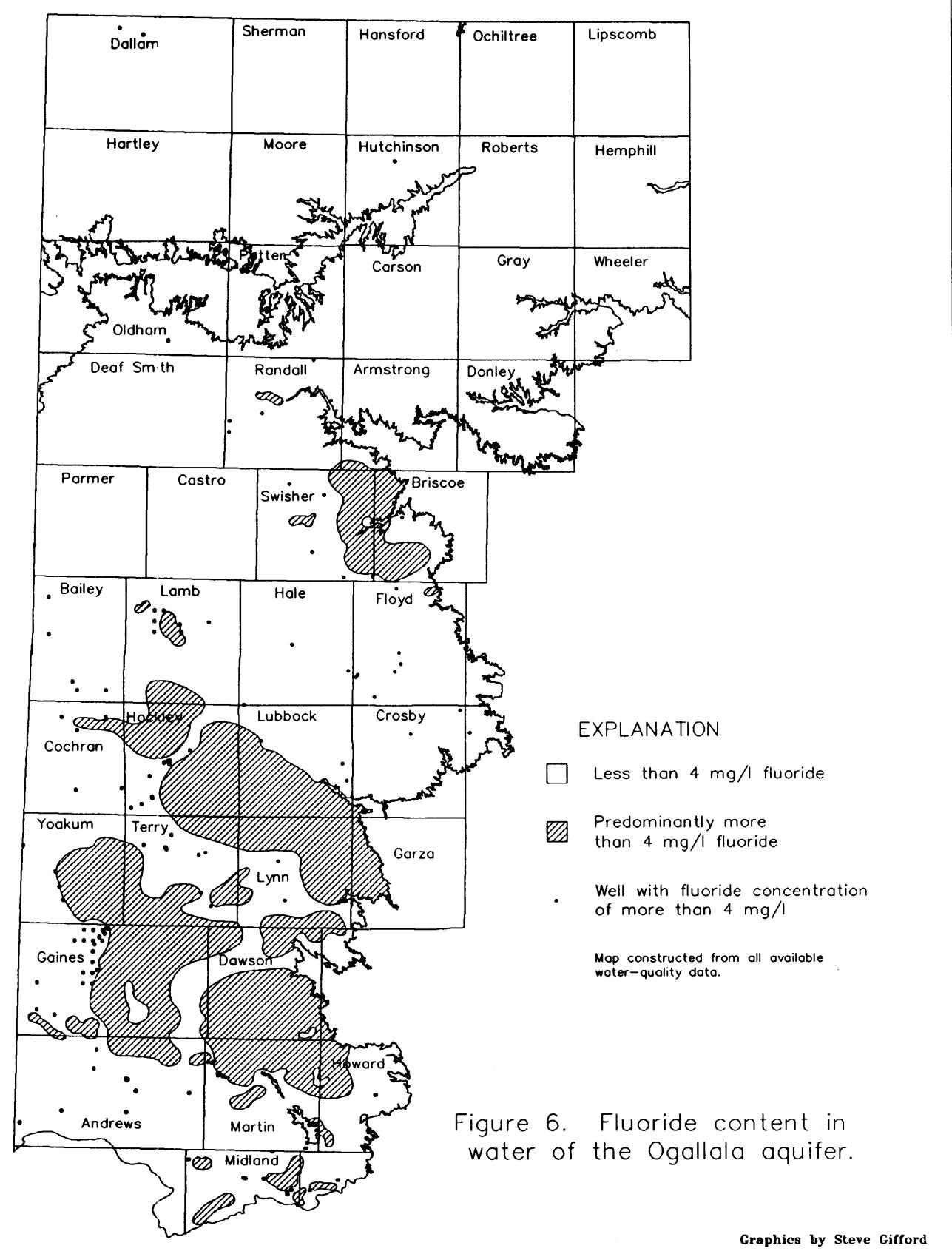
Other workers have discussed several reasons for these elevated concentrations of dissolved solids, chloride, sulfate, and fluoride. The primary argument is that vertical flow—from underlying Cretaceous aquifers in the south (Nativ, 1988), from the Dockum along the caprock escarpment in Deaf Smith, Floyd, Motley, Dickens, and Garza Counties (Nativ, 1988), and from Permian strata along the Caprock in Donley County (Knowles and others, 1984)—has allowed deeper, more highly mineralized waters to mix with Ogallala waters. Locally the water quality is affected by contamination from oil field brines and agricultural chemicals (including fertilizers), and by evaporation where the water table is very shallow.

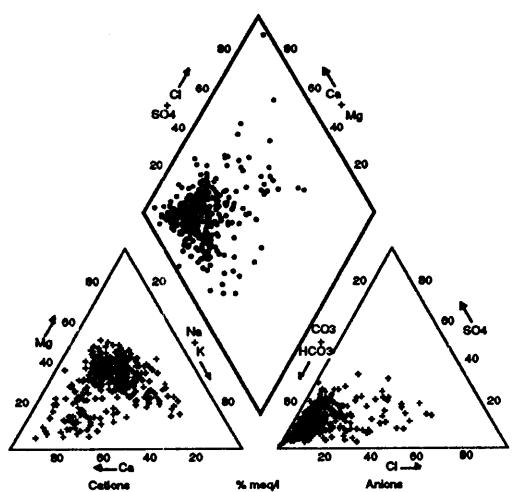
Nativ (1988) supported her arguments for discharge from underlying aquifers citing physical and chemical evidence. The map in Figure 2 indicates areas where the potentiometric surface of the Cretaceous and the Triassic Dockum aquifers may exceed that in water of nearby wells completed in the Ogallala. As several have considered Cretaceous strata to be hydrologically part of the High Plains aquifer, which includes the Ogallala (Knowles and others, 1984), and assuming that permeable contacts or hydraulic connections exist between the Ogallala and underlying aquifers, upward flow is possible where the potentiometric head in the underlying aquifers is higher.

