Ground-Water Quality Beneath Irrigated Agriculture in the Central High Plains Aquifer, 1999–2000

By Breton W. Bruce, Mark F. Becker, Larry M. Pope, and Jason J. Gurdak

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Foreword

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. (http://www.usgs.gov/). Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. (http://water.usgs.gov/nawqa). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. (http://water.usgs.gov/nawqa/nawqamap.html). Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings. (http://water.usgs.gov/nawqa/natsyn.html).

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
inch	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
meter (m)	3.281	foot
acre	640	square mile
milligram per liter (mg/L)	1.0	part per million
microgram per liter (μg/L)	1.0	part per billion
milliliter (mL)	0.0338	ounce, fluid
pound per acre (lb/acre)	1.121	kilogram per hectare
pound per square inch (lb/in^2)	6.895	kilopascal
square mile (mi^2)	2.590	square kilometer
million gallons per day (Mgal/d)	2.629	cubic meters per minute

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°C = 5/9\ (°F - 32)$$

$$°F = 9/5\ (°C) + 32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929; (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

OTHER ABBREVIATIONS:

micrometer, μm
milliequivalent, meq

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Abstract

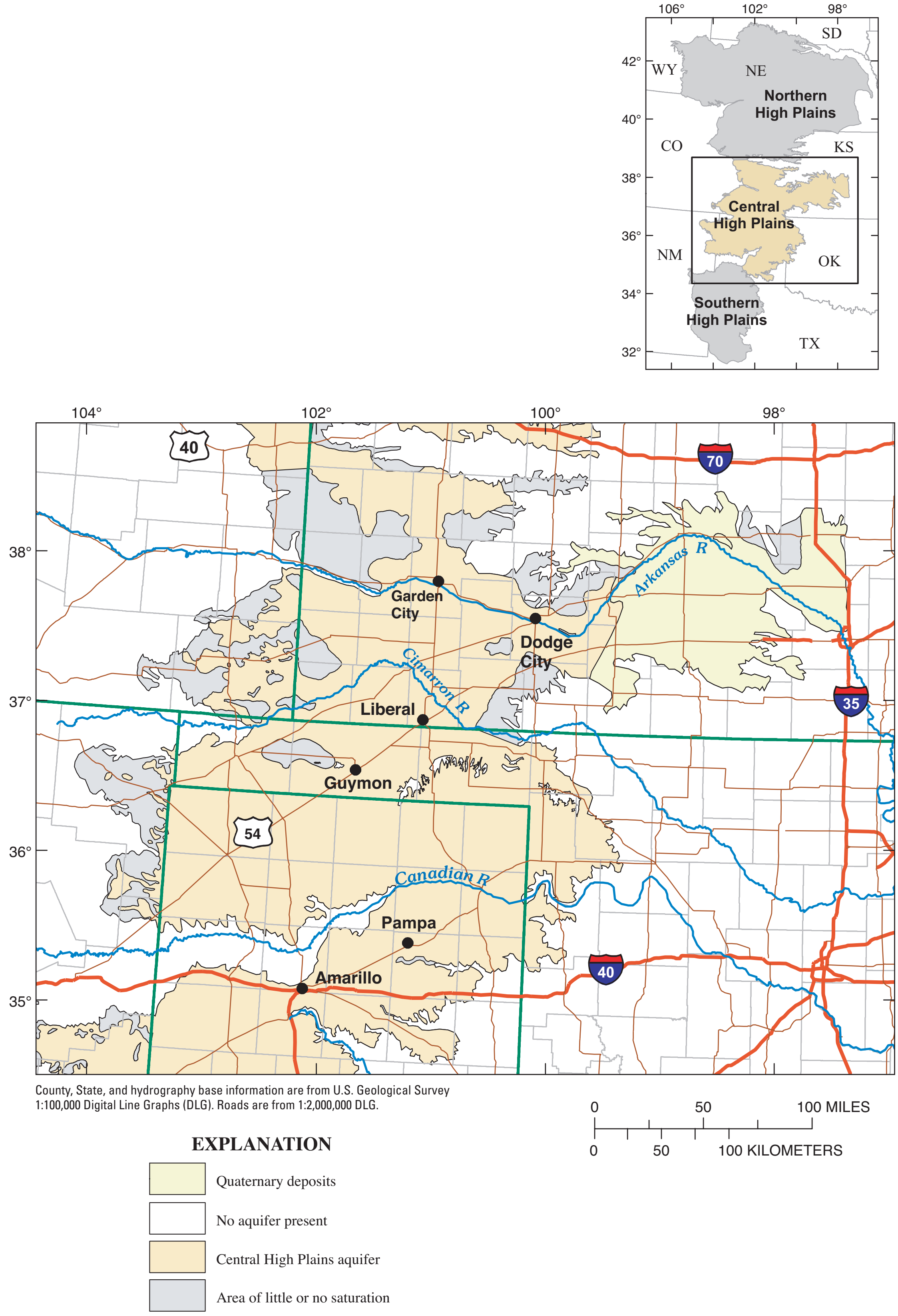
In 1999 and 2000, 30 water-quality monitoring wells were installed in the central High Plains aquifer to evaluate the quality of recently recharged ground water in areas of irrigated agriculture and to identify the factors affecting ground-water quality. Wells were installed adjacent to irrigated agricultural fields with 10- or 20-foot screened intervals placed near the water table. Each well was sampled once for about 100 water-quality constituents associated with agricultural practices. Water samples from 70 percent of the wells (21 of 30 sites) contained nitrate concentrations larger than expected background concentrations (about 3 mg/L as N) and detectable pesticides. Atrazine or its metabolite, deethylatrazine, were detected with greater frequency than other pesticides and were present in all 21 samples where pesticides were detected. The 21 samples with detectable pesticides also contained tritium concentrations large enough to indicate that at least some part of the water sample had been recharged within about the last 50 years. These 21 ground-water samples are considered to show water-quality effects related to irrigated agriculture. The remaining 9 ground-water samples contained no pesticides, small tritium concentrations, and nitrate concentrations less than 3.45 milligrams per liter as nitrogen. These samples are considered unaffected by the irrigated agricultural land-use setting. Nitrogen isotope ratios indicate that commercial fertilizer was the dominant source of nitrate in 13 of the 21 samples affected by irrigated agriculture. Nitrogen isotope ratios for 4 of these 21 samples were indicative of an animal waste source. Dissolved-solids concentrations were larger in samples affected by irrigated agriculture, with large sulfate concentrations having strong correlation with large dissolved solids concentrations in these samples. A strong statistical correlation is shown between samples affected by irrigated agriculture and sites with large rates of pesticide and nitrogen applications and shallow depths to ground water.

Introduction

Knowledge of the quality of the Nation's water resources is important because of the implications to human and aquatic health and because of the significant costs associated with decisions involving land and water management, conservation, and regulation. In 1991, the U.S. Geological Survey (USGS) began full implementation of the National Water-Quality Assessment (NAWQA) Program. The long-term goals of the NAWQA Program are to describe the status and trends in the quality of the Nation's surface- and ground-water resources and determine the natural and anthropogenic factors affecting water quality (Gilliom and others, 1995). More than 50 major river basins and aquifer systems are targeted for investigation under the NAWQA Program. Together, these include water resources available to more than 60 percent of the population and cover about one-half of the land area in the conterminous United States.

The High Plains Regional Ground Water study began in October 1998 and represents a modification of the traditional NAWQA design in that the ground-water resource is the primary focus. The High Plains aquifer is a nationally important water resource that underlies about 174,000 mi^2 in parts of eight Western States (fig. 1). About 27 percent of agricultural land in the United States is in the High Plains, and about 30 percent of all the ground water used for irrigation in the United States is pumped from this aquifer (Dennehy, 2000).

Water quality in the High Plains aquifer might be vulnerable to effects from land-surface activities; however, large depths to ground water in some areas could provide a buffer from these influences. The lack of a regionally extensive geologic barrier to impede downward migration of contaminants contributes to the potential for water-quality degradation from land-surface activities. Similarly, applications of large amounts of water at the land surface can be a driving force for downward migration of chemicals. Residential and urban settings, agricultural activities, and oil and gas exploration/development are potential sources of contaminants to this drinking-water aquifer.



County, State, and hydrography base information are from U.S. Geological Survey 1:100,000 Digital Line Graphs (DLG). Roads are from 1:2,000,000 DLG.

Figure 1. Location of the High Plains aquifer system and the boundaries of the central High Plains agricultural land-use study, 1999–2000.

NAWQA ground-water studies include a component designed to assess the relation between regionally significant land-use settings and the quality of recently recharged ground water. These land-use studies investigate the natural and human factors affecting ground-water quality in these settings. In a reconnaissance study of the effect of irrigated agriculture on water quality in the central High Plains aquifer, McMahon (2000) demonstrated that recently recharged water was present in the High Plains aquifer in selected areas with depths to water as great as 200 ft and that the quality of ground water in these areas was affected by agricultural land-use practices. Based on these findings, a more comprehensive and areally extensive NAWQA land-use study (LUS) was completed in 2000 to evaluate the regional effects of irrigated agriculture on ground-water quality in the central High Plains aquifer.

Purpose and Scope

This report describes the quality of recently recharged ground water beneath irrigated agricultural land in the central High Plains aquifer. Thirty water-quality monitoring wells were installed in proximity to irrigated fields in areas where depth to water was less than 200 ft. The 30 wells had short (generally 10 ft) well screens that were installed near the water table. The wells were sampled once between February 1999 and September 2000 and analyzed for approximately 100 constituents including major dissolved ions, nutrients (compounds of nitrogen and phosphorus), nitrogen isotopes, pesticides and pesticide metabolites, tritium, and dissolved organic carbon (DOC). Land use within about 500 meters of each well was characterized, and correlations between ground-water quality and the overlying land-use were explored.

Acknowledgments

The authors thank each landowner that allowed a monitoring well to be installed on their property. Without their open-minded, proactive attitude, this study would not have been possible. We also thank the following USGS employees: Carol Carlson, Mike Carlson, Chad Milligan, Marty Phillips, and Martin Schneider for their assistance with field activities; Cristi Hansen for her review and processing of site land-use data; and Sharon Qi for assisting with the preparation of graphics shown in this report. We also thank the following reviewers and editors for their contributions to this manuscript: Mary Kidd, Suzanne Paschke, and Andrew Ziegler.

Description of Study Area

For logistical reasons, the High Plains aquifer was subdivided into three regions of study (fig. 1). This land-use study was done within the central High Plains region in geologic units of Tertiary age or younger. Nonglacial deposits of Quaternary age lie east of the study area in south-central Kansas and, although part of the central High Plains aquifer, they were not investigated by this study. The boundaries used for the central High Plains region and the extent of the central High Plains aquifer are consistent with those described by Gutentag and others (1984). The central High Plains region covers an area of about 48,500 mi^2 in parts of Colorado, Kansas, New Mexico, Oklahoma, and Texas (fig. 1). The central High Plains aquifer studied here underlies about 38,000 mi^2 in all but the eastern part of the central High Plains (fig. 1).