Isotopic compositions in ground waters of the Ogallala and underlying Cretaceous aquifers are not similar in the northern part of the High Plains, but are in the southern part; both the Ogallala and Cretaceous have high tritium values and are heavy with regard to $\delta^{18}\text{O}$ and δD in the southern part (Nativ, 1988). The trilinear diagrams of recent data in Figure 7 illustrate that Ogallala ground water is primarily a Ca-HCO₃ to mixed-cation-HCO₃ type in the north where dissolved solids concentrations are lower. In the south, however, where dissolved solids concentrations are higher, the dominant facies is a Ca-Mg-Na-HCO₃-Cl due to increased amounts of sodium and chloride. Figure 7 illustrates the similarity in composition of waters from Cretaceous and Ogallala aquifers in the southern part of the study area, supporting the assumption of a hydraulic connection between the two (Nativ, 1988).

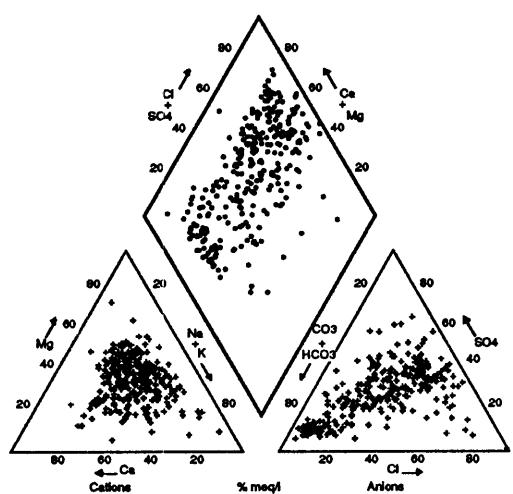
Hardness as CaCO₃

An analytical term used frequently is hardness, a calculation based on dissolved alkali earth metals. Typically, this calculation is based on the total concentration of calcium and magnesium ions, and is reported as calcium carbonate. Other metallic ions such as iron, aluminum, manganese, barium, strontium, and zinc, however, may be present in such considerable amounts as to require inclusion in the hardness reporting quantity. The property of hardness is associated primarily with reactions of water and soap; as the hardness increases, so does the soap-consuming ability of the water. Hard water forms scale in boilers, water heaters, and pipes. Hardness in excess of 180 mg/l is considered to be very hard. For general domestic use, the hardness of water is not

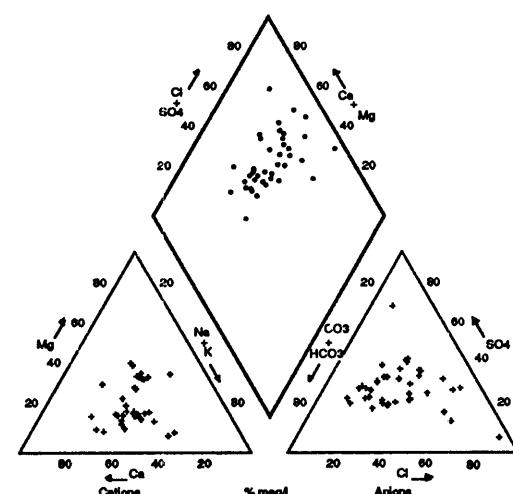




a). The Ogallala aquifer in the northern part of the study area contains primarily Ca-HCO₃ to mixed-cation-HCO₃ water.



b). The Ogallala aquifer in the southern part of the study area contains Ca-Mg-Na-HCO₃-Cl water.



c). Water in the Cretaceous aquifer with greater concentrations of Na and Cl has a chemical composition similar to Ogallala water in the south.

Figure 7. Piper diagrams of the ground water in the Ogallala and Cretaceous aquifers.

particularly objectionable until it exceeds 100 mg/l. Water softeners can be used to alleviate hard water and its associated problems. Ogallala ground water in both the northern and southern parts of the study area is very hard, averaging 230 and 421 mg/l CaCO₃, respectively.

Table 6 lists the remaining constituents or minor inorganics in samples collected from 1989 to 1992. The majority of these were below detection limits, therefore no average values were calculated. Greater ranges and some samples exceeding their respective MCLs were found in the south: three samples of arsenic, one sample each of chromium and iron, eight of manganese, and 11 of selenium.

Selenium

Selenium within the Ogallala also occurs naturally and is considered nutritionally essential at low levels. It is expected to be found in ground water in areas where soils or formations are rich in selenium; elsewhere, it appears only in public sewers due to industrial pollution in trace quantities (De Zuane, 1990). The EPA recently raised the primary MCL for selenium from ten to 50 µg/l. As illustrated on the map in Figure 8, the average concentration of selenium is higher in the south (15.9 µg/l) than in the north (3.8 µg/l). In the south, 118 of 288 samples had concentrations greater than ten µg/l, 18 of which were greater than 50 µg/l; in the north, only nine samples of 344 total had concentrations of selenium greater than 10 µg/l, of which only one was greater than 50 µg/l.

Table 6. Dissolved trace metal constituents in ground water of the Ogallala aquifer.

Parameter	% Above Detection	Range	% Above Detection	Range
	North		South	
Arsenic (µg/l)	2	<10 - 15	45	<10 - 79
Barium (µg/l)	99	<20 - 1290	95	<20 - 223
Boron (µg/l)	100	20 - 730	100	120 - 2520
Cadmium (µg/l)	0	<10	0	<10
Chromium (µg/l)	0	<20	2	<20 - 134
Copper (µg/l)	1	<20 - 29	8	<20 - 81
Iron (µg/l)	0	<20	46	<20 - 358
Antimony (µg/l)	0	<50	0	<50
Manganese (µg/l)	0	<20	6	<20 - 802
Molybdenum (µg/l)	1	<20 - 34	16	<20 - 269
Silver (µg/l)	0	<10	0	<10
Vanadium (µg/l)	33	<20 - 38	91	<20 - 532
Zinc (µg/l)	41	<20 - 462	38	<20 - 1070
Aluminum (µg/l)	0	<50	0	<50
Selenium (µg/l)	50	<2 - 72	92	<2 - 167
Iodide (mg/l)	82	<.1 - .93	42	<.1 - 2.4
Bromide (mg/l)	42	<.1 - 3	71	<.1 - 17.2
Mercury (µg/l)	1	<.2 - 1.1	2	<.2 - 0.7

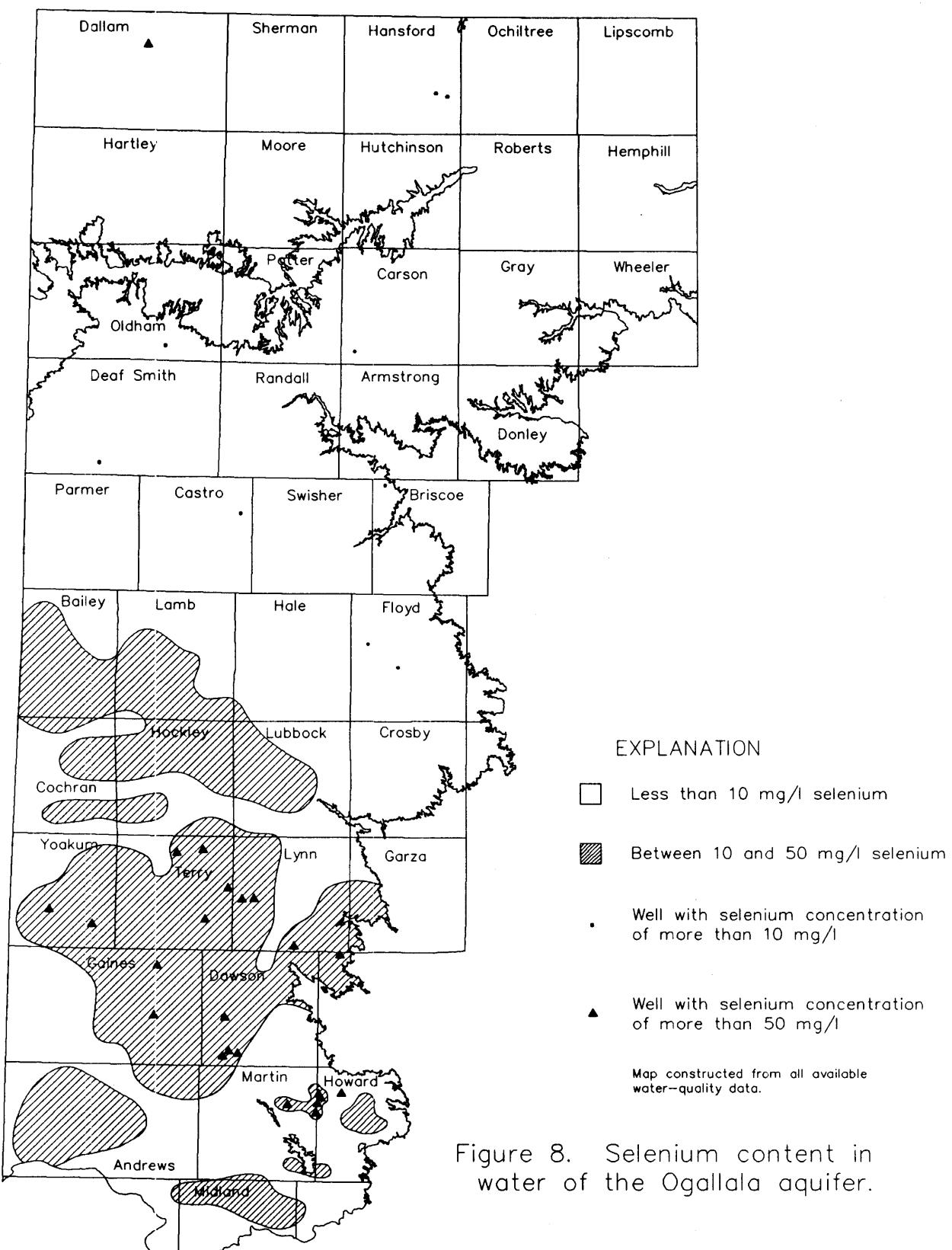


Figure 8. Selenium content in water of the Ogallala aquifer.

NUTRIENTS

Five nutrients were analyzed in each well: nitrate, nitrite, Kjeldahl, ammonia, and orthophosphate. Of these, only nitrate and nitrite have drinking water standards. Table 7 lists the percentages of wells with ranges of all samples or concentrations above detection limit and their ranges.