Hydrogeologic Setting

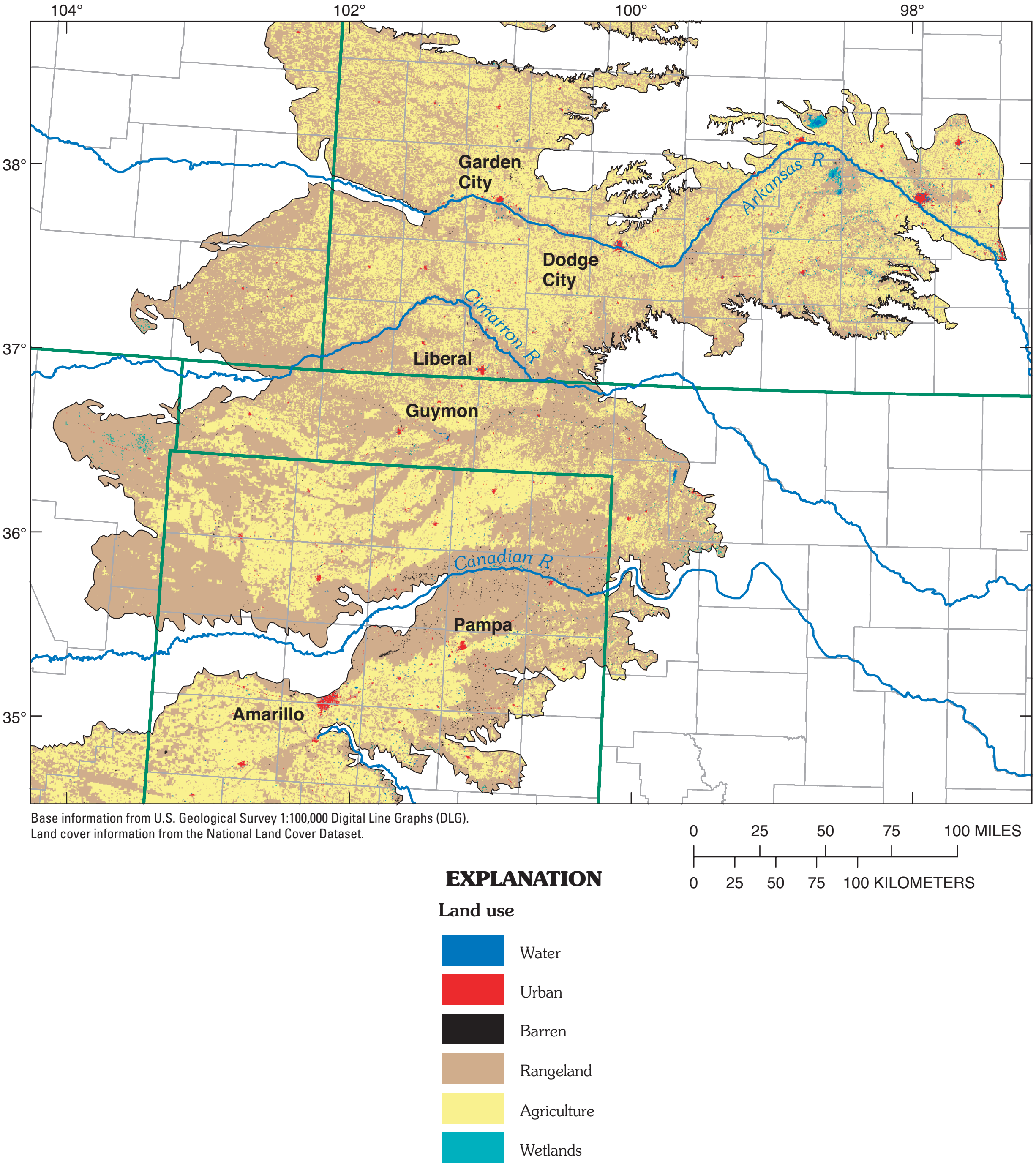
The hydrogeologic setting of the High Plains aquifer has been described in detail by Gutentag and others (1984) and Luckey and others (1986, 1988). Other localized studies describe the hydrogeology of subareas of the High Plains (Gutentag and others, 1981; Peckenpaugh and Dugan, 1983; Peckenpaugh and others, 1987; Nativ, 1988). The central High Plains aquifer is primarily composed of the Ogallala Formation (of Tertiary age) and generally can be described as interbedded sand, gravel, silt, and clay deposited by fluvial (stream) and eolian (windblown) processes. The sediments are poorly sorted and generally unconsolidated but in some locations are cemented by calcium carbonate and, to a lesser degree, silica. The Tertiary-age sediments are locally overlain by Quaternary-age alluvial gravel, dune sand, and loess deposits and are underlain by older bedrock formations.

Sand and gravel zones in the central High Plains aquifer are the primary source of water to wells and commonly yield between 100 and 2,000 gallons per minute (Gutentag and others, 1981). Ground water exists predominantly under unconfined conditions, though confined conditions might be present locally. Overlying Quaternary-age deposits and underlying bedrock formations can, where saturated, contribute water and solutes to the central High Plains aquifer. The regional water table slopes eastward with a gradient of about 0.002 (10.5 ft per mi; Luckey and Becker, 1998), and water movement generally is in that direction. The saturated thickness of the central High Plains aquifer is as much as 600 ft with the greatest saturated thickness in areas that overlie the deepest channels in the bedrock surface (McGuire and Fischer, 1999). Some areas in the western part of the central High Plains are underlain by Tertiary-age sediments but contain no water or are minimally saturated (fig. 1). Wells in this western part of the central High Plains commonly withdraw water from deeper bedrock units rather than the High Plains aquifer.

Water levels in the central High Plains aquifer have been declining since the area underwent extensive ground-water irrigation development in the 1950's. Luckey and others (1981) reported water-level declines of more than 100 ft in parts of the central High Plains for the period between predevelopment (1950) and 1980. McGuire (2001) calculated an average area-weighted decline rate of 0.33 ft per year for southwestern Kansas between predevelopment and 1980 and a decline rate of about 0.44 ft per year from 1980 to 1999.

Land Use

The central High Plains region is sparsely populated, and the area is dominated by an agricultural economy. About 57 percent of the study area is rangeland, 41 percent is active agricultural land, and less than 1 percent is considered an urban environment (U.S. Geological Survey, National Land Cover Data Set, nominal 1992). Figure 2 shows the distribution of land-use types in the central High Plains region. In 2000, the estimated population in the study area was about 340,000. Amarillo, Tex., is the largest city in the study area and had a population of 173,627 in 2000. Other major cities (and their 2000 populations) are Garden City, Kans. (28,000); Dodge City, Kans. (25,000); Liberal, Kans. (20,000); Pampa, Tex. (18,000); and Guymon, Okla. (11,000). Counties in the study area that do not encompass one of these major cities generally have rural populations of about 5,000 or less. (U.S. Census Bureau, 2000).



Base information from U.S. Geological Survey 1:100,000 Digital Line Graphs (DLG).
Land cover information from the National Land Cover Dataset.

Figure 2. Areal distribution of primary land-use types in the central High Plains, nominal 1992.

Of the 41 percent of central High Plains region that is under cultivation, about 68 percent is dry-land farming and about 32 percent is irrigated crop land (U.S. Geological Survey, National Land Characteristics Data Set, nominal 1992). Wheat, corn, and sorghum are the primary agricultural crops in the central High Plains region; other small grains and hay are minor crops. Generally, corn is an irrigated crop, whereas wheat and sorghum generally are not irrigated. Figure 3 shows the acres of land, by State, under the major crop types in the central High Plains region (U.S. Department of Agriculture, 2001).

Livestock production also is an important commodity in the central High Plains region with more than 4.5 million cattle and calves in inventory in 1997 (U.S. Department of Agriculture, 2001). Of the top 20 cattle-producing counties in the United States, 3 are in the central High Plains region (Finney County, Kansas; Texas County, Oklahoma; and Hansford County, Texas). Swine production, centered in the Guymon, Okla., area also is an important livestock commodity and is rapidly increasing. Though actual numbers of swine in inventory are not reported for every county in the central High Plains region, Texas County in Oklahoma ranked third in the Nation in 1997 with about 907,000 hogs in inventory (U.S. Department of Agriculture, 2001). The counties in Kansas, New Mexico, and Texas that border the Oklahoma panhandle are the largest producers of hogs and pigs in those States.

Fertilizer and Pesticide Use

The use of fertilizers and agricultural chemicals on crop land is of importance to a study of ground-water quality in the agriculturally dominated central High Plains region. Fertilizers provide nutrients (primarily nitrogen) needed by crops to optimize growth and production. Excess nitrogen applied to fields can leach to the ground-water system and cause elevated nitrate concentrations. Nitrate concentration in drinking water is a human health concern and is regulated by the U.S. Environmental Protection Agency. Manure and commercial fertilizer (generally in the form of anhydrous ammonia) are the primary forms of nitrogen applied to fields in the central High Plains region. Figure 4 shows the agricultural application rates (by county) for both forms of nitrogen in the study area.

Naturally occurring organic nitrogen accumulating in the soil zone due to plant decomposition also can be an important secondary source of nitrogen in agricultural settings. This soil organic nitrogen can be mobilized when the sod is first tilled, and this mobilization can create a pulse of nitrogen to the ground-water system. The largest nitrogen concentrations associated with this soil nitrogen pulse generally decrease over time; however, it might take several years (or decades) for the initial nitrogen pulse to migrate to the water table in areas with large depths to ground water. The concentrations of ground-water nitrate derived from soil organic nitrogen are likely to be smaller than those derived from annual fertilizer applications on crop lands with long agricultural histories.

Pesticides are chemicals used to control unwanted plants and insects in crops. They also are used to control weeds in lawns, rights-of-way, ponds, and ditches. The 10 most frequently applied pesticides in the central High Plains region (by pounds applied and acres applied) are listed in table 1. Different pesticides exhibit different levels of persistence and mobility in the environment. Some heavily applied compounds are rarely detected in ground water either because they quickly degrade in the near surface or they become strongly adsorbed to soil and sediment. The herbicide atrazine is heavily used for broadleaf

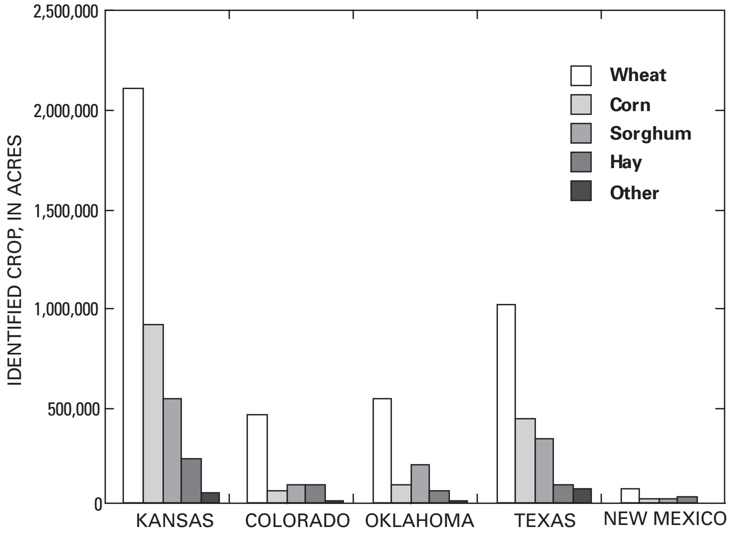
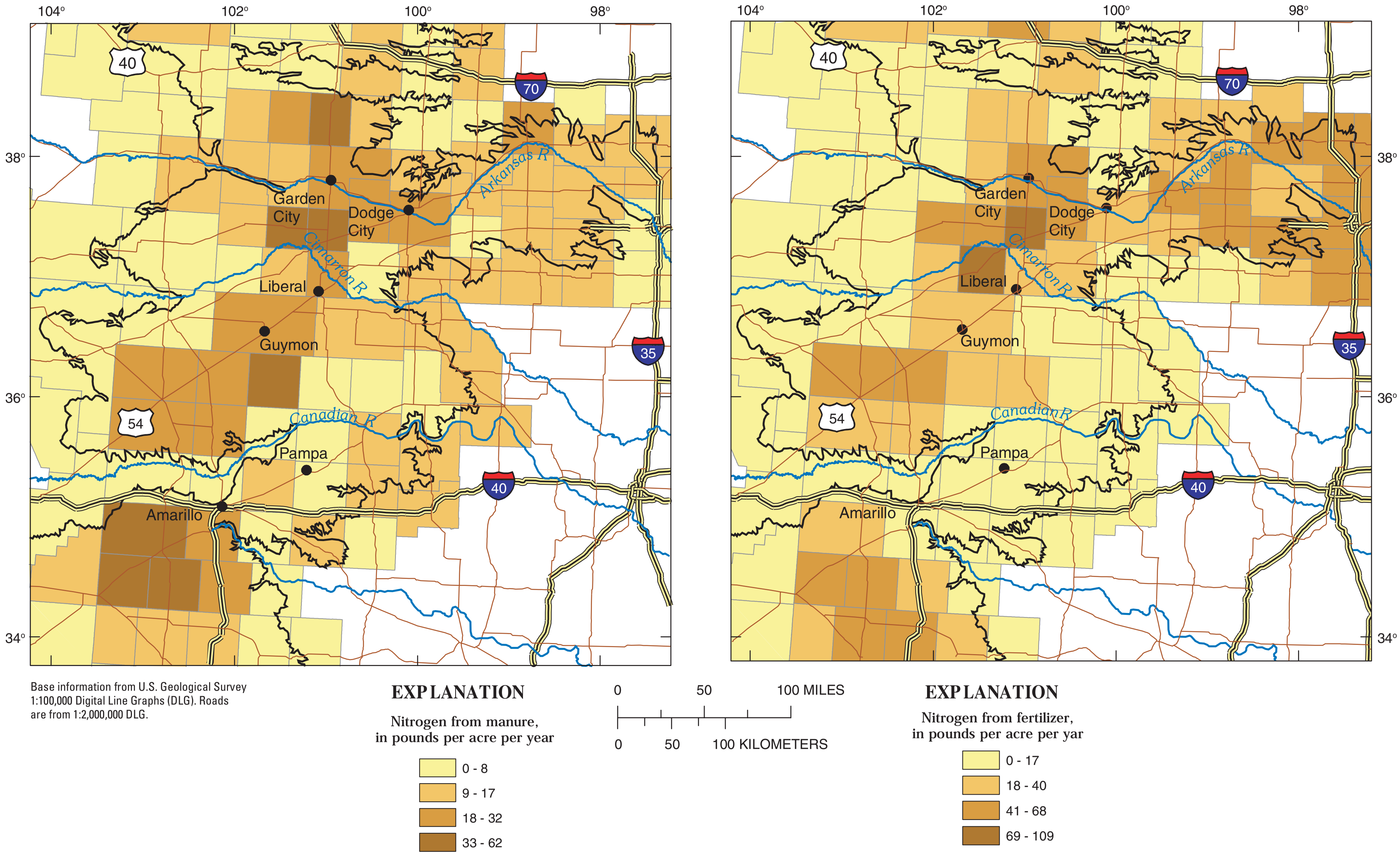


Figure 3. Number of acres planted in the primary agricultural crops in the central High Plains in 2001, by State.