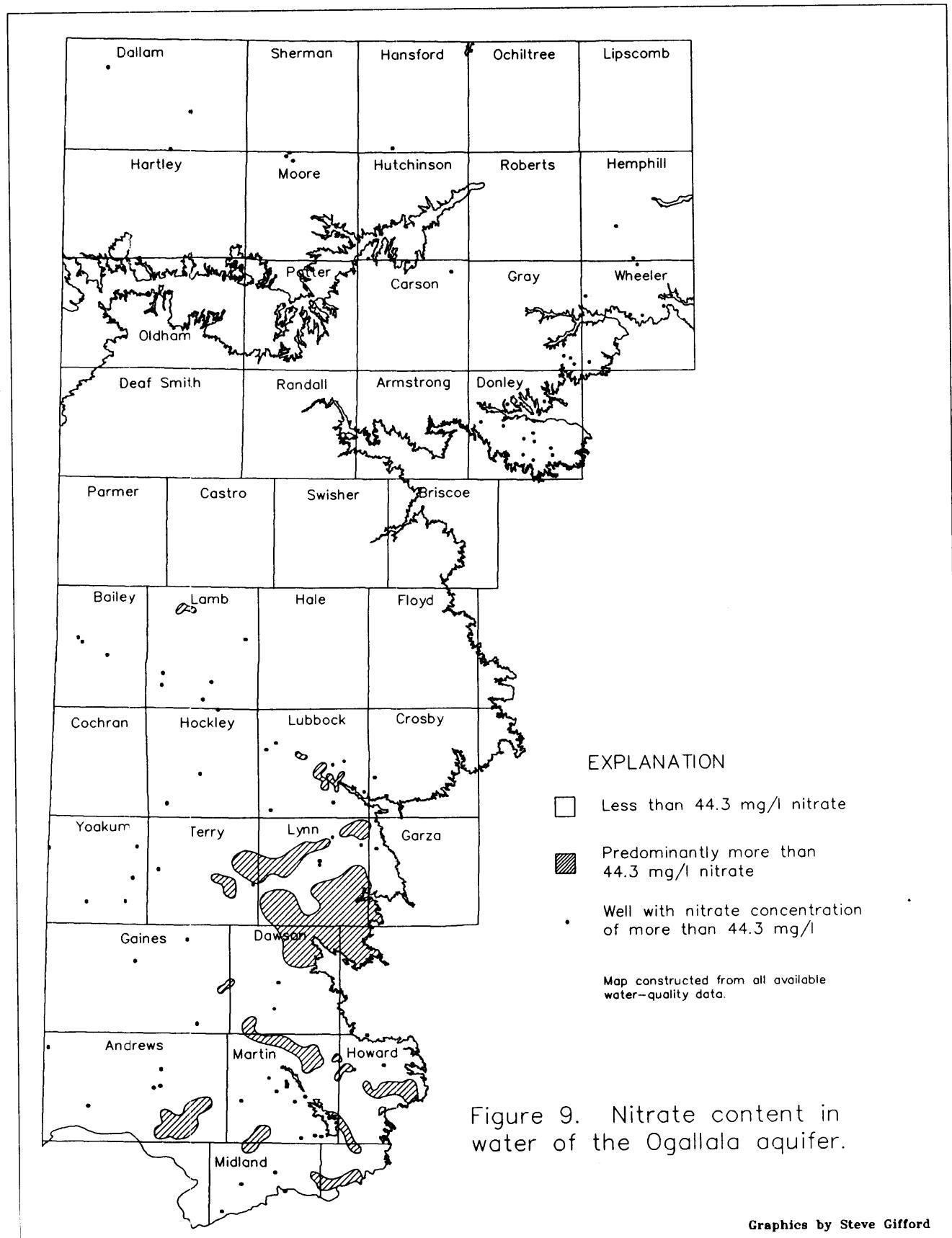
Table 7. Dissolved nutrients in ground water of the Ogallala aquifer.

Parameter	% Above Detection	Range	% Above Detection	Range
	North		South	
Ammonia (mg/l)	34	<.02 - 3.09	47	<.02 - 1
Nitrate (mg/l)	1	<.01 - .04	11	<.01 - 1
Nitrite (mg/l)	99	<.5 - 53.3	100	.5 - 335
Kjeldahl (mg/l)	93	<.1 - 9.7	71	<.1 - 1
Orthophosphate (mg/l)	42	<.01 - 0.4	80	<.01 - 1

Because of the heavy agricultural usage of the land in the study area, nitrate may be among the potential pollutants found in the region. Nitrate (NO_3^-) is a derivative of nitric acid and is one of the most important nutrient species. It is an end product of the aerobic stabilization of nitrogen, particularly organic nitrogen. Nitrate is used extensively as a fertilizer, as a food preservative, and as an oxidizing agent in the chemical industry. Nitrates are particularly detectable in soil and, therefore, ground water (De Zuane, 1990). Higher concentrations of nitrate in ground water should be expected where fertilizers are used, in decayed animal and vegetable matter, in leachates from sludge and refuse disposal, and in industrial discharges. The nitrate concentration of natural waters is typically higher than the nitrite concentration, as nitrites are oxidized to nitrates in these environments.