Base information from U.S. Geological Survey 1:100,000 Digital Line Graphs (DLG). Roads are from 1:2,000,000 DLG.

Figure 4. Distribution of nitrogen application rates, by county, from manure (1997) and commercial fertilizer (1999) in the central High Plains.

Table 1. Ten most frequently applied pesticides over the central High Plains aquifer between 1990 and 1995.

[Pesticide-use rates compiled by the National Center for Food and Agricultural Policy (NCFAP); applied to crop acreage from 1997 Census of Agriculture]

Rank	Weighted by pounds applied	Weighted by acres applied
1	Atrazine	2,4-D
2	2,4-D	Atrazine
3	Metolachlor	Metolachlor
4	Alachlor	Chlorpyrifos
5	Butylate	Dimethoate
6	Chlorpyrifos	Carbofuran
7	Dimethoate	Alachlor
8	Carbofuran	Terbufos
9	Terbufos	Cyanazine
10	Cyanazine	Butylate

weed and grass control in corn, sorghum, and other crops. Atrazine has been detected in ground water in many parts of the United States and is indicative of the effect of agricultural activities (particularly corn production) on ground-water quality. Figure 5 shows atrazine application rates, in pounds per acre by county, for the central High Plains region.

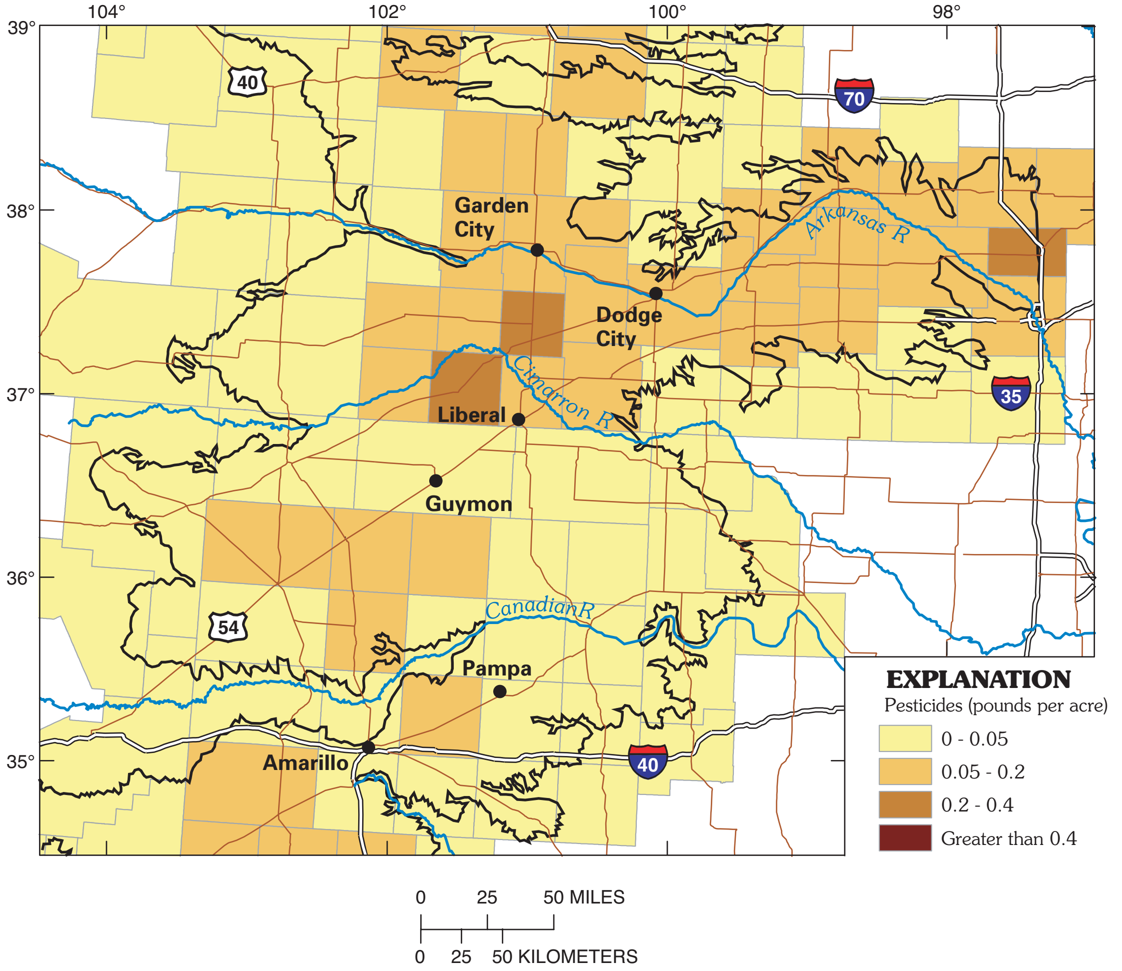


Figure 5. Distribution of atrazine application rates, by county, in the central High Plains.

Water Use

Ground water provides about 93 percent of the water used in the central High Plains region (U.S. Geological Survey, Aggregate Water-Use Data System, 1995). Few rivers cross the central High Plains, and surface water generally is not accessible away from river courses. Counties near the Arkansas River in Colorado and Kansas, the Canadian River in Texas, and the three counties in northeastern New Mexico that are part of the central High Plains region (fig. 1) have greater access to surface water and use the largest amount of this resource in the study area. Surface-water use in the central High Plains region is almost entirely for irrigation of crops with the exception of the city of Amarillo, Tex., which gets a large percentage of its public supply from Lake Meredith in Hutchinson County, Texas (about 44 Mgal/d). Many parts of the central High Plains region rely entirely upon ground water for human consumption and all other uses. Irrigated agriculture uses about 96 percent of this ground-water supply (U.S. Geological Survey, Aggregate Water-Use Data System, 1995). Other major uses of ground water in the central High Plains region are public supply, livestock, mining, thermoelectric power, and domestic self-supplied water (fig. 6). About 85 percent of the population in the central High Plains region is served by public-supply systems operated by the towns and cities; about 79 percent of these people are receiving ground water.

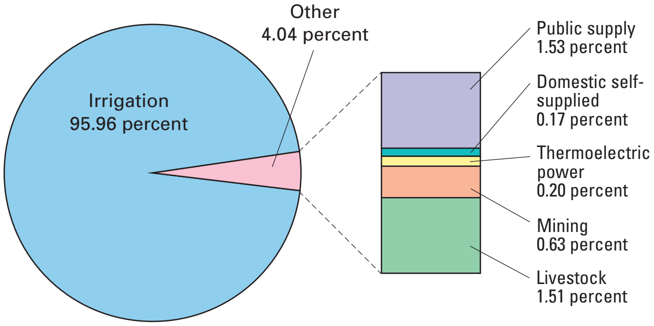


Figure 6. Primary ground-water uses in the central High Plains in 1995.

Study Design and Methods

Site Selection

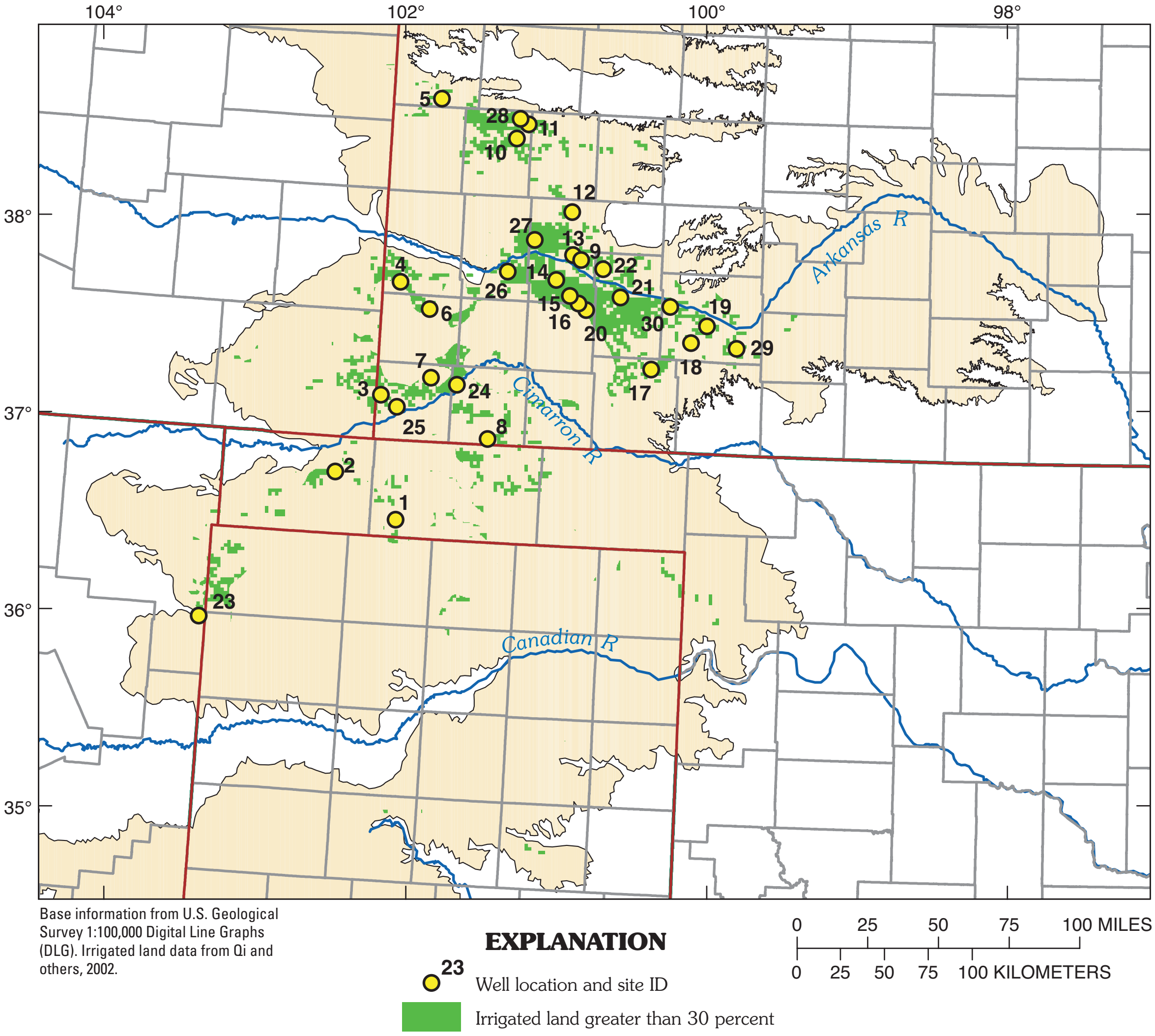
Because McMahon (2000) showed that ground water in the central High Plains region with a depth less than 200 ft below land surface was vulnerable to water-quality effects from agricultural land use, and because agriculture is such a dominant land use in this area, site selection for this land-use study focused on irrigated agricultural areas where depth to ground water was less than 200 ft. Areas of irrigated agriculture (nominal 1980) were determined using a Geographic Information System (GIS) raster data set (2-kilometer cell size) showing the percentage of irrigated lands in the central High Plains region (Thelin and Heimes, 1987). If more than 30 percent of a raster cell was identified as irrigated agriculture, the cell was classified as irrigated land. Depth to water was determined by surface interpolation of 1997 water-level point data measured from wells in the High Plains Water Level Monitoring Program (V.L. McGuire, U.S. Geological Survey, written commun., 1998). The irrigated lands and depth-to-water data sets were intersected to delineate areas that were greater than 30 percent irrigated and had depths to water less than 200 ft (fig. 7). Within these areas, a grid-based site-selection computer program (Scott, 1990) was used to select 30 randomly distributed primary sites for well installation. The site-selection program also selected a paired alternate site for each primary site. The alternate site was used only in the event that permission could not be acquired to install a well within a 2-mi radius of the primary site. Local landowners were contacted near each site, and permission to install and sample wells at 30 sites was granted; 22 primary sites and 8 alternate sites were used. The locations of the installed wells are shown in figure 7 along with the well numbers used to identify individual wells in this report.