Of 366 samples analyzed for nitrate in the northern part of the Texas High Plains, only two contained nitrogen in excess of the MCL (44.3 mg/l as NO_3^-); the average was 9.8 mg/l. In the southern part, about 20 percent (56 of 283) exceeded the MCL; the average was 31.8 mg/l. The map in Figure 9, constructed as were the maps of dissolved constituents, illustrates the locations of these wells. Reeves and Miller (1978) and Nativ (1988) suggest that the Ogallala is more susceptible to surface contamination from the leaching of nitrogen-based fertilizers in areas where sandy soils are intensively cultivated and the ground-water table is shallow. Well depths (and water levels) are generally shallower in the south. Twenty-two percent of the wells sampled in the south had water level depths of less than 100 feet and 49 percent at less than 200 feet, compared to 11 percent at depths less than 100 and 15 percent less than 200 feet in the north.

Nitrite (NO_2^-) is a derivative of nitrous acid. It is formed by the action of bacteria upon ammonia and organic nitrogen. Nitrite is used in industry as a food preservative (sodium and potassium salts), particularly in meat and cheese. Nitrite, when detected in potable water in considerable amounts, is an indication of sewage/bacterial contamination and inadequate disinfection (De Zuane, 1990). In such reducing environments, nitrites are not oxidized to nitrates. Large concentrations of nitrite in water may result in the potential formation of carcinogenic nitrosamines in the bloodstream. Of the total 584 nitrite analyses from wells in the north and south, only two were at the MCL of 1 mg/l; the average concentration was 0.01 mg/l in the north and 0.01 mg/l in the south.



No infant under the age of six months should drink ground water or any formula prepared from ground water which contains more than 10 mg/l nitrate as N (the equivalent MCL for nitrate as NO_3 is 44.3 mg/l) because it is known to cause methemoglobinemia, a sometimes fatal illness related to the impairment of the oxygen-carrying ability of the blood. Partial reduction of nitrates to nitrites takes place in human saliva and in the gastrointestinal tract of infants. Nitrite oxidizes the hemoglobin in the blood to methemoglobin, which is not an oxygen carrier. This may lead to anoxia and result in death (De Zuane, 1990).

The Kjeldahl value includes the amount of organic nitrogen plus ammonia (as N) in the water. To find the amount of organic nitrogen, the ammonia concentration is subtracted from the Kjeldahl value. Although there are no MCLs for ammonia or Kjeldahl, the presence of nitrate, nitrite, and ammonia in water are indicators of pollution. The average Kjeldahl value in the northern part of the study area was 0.13 mg/l and 0.24 mg/l in the south.

Phosphate (PO_4) in nature is found in phosphate rock and in the mineral apatite. It is an important source of the insoluble element phosphorous. Phosphate is also the inorganic component of bones and teeth. Water supplies may contain phosphate derived from natural contact with minerals or through pollution from the application of fertilizers, sewage, and industrial waste. The measurements reported in this study are only for the phosphorous content of orthophosphate, the type of phosphate used in fertilizers. The average phosphate value was 0.05 mg/l in the north and 0.06 mg/l in the south.

PESTICIDES

There are millions of synthetic organic chemicals in use throughout the world. Some are known by their "official name" as designated by the International Union of Pure and Applied Chemistry (IUPAC) and others by their commercial name. In the United States alone, more than 700 synthetic organic chemicals have been identified in drinking water. Many organic chemicals have no drinking water standards.

Because of the great number of potential chemical pollutants, three separate analyses for organic compounds were used: the first for Volatile Organic Compounds (VOCs); the second for pesticides (pesticide screen); and the third for other organic compounds referred to as the Gas Chromatograph/Mass Spectrometer (GC/MS) sample. Of primary importance were the priority pollutants designated by the United States Environmental Protection Agency (USEPA). All three analyses screened for these pollutants and also identified any others which may have been present. The type of analysis for each well was based on the use of the land (such as for agriculture or as pasture), presence of oil-production activities, and the type of industry in the locality.

In reporting organic chemicals, the term "quantitation limit" is used in addition to "detection limit." The quantitation limit is the real reporting limit and is about ten times as great as the detection limit of the instrument. This quantitation limit gives a very high confidence interval for the reported value (pers. comm., Jim Boyer, 1992). Occasionally, there may be organic chemicals present in the sample but not at quantitation levels. These chemicals are listed; but since they do not have the high confidence interval of the quantitation level, the well should be sampled a second time to confirm the presence of the contaminant. Even if the contaminant is confirmed, in most cases the amounts are so small as to be negligible.

Organics were detected in 11 wells in six counties, as listed in Table 8. The two reported organics in excess of their MCLs are carbon tetrachloride and bis (2-ethylhexyl) phthalate.

Table 8. Organic constituents in ground water of the Ogallala aquifer.

County	Well#	MCL (if any)	Organic Constituent
Andrews	2744613		.007 mg/l cyclohexanone
	2751501	.	.006 mg/l cyclohexanone
Gaines	2703601		.006 mg/l hexanol in water
	2705527		.007 mg/l cyclohexanone
Lubbock	2721702		.001 mg/l methy butenol
	2721702		.005 mg/l cyclohexanone
Lubbock	2317401	.005 mg/l	.014 mg/l carbon tetrachloride
	2317401		.006 mg/l chloroform
	2317409	.005 mg/l	.019 mg/l carbon tetrachloride
	2317409		.005 mg/l chloroform
	2317402	.005 mg/l	.049 mg/l 1,2-dichloropropane
	2317402		.027 mg/l naphthalene
	2317402	0.7 mg/l	.011 mg/l 1,2-dibromoethane
	2317402		.023 mg/l ethyl benzene in water
	2317402	.005 mg/l	.22 mg/l benzene
	2317402	1.0 mg/l	.11 mg/l toluene
Terry Yoakum	2317402	10.0 mg/l	.25 mg/l xylene Midland
	2763506	.006 mg/l	.017 mg/l bis (2-ethylhexyl) phthalate
	2464101		.0042 mg/l triiodo methane
	2452104	.005 mg/l	.0034 mg/l benzene, volatile analysis

RADIOACTIVITY

Gross alpha (α) radiation consists of the emissions of positively charged helium nuclei from the nucleus of atoms having high atomic weight. When the α particle is emitted from the atom, the atomic weight decreases by four atomic units. This radioactive decay is measured as gross α and in units of picocuries per liter (pCi/l). Alpha-emitting isotopes in natural waters are primarily isotopes of radium and radon which are members of the uranium and thorium disintegration series.