Well Installation

Wells were installed using a hollow-stem auger system so that no drilling fluids would be introduced during the drilling process. Boreholes were drilled to a depth approximately 20 ft below the water table, and a 2-inch-inside-diameter polyvinylchloride (PVC) well was installed through the center of the auger. The well included a bottom well point and 5-ft blank-casing sump attached to the bottom of a 10- or 20-ft screened interval. The top of the screened interval was placed about 5 ft below the estimated water table and blank riser-casing extended to land surface. The borehole annular space opposite the screened interval was backfilled during auger removal with 10–20 sieve silica sand to a level a few feet above the water table and a 5-ft bentonite-pellet plug was installed above the silica sand to seal the annular opening. Once the sand pack and bentonite plug were in place, the remaining augers were removed from the hole and the remaining annular space was filled to land surface with bentonite/cement grout. The surface was completed with either a 5-ft steel protective casing with locking cap or a flush-mount manhole cover even with land surface. Both types of surface completions were set in concrete pads designed to drain surface runoff away from the borehole. The construction details for the 30 monitoring wells installed for this study are listed in table 2.

Sample Collection

The 30 monitoring wells installed for this study were each sampled once between February 1999 and September 2000. Samples were collected by lowering a portable submersible pump into each well to about the middle of the screened interval



Base information from U.S. Geological Survey 1:100,000 Digital Line Graphs (DLG). Irrigated land data from Qi and others, 2002.

Figure 7. Distribution of irrigated agriculture greater than 30 percent in areas where ground water is less than 200 feet below land surface, and locations of wells installed to evaluate ground-water quality beneath irrigated fields in the central High Plains land-use study, 1999–2000.

and pumping water to a truck-mounted mobile water-quality laboratory where water samples were collected and processed. All equipment in contact with the water during sampling was composed of either stainless steel or Teflon.

Sampling procedures are described in detail in Koterba and others (1995). Prior to sample collection, at least three well volumes of water were purged from each well to remove any stagnant water. During purging, measurements of specific conductance, pH, water temperature, and dissolved oxygen were recorded every 5 minutes inside a closed-cell flow-through chamber until three consecutive stable readings were obtained. Turbidity also was measured every 5 minutes using a portable turbidity meter. Once stable readings for these water properties were obtained, the flow of water was redirected to a clean sampling chamber inside the mobile laboratory where water samples were immediately collected for analysis. Constituents analyzed for in the water samples collected for this study are listed in table 3.

Samples collected for the analysis of major ions, nutrients, and nitrogen isotopes were filtered through a 0.45-µm disposable capsule filter and captured in precleaned plastic bottles that were rinsed onsite with filtered ground water. Samples for major cation analysis were preserved with 2 mL of 7.5–7.7N nitric acid dispensed from individual polypropylene vials. Samples collected for pesticide and pesticide metabolite analyses were filtered through a methanol-rinsed stainless-steel filter stand containing a 0.7-µm glass-fiber filter. The pesticide samples were collected in cleaned and baked amber-glass bottles. Unfiltered samples for tritium analysis were collected in the sampling chamber directly from the pump discharge line in a manner that minimized agitation. Tritium sample bottles were filled and capped leaving no headspace, and the caps were sealed with plastic electrical tape. Finally, in an effort to avoid contact with methanol-rinsed sampling equipment, samples collected for DOC analysis were collected directly from the well after the portable submersible pump was removed. A single-

Table 2. Selected well-construction information for monitoring wells installed in the central High Plains aquifer and sampled as part of the agricultural land-use study, 1999–2000.

[BLS, below land surface]

Map index number (fig. 7)	Date of installation	Elevation[1] of installation land surface (feet)	Depth of completed well BLS (feet)	Depth to water BLS at time of sampling (feet)	Screened interval BLS (feet)	Sand-pack interval BLS (feet)
1	09–23–1999	3,460	198	186.8	187–197	177–198
2	08–17–2000	3,965	182	160.0	169–178	151–182
3	07–22–2000	3,623	113	96.7	101–110	86–114
4	06–11–2000	3,442	178	159.6	166–174	153–178
5	03–28–2000	3,655	199	186.5	186–196	180–199
6	06–21–2000	3,266	198	173.3	186–196	177–198
7	07–24–2000	3,324	197	181.7	184–194	166–197
8	06–20–1999	3,100	145	132.8	120–140	100–145
9	11–13–1998	2,904	133	122.7	107–127	90–135
10	03–24–2000	3,217	174	163.4	164–174	153–174
11	04–09–2000	3,181	182	171.3	167–176	161–182
12	04–04–2000	2,920	139	121.2	122–131	116–139
13	11–12–1998	2,853	94	70.4	68–88	57–101
14	06–30–2000	2,921	193	177.1	182–190	169–194
15	03–22–2000	2,890	170	151.4	157–167	139–170
16	04–01–2000	2,844	156	151.8	143–153	136–156
17	05–23–2000	2,520	31	13.0	16–25	11–31
18	06–05–2000	2,580	157	137.7	145–154	138–158
19	05–29–2000	2,520	115	99.2	102–112	96–115
20	11–14–1998	2,797	190	164.1	164–184	156–195
21	05–16–2000	2,740	149	137.7	136–146	130–149
22	05–13–2000	2,857	187	174.9	175–186	168–188
23	07–19–2000	4,463	180	169.6	170–178	156–184
24	07–27–2000	3,190	158	133.7	144–152	129–158
25	08–19–2000	3,531	113	99.8	102–110	85–114
26	06–27–2000	3,019	106	92.2	96–104	85–108
27	07–08–2000	2,977	162	150.9	150–160	141–162
28	04–13–2000	3,216	174	156.2	161–170	154–173
29	05–25–2000	2,470	149	134.4	138–146	127–149
30	05–11–2000	2,595	108	92.2	94–102	89–114

[1] Accuracy of elevation was within ±10 feet.

Table 3. Water-quality constituents and parameters analyzed in water samples collected in the central High Plains agricultural land-use study, 1999–2000.

[µg/L, micrograms per liter; pCi/L, picocuries per liter; mg/L, milligrams per liter; na, not applicable; USGS, U.S. Geological Survey; LC, lab code; SC, schedule]

Constituent	Analytical method reporting limit	Constituent	Analytical method reporting limit
Pesticides, USGS SC2001 by gas chromatography/mass spectrometry, in micrograms per liter			
2,6-Diethylaniline	0.003	Acetochlor	0.002
Alachlor	0.002	Atrazine	0.001
Azinphos-methyl	0.001	Benfluralin	0.002
Butylate	0.002	Carbaryl	0.003
Carbofuran	0.003	Chlorpyrifos	0.004
Cyanazine	0.004	DCPA	0.002
Deethylatrazine	0.002	Diazinon	0.012
Dieldrin	0.001	Disulfoton	0.02
EPTC	0.002	Ethalfluralin	0.004
Ethoprop	0.003	Fonofos	0.003
Lindane	0.004	Linuron	0.002
Malathion	0.005	Metolachlor	0.002
Metribuzin	0.004	Molinate	0.004
Napropamide	0.003	Parathion	0.007
Parathion-methyl	0.006	Pebulate	0.004
Pendimethalin	0.004	Permethrin	0.005
Phorate	0.002	Pronamide	0.003
Prometon	0.02	Propachlor	0.007
Propanil	0.004	Propargite	0.01
Simazine	0.005	Tebuthiuron	0.01
Terbacil	0.007	Terbufos	0.01
Thiobencarb	0.002	Triallate	0.001
Trifluralin	0.002	alpha-HCH	0.002
p,p'-DDE	0.006		
Pesticide metabolites, USGS custom method Liquid Chromatography Acetamide Analysis, in micrograms per liter			
Acetochlor ESA	0.05	Acetochlor oxanilic acid	0.05
Alachlor ESA	0.05	Alachlor oxanilic acid	0.05
Metolachlor ESA	0.05	Metolachlor oxanilic acid	0.05
Major ions, USGS SC2750, in milligrams per liter (unless noted)			
Bromide	0.01	Calcium	0.02
Chloride	0.29	Fluoride	0.1
Iron	10.0 µg/L	Magnesium	0.014
Potassium	0.24	Silica	0.09
Sodium	0.09	Solids, residue	10.0
Sulfate	0.31		
Nutrients, USGS SC2752, in milligrams per liter			
Nitrogen, ammonia	0.02	Nitrogen, ammonia plus organic nitrogen	0.1
Nitrogen, nitrite	0.01	Nitrogen, nitrite plus nitrate	0.05
Phosphorus	0.06	Orthophosphate	0.01
Radionuclides and other constituents (units as noted)			
Radon, USGS LC1369	26 pCi/L	Tritium, USGS LC1565	1.0 pCi/L
Dissolved organic carbon, USGS SC2085	0.33 mg/L	Nitrogen-15/Nitrogen-14, per mil	na

use, precleaned disposable plastic bailer was lowered into the well and filled with water. The bailer was rinsed three times with ground water, and then ground water was poured directly from the bailer into a clean, stainless-steel, pressure-filtration funnel equipped with a 0.45-µm silver filter. The ground water was forced through the silver filter using purified nitrogen gas at a pressure not exceeding 15 lb/in^2. The DOC sample was collected in a cleaned and baked amber-glass bottle. All nutrient, nitrogen isotope, pesticide, and DOC samples were immediately placed on ice and chilled until delivered to the laboratory for analysis.

With the exception of certain pesticide metabolites, all water-quality samples were analyzed at the USGS National Water-Quality Laboratory (NWQL) in Lakewood, Colo. Six pesticide metabolites were analyzed at the USGS Organic Geochemistry Research Laboratory in Lawrence, Kans. References for the analytical methods used for each analysis are provided in table 4. The results for all water-quality analyses performed during this study are provided in table 9 in the “Supplemental Information” section at the back of this report.

Land-Use Classification

To document the land-use characteristics in the vicinity of sampled wells, land-use and land-cover information was collected using the procedures described in Koterba (1998). Detailed land-use/land-cover information was recorded in both written and map format for a 50-m buffer and a 500-m buffer around each well. Characterization of the 50-m buffer was intended to document activities in proximity to the well and identify potential contaminant point sources that might directly affect ground-water quality near the well. Characterization of the 500-m buffer was intended to describe the overall land use/land cover most likely to be associated with the recharge area around the well. Though some wells might not receive significant recharge from within the 500-m buffer zone, characterization of the 500-m zone is assumed to represent the average land-use setting for a much larger area around the well (Koterba, 1998).

Land use/land cover within the 50-m buffer zone was recorded in tabular form on the Land-Use Land-Cover Field Sheet (LULCFS) presented in Koterba (1998) and also on a scale drawing of the buffer zone. The LULCFS includes information regarding precise well location, land-use practices, local land-use features, soil characteristics, and well characteristics. The scale drawing of the 50-m buffer zone shows the location of the sampled well and any buildings, fields, equipment, chemical, fuel, and feed storage, or other potential contaminant sources near the well. Each of the wells installed for this study was purposely located next to an irrigated field and away from farm operations. No point sources for potential contamination were identified in the land-use coding of the 50-m buffer for any of the 30 wells sampled.

Land use/land cover within the 500-m buffer zone also was recorded in tabular form on the LULCFS and included local features, crop types, irrigation and drainage practices, and apparent fertilizer and pesticide practices. The location and types of field crops and other land cover in the 500-m buffer zone were drawn on mylar overlays using black-and-white aerial photographs as templates. The aerial photographs (nominal 1990) were obtained from the National Aerial Photography Program and had an average scale of about 1:20,000. The overlays provide a means to update and correct the images on the aerial photographs and allow an estimate of the percentage of identified land covers within the 500-m buffer zone. All land-use/land-cover data are archived in the NAWQA National Data Warehouse maintained by the USGS.

Table 4. Laboratory analysis methods for measured water-quality constituents in the central High Plains agricultural land-use study, 1999–2000.

[USGS, U.S. Geological Survey; GC/MS, gas chromatography/mass spectrometry; LCAA, Liquid Chromatography Acetamide Analysis; HPLC, high-performance liquid chromatography; UV, ultraviolet]

Constituent or constituent group	Analysis method	Method reference
Major ions (USGS schedule 2750)	Atomic absorption spectrometry	Fishman (1993)
Nutrients (USGS schedule 2752)	Various methods	Fishman (1993)
Nitrogen isotopes (USGS lab code 1718)	Mass spectrometry of nitrogen gas	Flipse and Bonner (1985)
Pesticides (USGS schedule 2001)	Solid phase extraction using a C-18 cartridge and GC/MS	Zaugg and others (1995)
Pesticide metabolites (USGS analysis LCAA - Kansas District)	Solid phase extraction and HPLC	Hostetler and Thurman (2000)
Dissolved organic carbon (USGS schedule 2085)	UV-promoted persulfate oxidation and infrared spectrometry	Brenton and Arnett (1993)
Tritium (USGS lab code 1565)	Electrolytic enrichment with gas counting	Ostlund and Dorsey (1975)

Quality Control

Quality-control (QC) samples were collected to evaluate the effectiveness of equipment cleaning and variability of water-quality data as a result of sample collection, processing, and analysis. The QC samples included field-blank samples, replicate environmental samples, and field-matrix spike samples. The QC samples were collected at a frequency of about 30 percent of the environmental samples collected from wells; 4 field-blank samples, 4 replicate environmental samples, and 3 field-matrix spike samples were collected in addition to the 30 environmental samples.

Field-blank samples were collected to document thorough decontamination of sampling equipment and that field procedures did not contaminate samples. Quality-assured organic-free or inorganic-free water is provided for blank-sample processing by the USGS for the NAWQA Program. The field-blank water was passed through all sampling equipment, including filters, and collected using the same procedures as those for environmental samples. Field-blank samples were analyzed for concentrations of major ions, nutrients, pesticides, and DOC. Few water-quality constituents were detected in the field-blank samples (table 5), and no nutrient or pesticide constituents were detected in field-blank samples. The detection of only a few constituents in the field-blank samples indicates that decontamination procedures were adequate and that field procedures allowed minimal contamination of environmental samples.

Replicate samples were collected to assess the combined effects of field and laboratory procedures on measurement variability. Sequential replicate samples (samples collected consecutively as opposed to simultaneously) were collected in the same manner as the environmental samples for major ions, nutrients, and DOC analyses. Replication of pesticide sampling was accomplished during the field-matrix spike sampling process. The relative percent difference (RPD) between reported concentrations of replicate samples was calculated using the formula:

$$RPD = \frac{|Sample1 - Sample2|}{\left[\frac{(Sample1 + Sample2)}{2}\right]} \times 100$$

Perfect replication between paired analyses would yield an RPD of 0 percent. The RPD was not calculated if one or both analyses for a replicate pair were less than the analytical method reporting limits (MRL). Generally, about 90 percent of the RPD's were less than 5 percent, which indicated an acceptable level of field and laboratory effect on measurement variability (table 6). Four constituents had relatively high average RPD's (bromide, 128.6 percent; terbacil, 22.6 percent; deethylatrazine, 21.8 percent; and DOC, 9.9), which is attributed to the relatively large differences in concentrations close to the analytical MRL for these constituents.

Field-matrix spike samples for pesticides were collected to determine bias and variability from matrix interference on analyte recovery and to evaluate the degradation of constituent concentrations during sample processing, shipping, and analysis. Field-matrix spikes involve injecting replicate environmental pesticide samples with known concentrations of multiple pesticides at the sampling site and submitting the samples to the laboratory for analysis. A spike recovery of 100 percent would indicate no matrix interference or degradation for that constituent. Replicate field-matrix spike samples also were collected for two of the three field-matrix spike samples, and the RPD between replicate field-matrix spike samples was calculated (table 6).

The percent recovery for each spiked pesticide compound can be found in table 8 in the "Supplemental Information" section at the back of this report. A summary of percent recoveries for spiked samples is provided at the bottom of table 6. Median percent recoveries for pesticide compounds were very close to 100 percent (table 6). The median percent recoveries for 25 of the 47 spiked pesticides were greater than 100 percent. The median percent recoveries for approximately 55 percent (26 of 47) of the pesticides was between 90 and 110 percent,

Table 5. Constituents detected in quality-control blank samples in the central High Plains agricultural land-use study, 1999–2000.

[mg/L, milligrams per liter; <, less than]

Constituent	Number of detections/ number of samples	Median concentration in blank samples (mg/L)	Maximum concentration in blank samples (mg/L)
Major ions			
Bromide	1/4	<0.01	0.02
Calcium	3/4	0.05	0.06
Other constituents			
Dissolved organic carbon	1/4	<0.33	0.49

Table 6. Summary of relative percent differences (RPD's) for replicate samples, and percent recoveries for field-matrix spike analytes, in the central High Plains agricultural land-use study, 1999–2000.

Compound class	Percentile					Count	Minimum	Maximum
	10	25	50	75	90			
			Environmental sample replication (relative percent difference, in percent)					
Dissolved organic carbon	2.4	5.7	9.9	12.3	12.5	4	0.1	12.6
Major ions	0.2	0.5	1.4	2.6	5.5	44	0.0	128.6
Nutrients	0.0	0.2	1.8	4.1	5.4	11	0.0	9.5
			Field-matrix spike replication (relative percent difference, in percent)					
Pesticides	0.2	0.9	2.4	5.3	10.8	94	0.0	22.6
			Field-matrix spike recoveries (in percent)					
Pesticides	71.4	90.8	100.9	109.5	131.0	235	47.8	194.4

including most of the commonly used pesticides for agricultural practices within the study area. Although the median percent recovery for atrazine was 132 percent, it is still within the range (60 to 140 percent recovery) of acceptable laboratory precision (Mark Sandstrom, U.S. Geological Survey National Water Quality Laboratory, written commun., 2001). The median percent recoveries for carbaryl, methylazinphos, and carbofuran were unusually high (greater than 140 percent); however, these pesticides were not detected in ground water during this study. An acceptable percent recovery for pesticides indicates sample processing and analytical methods provided a reasonable representation of pesticide concentrations in environmental samples.

Ground-Water Quality Beneath Irrigated Fields

The results of all water analyses performed during this study are provided in table 9 in the "Supplemental Information" section at the back of this report. The following discussion provides an overview of ground-water quality beneath irrigated agricultural fields in the central High Plains.

Major Dissolved Ions and Water Properties

A summary of the concentrations of the major dissolved ions analyzed in the 30 water samples and the range of the water properties measured onsite during sample collection are given in table 7. Though none of the wells sampled are used as a drinking-water source, applicable national drinking-water standards are provided as a frame of reference for the quality of the collected samples. Major dissolved ions account for the bulk of dissolved constituents in natural water samples. These dissolved constituents generally are derived from rock/water interactions; however, reuse of water can increase constituent concentrations through repeated exposure to weathered rock minerals or through evaporation that removes water but leaves the minerals behind. Evaporative concentration would tend to increase the concentration of all dissolved ions, whereas exposure to weathered rock would affect only selected constituents.

In general, the major-ion chemistry of the collected water samples indicates a resource of acceptable quality. Though some water samples had sufficient dissolved ions to be considered "hard" water, the drinking-water standards shown in table 7 were, for the most part, not exceeded. One notable exception is the large concentrations of sulfate. The sulfate concentrations for several samples exceeded the National Secondary Drinking-Water standard (250 mg/L). The large sulfate concentrations (>250 mg/L) are primarily responsible for the large dissolved solids concentrations in the same samples. Also of note (table 7) are the data on dissolved-oxygen concentrations in ground water of this study area. Generally, the ground water is well oxygenated; however, the dissolved oxygen concentration of one sample can be considered suboxic (less than 1.0 mg/L). Low dissolved-oxygen conditions (<1 mg/L) can affect the concentration of other dissolved constituents by altering the oxidation/reduction reactions in the ground-water environment. This condition will be discussed in greater detail later in this report.

Nutrients and Pesticides

Each water sample was analyzed for 6 nutrient compounds (compounds of nitrogen and phosphorus), and 53 pesticides and pesticide metabolites (table 3). Nutrient compounds can be derived from natural processes such as mineral weathering or decay of organic material in the soil zone, or from anthropogenic influences like septic waste disposal or agricultural

Table 7. Summary statistics for major dissolved ions and water properties for 30 ground-water samples collected as part of the central High Plains agricultural land-use study, 1999–2000.

[mg/L, milligrams per liter; SMCL, secondary maximum contaminant level; MCL, maximum contaminant level; µS/cm, microsiemens per centimenter; °C, degrees Celsius; NTU, nephelometric turbidity units; >, greater than]

Constituent	Major ion concentration (mg/L)			Applicable drinking-water standards
	Minimum	Median	Maximum	
Alkalinity	97	193	363	
Bromide	0.07	0.23	1.43	
Calcium	37.1	78.8	410	
Chloride	6.30	30.9	223	250 (SMCL)
Fluoride	0.3	0.8	2.4	4.0 (MCL)
Magnesium	9.04	22.4	220	
Potassium	1.99	5.54	14.9	
Silica	10.8	29.7	64.5	
Sodium	8.98	31.7	503	
Sulfate	10.6	113	2,360	250 (SMCL)
Sum of dissolved solids	277	491	4,512	500 (SMCL)

Water properties	Field parameters			Applicable drinking-water standards
	Minimum	Median	Maximum	
Dissolved oxygen (in mg/L)	0.6	6.7	7.9	
pH (in standard units)	6.8	7.4	7.9	6.5–8.5 (SMCL)
Specific conductance (in µS/cm at 25°C)	385	740	3,770	
Temperature (in °C)	12.1	17.7	21.0	
Turbidity (in NTU)	0.57	5.3	>1,000	

practices. Large nutrient concentrations in ground-water samples generally are related to anthropogenic influences on water quality. The occurrence of pesticides in ground water is solely the result of the use, handling, or storage of these compounds at the land surface and subsequent migration to the ground-water system.

The inorganic compounds of phosphorus have relatively low solubilities in natural waters and, unless influenced by a substantial local source, usually occur in small concentrations (Hem, 1989). The concentrations of dissolved phosphorus and orthophosphate measured in the 30 water samples collected for this study were small; median concentrations were 0.008 mg/L and less than 0.01 mg/L, respectively. The maximum concentration of dissolved phosphorus measured in the 30 water samples was 0.047 mg/L.

The nitrogen compounds measured during this study were ammonium, ammonium plus organic nitrogen, nitrite, and nitrite plus nitrate. Only 4 of 30 samples had detectable ammonium (concentrations larger than the analytical method reporting limit of <0.02 mg/L) and the concentrations were small, from 0.025 to 0.534 mg/L. Because ammonium concentrations in the water samples were small, the concentrations reported for ammonium plus organic nitrogen were primarily due to the presence of organic nitrogen. Ammonium plus organic nitrogen concentrations exceeded the MRL (0.1 mg/L) in 16 of 30 samples, and these concentrations ranged from 0.1 to 0.66 mg/L.

Nitrite exceeded the laboratory MRL (0.01 mg/L) in only 6 of 30 samples. The concentrations of nitrite detected were small, ranging from 0.011 to 1.09 mg/L, which indicates that the concentrations reported for nitrite plus nitrate were composed almost entirely of nitrate. Hereinafter, nitrite plus nitrate will be referred to as the “nitrate concentration.”

Nitrate concentrations exceeded the MRL (0.05 mg/L) in all 30 water samples ranging from 0.248 to 61.1 mg/L as nitrogen with a median concentration of 7.05 mg/L. The national drinking-water standard maximum contaminant level (MCL) for nitrate as nitrogen is 10 mg/L (U.S. Environmental Protection Agency, 2003). The MCL for nitrate was exceeded in 10 of the 30 (33 percent) water samples collected.