A major contributing factor to the gross α radiation is the combined radiation of Ra²²⁶ and Ra²²⁸. Both of these isotopes are α -emitters. Ra²²⁶ is a disintegration product of uranium (U²³⁸), whereas Ra²²⁸ is a disintegration product of thorium (Th²³²). Ra²²⁶ decays to Rn²²⁶ (radon gas), which is also an α -emitter.

Gross beta (β) radiation consists of the emission of high energy electrons and positrons from the nucleus of atoms having high atomic weight. During the production of a β particle, the neutron of the atom is converted to a proton and an electron is emitted as a β particle. When a β particle is emitted from an atom, the atomic number of the atom increases one unit. Natural β -emitting isotopes are those in the uranium and thorium disintegration series, but there are other natural sources as well.

Table 9 lists ranges of radiation values and averages where appropriate. Locations and exact values are indicated on the map in Figure 10 where concentrations of radioactive constituents exceeded MCLs. All but three of the wells are in the southern part of the study area, with the majority close to the southeastern limits of the aquifer. The naturally occurring radioactivity found in all of these Ogallala samples is associated with the disintegration of uranium-bearing deposits found in the Triassic Dockum, a unit which crops out adjacent to the Ogallala in Oldham and Potter Counties and along the eastern escarpment (Cech and others, 1987; Kier and others, 1977).

Table 9. Dissolved radioactive particles in ground water of the Ogallala aquifer.

Parameter	% Above Detection North	Range North	% Above Detection South	Range South
Gross Alpha (pCi/l)	94	<2.0 - 37 (Avg - 6.6)	100	2.3 - 76 (Avg - 11.9)
Gross Beta (pCi/l)	87	<4.0 - 29 (Avg - 7.1)	95	<4.0 - 104 (Avg - 15.1)
Radium-226 (pCi/l)	68	<0.2 - 1.9	61	<0.2 - 6.5
Radium-228 (pCi/l)	10	<1.0 - 2.3	31	<1.0 - 7.9