Of the 53 pesticides and pesticide metabolites analyzed in water samples from this study (see table 3), 8 different pesticides and the metabolites for 4 of these pesticides were detected in one or more samples (fig. 8). Atrazine (detected in 20 of 30 wells) and its metabolite, deethylatrazine (21 of 30 wells), were by far the most frequently detected pesticide compounds occurring in about 70 percent of the water samples. In all, 21 different wells had at least 1 or more detectable pesticide, and as many as 11 separate pesticide or metabolite compounds were present in an individual well (well 19; table 9). Atrazine

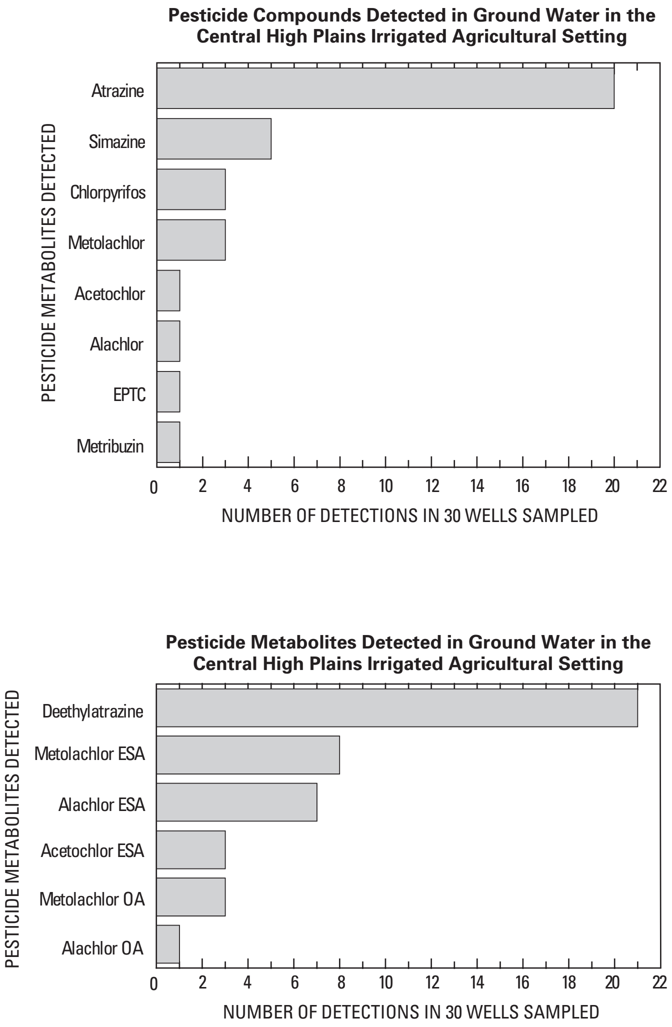


Figure 8. Detection frequency for pesticides and pesticide metabolites in ground water beneath irrigated agricultural fields in the central High Plains, 1999–2000.

and deethylatrazine were detected in all wells containing other pesticide compounds. For the pesticides whose metabolites also were detected, the metabolites were detected more frequently than the parent compounds.This finding indicates that sampling for these pesticide metabolites in ground water might be the best method to evaluate the water-quality effect of using the parent compound at the land surface.

Tritium

Tritium is an isotope of hydrogen that has two hydrologically important sources: the interaction of nitrogen with cosmic radiation in the upper atmosphere, and nuclear fusion primarily associated with the atmospheric detonation of hydrogen bombs in the 1950's and 1960's. Hydrologists have used tritium for several years to estimate the relative age of ground water; that is, to determine approximately when the water was recharged to the aquifer and isolated from the atmospheric source of tritium. Once the water is isolated from the tritium source, tritium concentrations gradually are reduced by radioactive decay with a half-life of 12.43 years. The concentrations of natural "pre-bomb" tritium in precipitation that recharged the aquifer before 1952 have decreased to very low concentrations (less than 1.5 picocuries per liter, pCi/L) in ground water (Thatcher, 1962). The atmospheric tritium produced by hydrogen bombs, beginning about 1952, reached concentrations thousands of times greater than those produced naturally. This "bomb peak" was incorporated into rainfall and recharged to aquifers worldwide. Due to its large initial concentration, some of the post-1952 tritium is still present after decades of isolation. Tritium analysis provides a relative age for ground water; samples generally are determined to be of pre-1952 or post-1952 age. The presence of more than 1.5 pCi/L tritium in ground water indicates that at least some part of the water sample was recharged after 1952.

The tritium concentrations determined for water samples collected during this study ranged from less than 1.0 to 39.7 pCi/L with a median of 7.0 pCi/L (table 9). The tritium concentrations for 23 of 30 samples were greater than 1.5 pCi/L and are considered to have some component of recently recharged water. Tritium concentrations for the remaining seven water samples were less than 1.5 pCi/L and are probably composed primarily of water from earlier (pre-1952) recharge events.

Dissolved Organic Carbon

Dissolved organic carbon (DOC) in water samples can be a result of natural sources or an indicator of anthropogenic effects on water quality (Hem, 1989). Natural sources can include decaying plant material from near the land surface or interaction of ground water with petroleum deposits in the subsurface. Possible anthropogenic sources can include improper disposal or spills of hydrocarbons at the land surface, oil-lubricated ground-water pumping systems, petroleum exploration and development, septic system discharges, and use of oil-based dispersants during application of agricultural chemicals. Substantial amounts of DOC in the ground-water system can provide a food source for microbial communities. Microbial metabolism of DOC can affect the oxidation/reduction (redox) conditions in the subsurface, which in turn can affect concentrations of dissolved oxygen and many other water-quality constituents.

The DOC concentrations determined for the samples collected during this study generally were small with concentrations ranging from 0.45 to 24.2 mg/L and a median concentration of 2.31 mg/L (table 9). DOC concentrations of only two samples were larger than 6.5 mg/L (well 2, 14.0 mg/L; and well 19, 24.2 mg/L). These water samples were well oxygenated (7.4 and 7.6 mg/L dissolved oxygen, respectively). One sample in this study (from well 16) did have a dissolved-oxygen concentration small enough to be considered suboxic (0.61 mg/L). The small nitrate (0.248 mg/L) and large manganese (744 µg/L) concentrations in this water sample suggest a low redox condition with probable denitrification and manganese reduction. The DOC concentration in this water sample was not especially large (2.54 mg/L) indicating that large DOC concentrations are not correlated with reducing conditions in this study. Evidence of an organic-rich shale contacted at the bottom of the borehole during well installation is considered the primary reason for the suboxic conditions at this sampling site.

Relation Between Land Use and Water Quality

Land-use characteristics within a study area can be one of the most important factors affecting ground-water quality. Agricultural chemicals and irrigation water applied at the land surface in the central High Plains provide the source and transport mechanism for constituents that might affect ground-water quality. All the wells sampled for this study were installed in proximity to irrigated fields where corn was the primary long-term crop. Because the land-use setting was very similar around each well, no attempt was made to correlate slight differences in land use near individual wells with minor differences in water quality between samples collected from these wells. Alternatively, this report identifies those sampling sites where water quality was affected (and unaffected) by agricultural activities and evaluates the differing land-use and hydrologic factors associated with these locations. Correlating land-use and hydrologic factors with water-quality effects can help identify other areas of the central High Plains that might be vulnerable to these effects.

Nutrients, Pesticides, and Tritium

The presence of agricultural chemicals in ground water collected beneath irrigated fields provides direct evidence of the effect of irrigated agriculture on ground-water quality. Pesticides and nutrients, especially nitrogen, commonly are used on agricultural fields to increase crop yields. Selected pesticides are widely used with certain crop types, and their presence would be expected in ground water if the local land-use setting was affecting the water quality. For example, though atrazine has numerous agricultural and nonagricultural applications, the primary use of atrazine in many parts of the country is season-long control of weeds in corn, sorghum, and other grain crops—the predominant agricultural products of the central High Plains (fig. 3). At the time of this study, atrazine was the most heavily used herbicide in the central High Plains (in pounds applied to fields) and ranks second in number of acres to which it is applied (table 1). The presence of atrazine in ground-water samples is direct evidence of water-quality effects from the overlying land-use setting.

Nitrate can be produced by the natural decomposition of organic material in the soil and, under oxygenated conditions, is likely to be present in most natural waters (Mueller and Helsel, 1996). Large concentrations of nitrate, however, are generally considered indicative of anthropogenic effects. To estimate what nitrate concentration would be indicative of anthropogenic effects, the USGS NAWQA Program has analyzed nitrate data from ground-water samples collected throughout the Nation from areas having minimal effects from agriculture, cities, or other human activities (Mueller and Helsel, 1996). This analysis indicates that the national average background-nitrate concentration for water unaffected by human sources generally was less than 2.0 mg/L. McMahon (2000) and Bruce and Oelsner (2001), however, suggest that the natural background concentration of nitrate in the central High Plains aquifer is slightly larger than the published USGS national average. Information also is available on the chemistry of paleorecharge conditions in the central High Plains (Peter McMahon and others, U.S. Geological Survey, unpub. data, 2002) that shows nitrate concentrations in paleorecharge water (water with no tritium present) range from 0.43 to 3.5 mg/L with a median concentration of 2.5 mg/L. Similarly, Becker and others (2002) report nitrate concentrations for 74 domestic well samples in the central High Plains aquifer. The nitrate concentrations for 32 wells in Becker and others (2002) with no detectable tritium range from 1.07 to 3.98 mg/L with a median nitrate concentration of 2.04 mg/L.

Nitrate, several pesticides, and selected pesticide metabolites were detected in the water samples collected for this study. Figure 9 shows the concentrations of nitrate and tritium in the 30 water samples, arranged in order of increasing nitrate concentration. Nitrate concentrations for 19 of the 30 water samples were larger than the 3.5-mg/L maximum concentration calculated for paleorecharge. Figure 9 also indicates water samples with detectable concentrations of pesticides or pesticide metabolites; these samples are represented by red triangles in this figure. Of the 30 samples collected, every sample with a nitrate concentration larger than the 3.45 mg/L (20 samples) contained detectable quantities of pesticides. The only other sample with detectable pesticides (well 16) had the smallest nitrate concentration measured during the study (0.248 mg/L). This sample had a dissolved-oxygen concentration of 0.61 mg/L, indicating that suboxic conditions exist at well number 16. The low nitrate concentration observed at well 16 is likely the result of denitrification processes.

The relation between pesticide detection, large (greater than 2.5 mg/L) nitrate concentrations, and tritium concentrations indicative of recently recharge ground water is strong (fig. 9). Recently recharged (post-1952) ground water would be expected in samples showing water-quality effects of the overlying agricultural setting, and this is indeed the case. Even the sample that has apparently undergone denitrification contains sufficient tritium (4.8 pCi/L) to indicate a component of recent recharge. A sample that has undergone denitrification would have the nitrate concentration reduced by microbial processes, but tritium and pesticide compounds generally would remain unaffected. This sample does contain pesticides and tritium, verifying the occurrence of recently recharged water and agricultural effects. For the remainder of this report, the 21 water

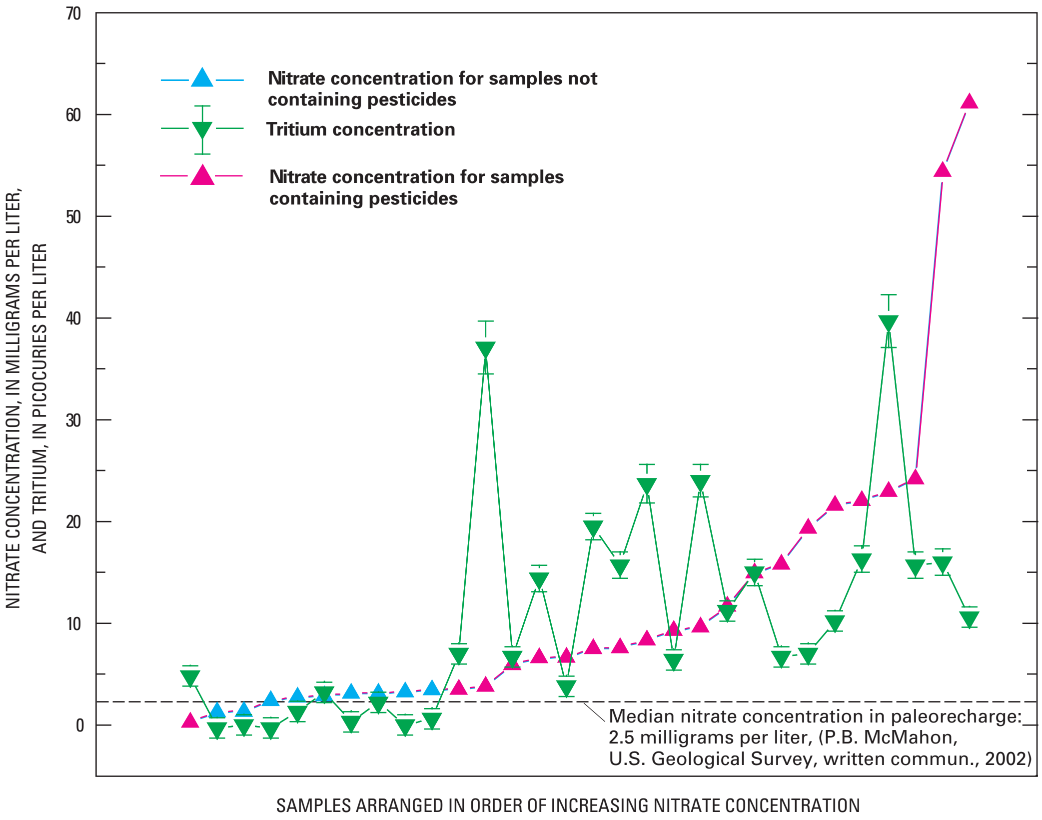


Figure 9. Relation between nitrate and tritium concentrations and the detection of pesticides beneath irrigated agricultural fields in the central High Plains, 1999–2000.

samples (70 percent of those sampled) with detectable pesticides, large nitrate concentrations (with the exception of the sample affected by denitrification), and tritium concentrations indicating recent recharge, are considered to be affected by the overlying irrigated agricultural setting.