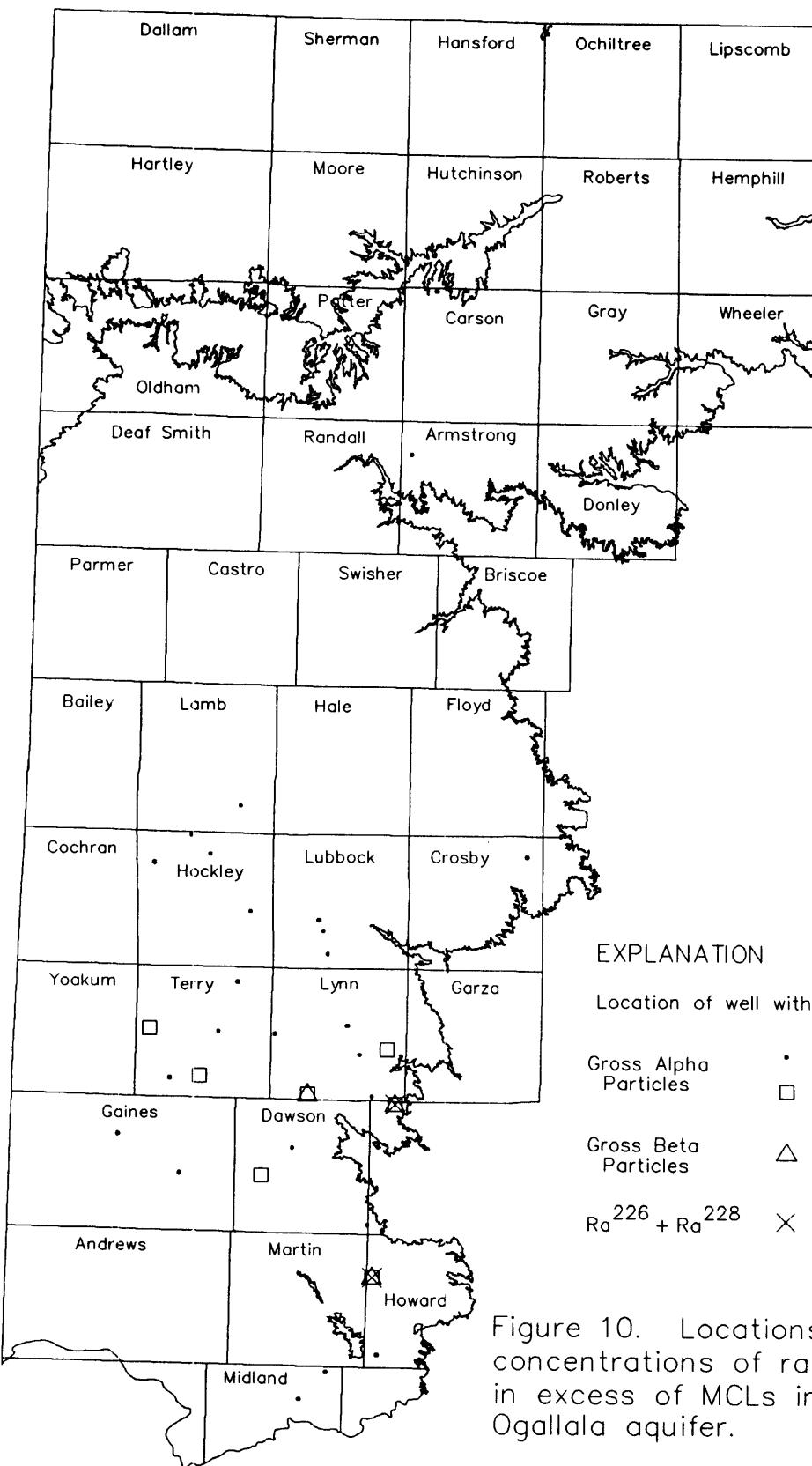


Figure 10. Locations of wells with concentrations of radioactive particles in excess of MCLs in water of the Ogallala aquifer.

Graphics by Steve Gifford

COMPARISON TO PREVIOUS WORK

Although most early investigations about the Ogallala aquifer concentrated on the amount of ground water in storage, pumpage, and water-level declines, brief discussions of water quality have been included in some reports. Chemical analyses of 79 wells sampled during the late 1940s and 1950s in the northern High Plains (north of the Canadian River) indicated that dissolved constituents in the majority of wells met U.S. Public Health Service standards (Alexander, 1961). However, Alexander's report also noted excessive hardness of the ground water, a fluoride range of 0.4 to 2.4 mg/l in which half the samples exceeded the 1.5 mg/l in effect at that time, and one or two samples exceeding the recommended limit of nitrate and iron.

In the southern High Plains (south of the Canadian River), Cronin (1964, 1969) discussed Ogallala water quality as determined from the analyses of 42 samples collected during the 1950s. Although chloride was within the required limit, four samples contained excessive sulfate, two samples contained excessive iron, and 25 samples contained dissolved solids in excess of 500 mg/l, with five exceeding 1,000 mg/l. Fluoride content was greater than 1.5 mg/l in 38 of the 42 samples. Cronin remarked on the association of the samples containing higher fluoride, dissolved solids, and sulfates with those areas in the Ogallala that were underlain by Lower Cretaceous rocks.

Later reports corroborated these findings and included more examples of water of poor quality, particularly in the southern High Plains. Reeves and Miller (1978) attributed the relatively large dissolved-solids and chloride concentrations to seepage from saline lakes, and the excessive nitrate to the leaching of nitrogen-based fertilizers in areas of shallow water tables. Feder and Krothe (1981) documented excessive selenium and fluoride concentrations. Knowles and others (1984), using data from more than 2,000 analyses, mapped concentrations of dissolved solids and chloride. Gutentag and others (1984) mapped dissolved solids and sodium concentrations in the entire extent of the Ogallala from South Dakota to Texas. The increase in fluoride, dissolved solids, and chloride from north to south was discussed and attributed to contributions of more mineralized water from Lower Cretaceous formations.

The Texas Water Commission (1989), using TWDB data, recently published maps of dissolved solids, chloride, and sulfate concentrations in the Ogallala. In one of the most thorough examinations of Ogallala water quality in Texas, Nativ (1988) evaluated 3,562 samples (using mostly TWDB data) and published maps of hydraulic head differences between the Ogallala and underlying formations, dissolved solids concentrations, hydrochemical facies, tritium concentrations, distribution of $\delta^{18}\text{O}$, distribution of $\delta^{34}\text{S}$, and arsenic concentrations. Most recently, Ashworth and others (1991) discussed concentrations of dissolved solids and chloride in the southern part of the study area.

In this report, major cations found to be in excess in a significant number of wells included dissolved solids, chloride, sulfate, and fluoride, in addition to the trace metal selenium and the nutrient nitrate. Samples from the southern part of the study area contained higher average values and greater extremes of all major cations and anions, as indicated in Table 5. The ranges of dissolved trace metals were also greater in the south, as indicated in Table 6. The mapped concentrations of these cations in Figures 3, 4, 5, 6, and 8 graphically portray the greater concentrations in the south.

A review of the historical Ogallala water-quality data from the 1970 to 1975 and the 1989 to 1992 sampling periods reveals that average concentrations were greater in the southern part of the study area 20 years ago than they are today (Table 10). Surprisingly, however, averages of major anions and cations in the south appear to indicate that water quality in the north has improved slightly (with the exception of sulfate) from the early '70s to the latest sampling period. Excluding strontium, the overall change or improvement in water quality from the early '70s to the present can be expressed as ten percent. The reverse trend apparently exists for water quality in the south, with the exception of chloride and hardness; here a 12 percent deterioration in water quality can be argued to have occurred. Comparison of selenium averages over time reveals similar trends: in the north, the average for the early '70s is somewhat higher—4.8 compared to 3.8 mg/l; in the south, the average for the early '70s of 14.7 compared to the recent 15.9 mg/l indicates a slight deterioration of water quality with time.

Table 10. Comparison of present-day average concentrations of major cations and anions with early '70s averages in Ogallala ground water samples.

Parameter	Average North (70 - 75)	Average North (89 - 92)	Average South (70 - 75)	Average South (89 - 92)
Silica (mg/l)	36	35	44	51
Calcium (mg/l)	50	49	89	104
Magnesium (mg/l)	27	26	53	78
Potassium (mg/l)	6.9	6.1	12.9	14.2
Sodium (mg/l)	43	36	120	156
Strontium (mg/l)	—	1.2	—	4.2
Carbonate (mg/l)	272	263	287	298
Sulfate (mg/l)	43	46	185	285
Chloride (mg/l)	38	29	192	156
Fluoride (mg/l)	2.1	1.6	3.1	3.5
Dissolved Solids (mg/l)	384	366	841	1,132
Hardness-Calcium Carbonate (mg/l)	237	230	443	421

Several earlier studies have identified nitrates in the study area including: Reeves and Miller (1978); Strause (1987), whose study indicated that 25 percent of all analyses from wells throughout the Ogallala exceeded the MCL; and Aurelius (1989), whose report of the 1988 Texas Department of Agriculture (TDA) survey of 67 wells indicated that 43 wells contained nitrate equal to or above the MCL. Although the sampling methodology used by the TWDB in the early '70s may not have resulted in consistently accurate determinations of nitrate concentrations, general comparisons are still valid. In the northern part of the study area, the average for the early '70s compared to the average for the recent sampling period is somewhat higher, or 12 compared to 9.8 mg/l; in the south, comparison of the early '70s average of 11 with the recent 31.8 mg/l indicates definite deterioration of water quality over time.

Few previous efforts had been made to systematically monitor pesticides or radioactivity within the Ogallala. The TWDB sampling for these data in all of the High Plains occurred for the first time for this study, although the Board has contributed to sampling efforts to identify isolated cases of pesticide-related ground-water pollution in the past. In 1984, the TDA tested 101 wells in Howard and Martin Counties and found 34 contained arsenic exceeding federal standards (TDA, 1988). In 1988, High

Plains Underground Water Conservation District No. 1 monitored 90 irrigation wells in 15 High Plains counties for pesticides (McReynolds, 1988). Although trace amounts of six chemicals were found in 14 of 589 total analyses, all of which fell below the EPA-proposed health advisory limit for each identified chemical, no trace amounts were found during retesting. In 1988, the TDA survey of 67 wells in Dawson, Howard, Lynn, Martin, and Terry Counties (Aurlius, 1989) revealed the presence of the same three pesticides in three wells in Howard, Lynn, and Martin Counties, as well as the presence of arsenic in concentrations at or above the MCL in 24 wells in all counties except Lynn. Analyses completed for this study revealed no excessive arsenic, and the small number of other organic pollutants was insignificant (Table 8).

As part of efforts to evaluate the rate of recharge to the Ogallala, the Bureau of Economic Geology compared levels of tritium in ground water with levels in past precipitation (Nativ and Smith, 1987) and discovered that tritium levels were higher in ground water in the southern part of the High Plains. Cech and others (1987) obtained 70 samples from 21 counties in the High Plains and found radium-226 concentrations mostly below 0.5 pCi/l with a slight increase (to no more than 1.7 pCi/l) in the east. Cech mapped radioactive deposits in Texas by superimposing radium and radon data gathered for the 1987 report on a map of uranium deposits adapted from Kier and others (1987). In 1988, Cech and others mapped concentrations of radon-222 from 150 samples collected statewide. Twenty of these were obtained from seven counties in the northern High Plains and ranged from about 100 pCi/l to nearly 1,000 pCi/l, with a median concentration of about 300 pCi/l. Thirty-one of the total 33 samples in this report with excessive radioactive constituents occurred in wells in the southeast, consistent with the increased trend in radium-226 as mapped by Cech in 1987.

CONCLUSIONS

Wells were sampled in accordance with quality control and quality assurance directives established in the TWDB sampling manual. Most analyses were conducted by the TDH and some by Texas Tech University using EPA-approved procedures and were completed within the required holding times.

The average dissolved-solids content, a main factor determining or limiting the use of ground water, of 1,132 mg/l in the southern part of the study area exceeds the secondary drinking water standard. Twenty-eight percent of the wells sampled for chloride, 33 percent for sulfate, 40 percent for fluoride, 41 percent for selenium, and 20 percent for nitrate contained concentrations in excess of the primary drinking standards. Percentages of excess concentrations in wells in the northern part of the study area, however, were negligible. Hardness averaged in excess of 400 mg/l in the south and 230 mg/l in the north, both considered very hard.

The water-quality problems determined from this study have been well documented in previous reports published by the TWDB and others. Whereas a slight amelioration in water quality in the north during the past 20 years was determined from examination of and comparison with older data, a somewhat more significant deterioration in water quality occurred in the south during the same period. Aquifer-wide concentrations of fluoride and selenium had not been previously mapped.

The TWDB completed aquifer-wide sampling for organics and radioactivity in the Ogallala for the first time during this study. Eighteen samples from 11 wells contained organics, most of which have no MCL set by the EPA. In Lubbock County, two nearby wells contained excessive carbon tetrachloride. In Midland County, one well contained excessive bis (2-ethylhexyl) phthalate. This study revealed no excessive arsenic as determined by the 1988 and 1989 TDA studies.

Excessive radioactive constituents were identified in 31 wells, most of which were in the southeast in close proximity to the Triassic Dockum uranium-bearing strata corroborating findings by Cech and others in 1987. Each of these wells contained excessive alpha concentrations; only three wells contained excessive gross beta particles, and two contained excessive combined radium.

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