Of the 30 samples collected during this study, 9 did not contain detectable pesticides and had relatively small concentrations of nitrate. These samples are indicated by the triangular blue symbols in figure 9. Generally, these nine samples also had small concentrations of tritium, indicating a lessor component of recent ground-water recharge. Two of these water samples (from wells 2 and 4) had tritium concentrations above the 1.5-pCi/L cutoff between pre-1952 and post-1952 water ages. These tritium concentrations, 2.2 pCi/L in well 2 and 3.2 pCi/L in well 4, were large enough to consider these samples as having some component of recent recharge, but no pesticides were detected in these water samples. The nitrate concentrations for these samples were 3.08 mg/L in well 2 and 2.85 mg/L in well 4, which are less than the 3.5 mg/L maximum paleorecharge concentration from McMahon and others (unpub. data, 2002). Although two of these nine water samples have slightly elevated tritium concentrations, they do not display the other possible effects of the overlying irrigated agriculture. For the purposes of interpretation, these nine samples are considered to be unaffected by agricultural activities.

Nitrogen Isotopes

The ^{15}N/^{14}N nitrogen isotope ratio in dissolved nitrate can be indicative of the source of the nitrate in ground water (Edwards, 1973; Kreitler, 1975). Although the exact boundary between ^{15}N/^{14}N isotope ratios for different nitrogen sources can vary from one study area to another, generally speaking, ^{15}N/^{14}N isotope ratios between –2 and +4.0 per mil (per thousand, ‰) are related to commercial fertilizers (for example, anhydrous ammonia) produced from atmospheric nitrogen sources; nitrogen isotope ratios between +4.0‰ and +9.0‰ are the result of the decay of organic material in the soil; and nitrogen isotope ratios greater than +9.0‰ are indicative of animal waste (Edwards, 1973). Animal waste sources include human and wildlife sources as well as livestock manure.

Identifying nitrate sources using the ^{15}N/^{14}N ratio does have some limitations. The boundary between ^{15}N/^{14}N ratios for commercial fertilizer and soil nitrogen is the least precise, and the ranges probably overlap (Kreitler, 1975). Isotope ratios as large as +6.5‰ have been observed under fields that received only commercial fertilizers (Flipse and Bonner, 1985). Isotope ratios in uncultivated soils with only natural organic nitrogen have been measured as low as +2.0‰. The larger ratios observed in areas of commercial fertilizer applications might be partly due to isotopic fractionation during volatile loss of applied ammonia. Another possibility is a mixing of nitrogen in commercial fertilizer with possibly large amounts of soil nitrogen in newly tilled fields. The large release of nitrogen due to the breakup of natural soils has not received much attention but is an important source of nitrogen to shallow ground water (Kreitler, 1975). Additionally, some natural processes, such as microbially mediated denitrification in anaerobic water, can alter the initial isotope composition of nitrate. Denitrification reduces the nitrate concentration and increases the nitrogen isotope ratio as microbial processes preferentially remove the lighter nitrogen molecules.

Nitrogen isotopes were useful for identifying nitrate sources in this study. Figure 10 is a scatterplot of nitrate concentration relative to nitrogen isotope ratio for the 30 samples collected during this study. The colored areas of the graph depict the three generalized ranges of isotope values that identify commercial fertilizer, soil nitrogen, and animal waste. The 30 symbols plotted on figure 10 representing individual samples are color coded to indicated those samples identified as affected (red) and unaffected (blue) by agricultural surface activities. The unaffected samples generally had the smallest nitrate concentrations (median nitrate concentration of 2.85 mg/L), and their nitrogen isotope ratios fall in the range indicative of soil nitrogen. These results support the earlier conclusion that these nine samples are not affected by the overlying irrigated agriculture. This result does not mean that these samples will never show the effects of the overlying land-use practices. It simply means that, at the time of this sampling, there was no evidence of agricultural effects.

Other data shown in figure 10 support the conclusion that irrigated agriculture has affected water quality, and the figure indicates possible sources for the observed nitrate concentrations. Eight of the samples in figure 10 plot within the nitrogen isotope range indicative of commercial fertilizer (less than +4.0‰). These samples also contain at least one pesticide, have nitrate concentrations larger than the suggested maximum value for paleorecharge, and have relatively large tritium concentrations (table 9). Nitrate concentrations in these water samples apparently are the result of commercial nitrogen fertilizer leaching to the water table. The depth to water in one of these wells was 181 feet below land surface, indicating that agricultural chemicals may have migrated through at least that thickness of overlying sediment to reach the ground water. The five samples that have relatively large nitrate concentrations and pesticide detections, but have nitrogen isotope ratios between +4.0 and +5.0, also are considered to be affected by agricultural activities, with the primary source of the nitrate being commercial fertilizer. There may be some component of soil (or possibly animal waste) nitrogen in these five samples or a slight enrichment in the heavier isotope due to volatilization or microbial activity. Their isotopic ratios, however, are only slightly larger than the generally accepted range for commercial fertilizer and well within the maximum upper bound for commercial fertilizer discussed previously. In all, 13 of the 21 affected water samples

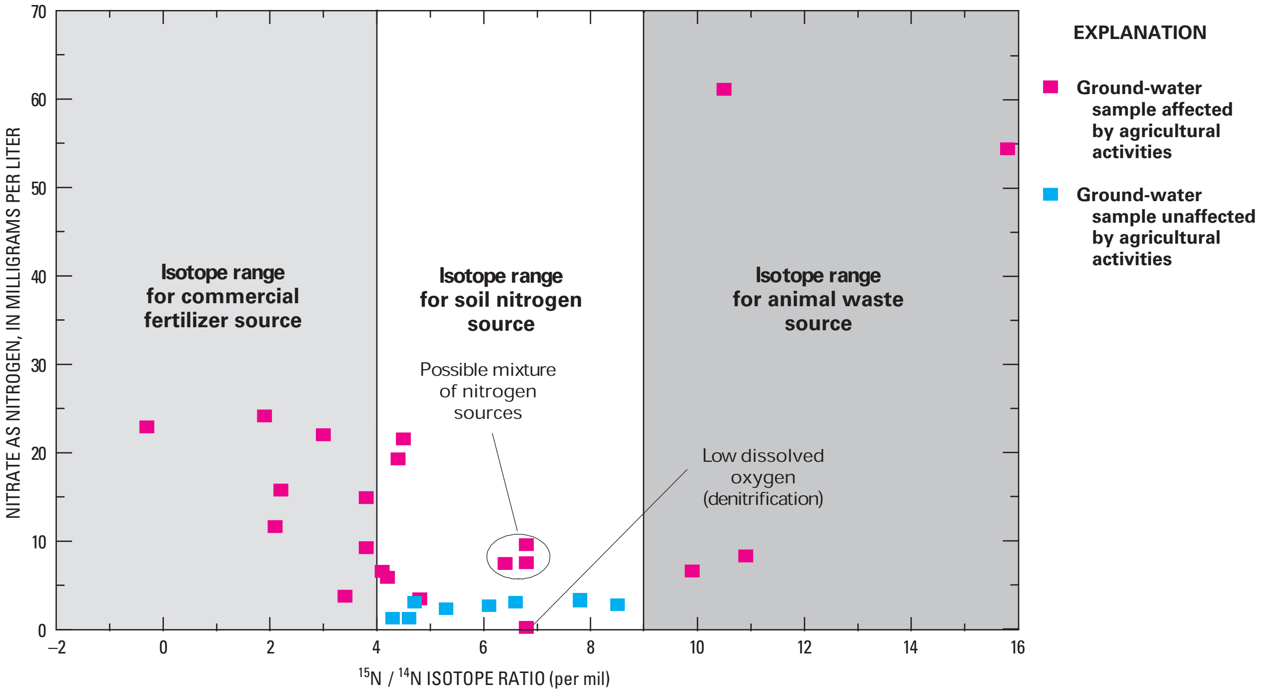


Figure 10. Relation between nitrate concentration and nitrogen isotope ratio in water samples from beneath irrigated agricultural fields in the central High Plains, 1999–2000.

are considered to have commercial fertilizer as the primary source of anthropogenic nitrate.

Nitrate concentrations in four samples were greater than 6.5 mg/L (fig. 10) and nitrogen isotope ratios were greater than +9, indicating an animal waste source. All four of these samples also contained pesticide compounds and relatively large tritium concentrations. These results suggest that these wells are affected by irrigated agriculture where manure has been applied as the primary nitrogen fertilizer. The large nitrate concentration observed in well 12 (61.1 mg/L), however, could be related to domestic waste disposal at this site. Well 12 is located at the boundary between an irrigated corn field and a residential farmyard, and the leach field for domestic waste disposal was approximately 245 ft from the well. The water sample from well 12 did contain agricultural pesticide compounds, indicating at least some effect from agricultural activities, but the very large nitrate concentration in the isotope range of animal waste could indicate local contamination from the domestic leach field. The other relatively large nitrate concentration shown in figure 10 (54.4 mg/L in well 9) is probably related to manure applications. Well 9 is adjacent to a corn field that has, for many years, been fertilized with manure from a nearby feedlot. The nitrogen-isotope data indicate that this manure application is the probable source of the large nitrate concentration in ground water.

More difficult to interpret are the samples plotted in figure 10 that contain pesticides and elevated nitrate concentrations (therefore, considered affected by agricultural activities) but have nitrogen isotope ratios indicative of a soil nitrogen source. One sample is identified as affected by denitrification (well 16). The sample from well 16 had the smallest nitrate concentration measured during this study but also contained recently recharged water and pesticide compounds (table 9). This water sample was collected at a site where the ground water was suboxic (dissolved oxygen was 0.61 mg/L). Denitrification is likely to occur under these conditions and would reduce the nitrate concentration and cause the nitrogen isotope ratio to increase but would not affect the tritium or pesticide concentrations. The nitrate in the water sample from well 16 may have originally come from commercial fertilizer applications, but the denitrification process shifted the nitrogen isotope ratio into the range indicative of soil nitrogen.

Three other samples in figure 10 contain recently recharged water, have relatively large nitrate concentrations, and detectable pesticides, but also plot in a cluster in the isotopic range indicative of a soil nitrogen source. It is not clear why these samples show evidence of agricultural effects yet have nitrogen isotope ratios indicative of natural soil nitrogen. It is possible that a mixture of waters with both large and small isotope ratios could result in the observed ratios, but a mixing scenario cannot be verified with the data collected during this study. These three affected wells (numbers 13, 28, and 30) are not geographically near one another (fig. 7); therefore, this water-quality result cannot be attributed to hydrologic conditions or land-use practices that are unique to a specific part of the study area. Although the source of the relatively large nitrate concentrations is not clear, these samples have been affected by the overlying agricultural land use, as indicated by the detection of pesticide compounds.

Dissolved Solids and Major Ions

The dissolved-solids content (similar to salt content) of ground water used for irrigation is of concern to farmers because it can affect crop health and yields. Large dissolved-solids concentrations (greater than 500 mg/L) also constrain the usefulness of water for drinking and other purposes. It is, therefore, also of interest to this study whether agricultural practices might be increasing dissolved-solids concentrations in the ground water.

The dissolved-solids concentration in a water sample is composed of the sum of the major dissolved ion concentrations in solution. The major ions in water generally are the constituents calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), carbonate alkalinity (as $CaCO_3$), and to a minor extent fluoride (F). Bruce and Oelsner (2001) and Becker and others (2002) provide a broad-scale assessment of water-quality conditions from randomly distributed public-supply and domestic-supply wells across the central High Plains. These studies reported little difference in major-ion chemistry across the study area but provide a baseline assessment of major-ion chemistry against which wells affected by agricultural activities in this study can be compared.

In the agricultural land-use study reported here, the water quality at 21 of 30 wells has been identified as affected by agricultural land use as evidenced by relatively large concentrations of nitrate and tritium, the detection of pesticides, and nitrogen isotope ratios indicating agricultural sources for much of the nitrate. The concentrations of dissolved solids in these agriculturally affected samples were significantly larger than those from the unaffected samples (fig. 11). The range of dissolved-solids concentrations for the affected water samples was from 300 to 4,510 mg/L with a median concentration of 675 mg/L (table 9). The range of dissolved-solids concentrations for the unaffected water samples was from 277 to 542 mg/L with a median concentration of 374 mg/L (table 9). Statistical significance of these data was determined by the Wilcoxon rank-sum test *p*-value (Helsel and Hirsch, 1995). The Wilcoxon rank-sum test *p*-value is used to evaluate whether one group of data tends to have larger values than a second group of data. The calculated *p*-value of 0.005 shown in figure 11 indicates that, at a 99.5-percent confidence level, the dissolved-solids concentrations in the agriculturally affected water samples were significantly larger than the dissolved-solids concentrations in the unaffected water samples.

Trilinear diagrams allow the simultaneous graphical comparison of the relative percentages of major-ion concentrations (in terms of total milliequivalents per liter) for numerous whole-water samples and provide a means to determine which of the major ions in this data set were most affected by agricultural activities. Figure 12 shows the major-ion compositions for the 30 agricultural water samples collected for this study and for

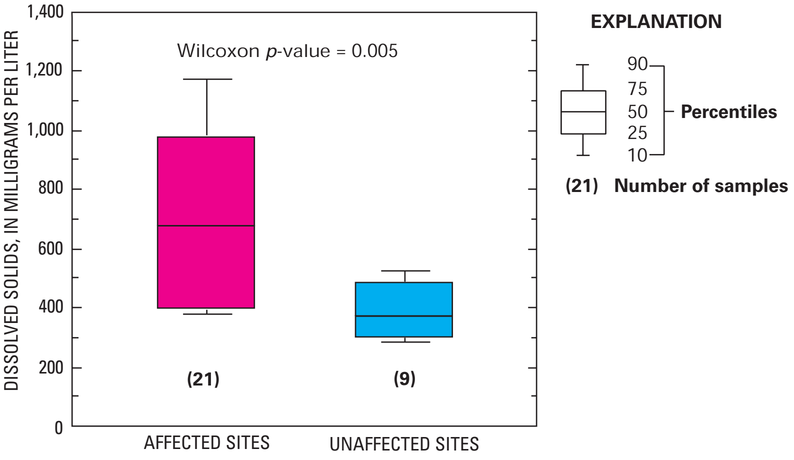


Figure 11. Distribution of dissolved-solids concentrations for sites affected and unaffected by agricultural land use in the central High Plains, 1999–2000.

randomly distributed samples from the 15 domestic-supply wells and 15 public-supply wells sampled in the central High Plains as reported by Bruce and Oelsner (2001) and Becker and others (2002). Most of the samples collected from the domestic-supply, public-supply, and unaffected agricultural wells (fig. 12, in blue) cluster in the same part of the trilinear diagram indicating similar major-ion chemistry dominated by calcium-bicarbonate type water. Water samples affected by agriculture (fig. 12, red circles) range from calcium-carbonate to calcium-sulfate type water and exhibit a shift in the dominant anion from bicarbonate to sulfate.

Comparing sulfate concentrations in more detail, sulfate concentrations in water samples affected by agricultural activities were larger than those that were unaffected by agriculture (fig. 13A). The range of sulfate concentrations for the affected water samples was from 24.5 to 2,360 mg/L with a median concentration of 152 mg/L (table 9). The range of sulfate concentrations for the unaffected water samples was from 10.6 to 161 mg/L with a median concentration of 78 mg/L (table 9). The Wilcoxon rank-sum test *p*-value shown in figure 13A ($p = 0.07$) indicates that the sulfate concentrations in the affected water samples were significantly larger (at the 93-percent confidence level) than those from the unaffected samples. Sulfate concentrations in this study also are highly correlated with dissolved-solids concentrations ($p < 0.0001$, fig. 13B). Sulfate concentrations in the ground water of this study area were apparently affected by irrigated agricultural land-use practices and play an important part in the increase in dissolved solids in the ground-water resource. The increase in sulfate concentrations beneath irrigated fields could be caused by sulfate leaching from selected sedimentary deposits during infiltration of irrigation water or the application of sulfur-containing agricultural chemicals that migrate to the ground-water system.

Land-Use and Hydrogeologic Factors Affecting Ground-Water Quality

A number of land-use and hydrogeologic factors have the potential to control the relative effect of agricultural activities on ground-water quality. All wells in this study, however, were located in very similar land-use settings (adjacent to irrigated corn fields), and the detailed information was not available to determine how minor differences in land-use practices near individual wells related to minor differences in ground-water quality between these locations. Instead, the relative magnitude of five selected land-use and hydrogeologic factors were correlated with water-quality samples determined to be either affected (21 samples) or unaffected (9 samples) by irrigated agriculture. The five factors evaluated were (1) the percentage of irrigated land within the 500-m circular buffer zone coded around each well, (2) the number of years the land near each well had been irrigated, (3) application rate of atrazine in the county containing each well, (4) application rate of nitrogen in the county containing each well, and (5) depth to ground water at time of sample collection.

The percentage of irrigated agriculture in the areas around sampled wells may correlate with land-use effects on ground-water quality; that is, the more irrigated land near a well, the more likely agricultural chemicals will be present in the ground water. The estimated amount of irrigated land within the 500-m circular buffer around the sampled wells (as diagramed in the field during water sampling, nominal 2000) was relatively similar for both the unaffected and affected subsets of wells. The minimum, median, and maximum percentages of irrigated land within 500 meters of the nine unaffected wells were 17 percent, 45 percent, and 95 percent, respectively. The minimum,

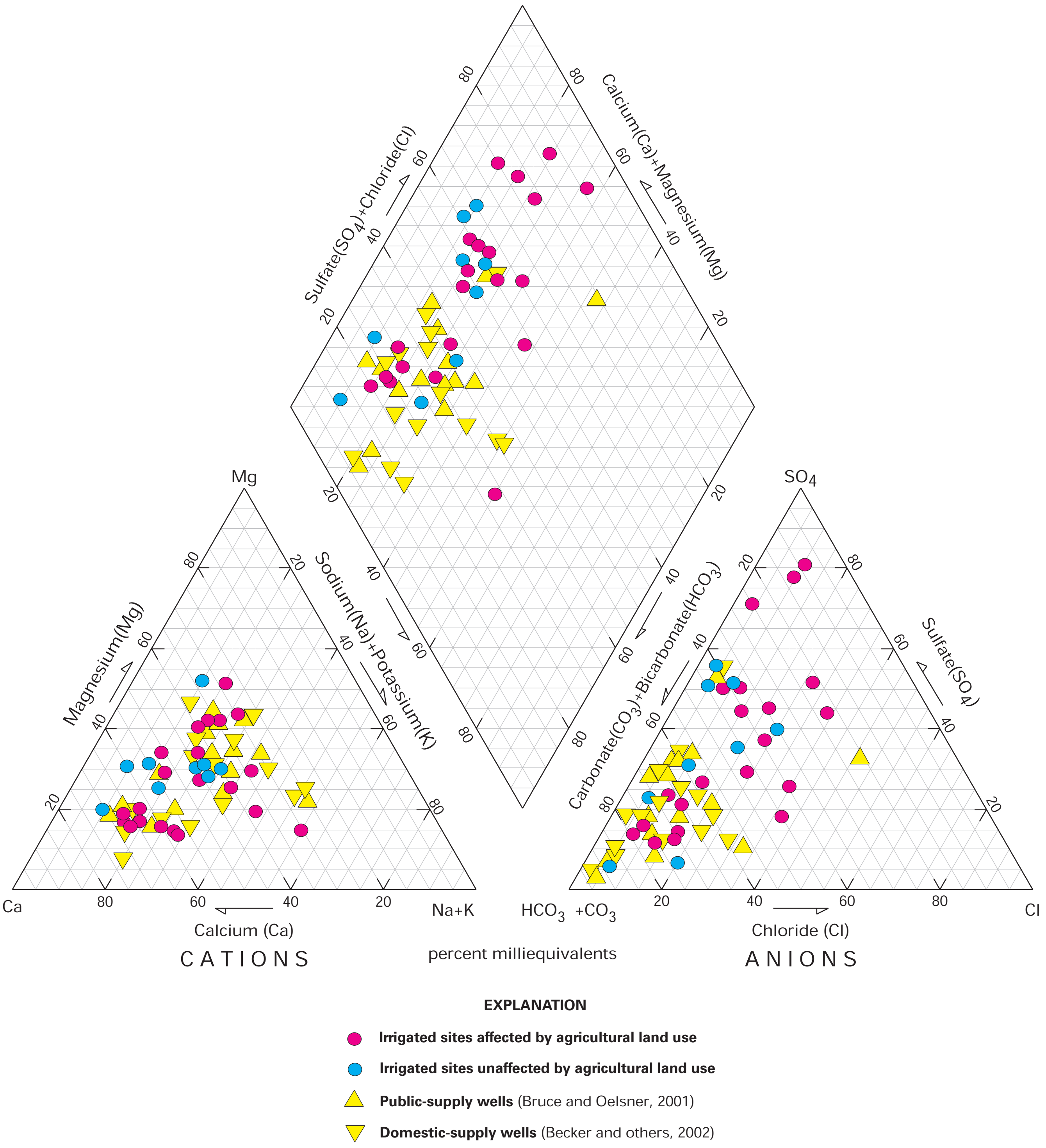


Figure 12. Relative major ion composition of ground-water samples collected beneath irrigated agricultural fields and nonagricultural areas in the central High Plains, 1999–2000.

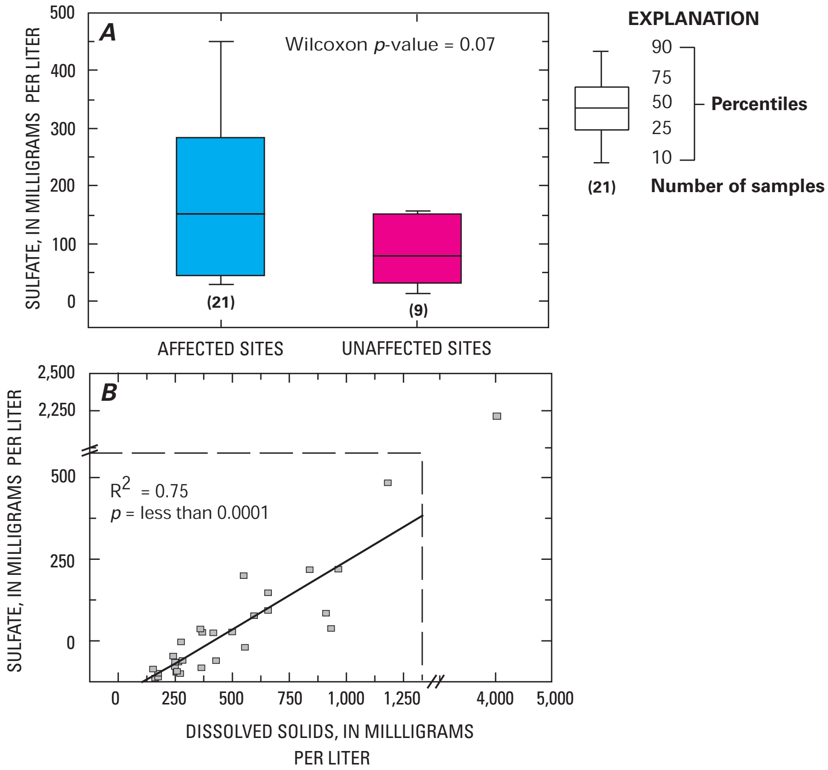


Figure 13. Distribution of sulfate concentrations (*A*) for sites affected and unaffected by irrigated agriculture in the central High Plains, and (*B*) relative to dissolved solids concentrations for 30 samples collected beneath irrigated fields in the central High Plains, 1999–2000.

median, and maximum percentage of irrigated land within 500 meters of the 21 affected wells was 20 percent, 70 percent, and 90 percent, respectively. Because of the similarity in the amount of irrigated land between the unaffected and affected wells, irrigation density did not strongly correlate with whether ground-water quality was affected by agricultural activities. The large *p*-value for this comparison (0.4972) indicates a low level of confidence that differences in irrigation density exist between the affected and unaffected wells.

Figure 14 shows statistical boxplots, oriented horizontally, that depict the percentile values determined for the four remaining land-use and hydrogeologic factors previously indicated. For each factor there are two boxplots: one representing the values for the subset of unaffected wells (blue), and one representing the values for the subset of affected wells (red). The vertical line near the center of each boxplot represents the median for that subset of data. The left and right edges of the box itself represent the 25th and 75th percentiles, respectively, and the left and right ends of the whiskers on each box represent the 5th and 95th percentiles, respectively. Associated with each category is a statistical *p*-value calculated using the Mann-Whitney rank-sum test (Helsel and Hirsch, 1995, p. 118). The Mann-Whitney test assesses the likelihood that the two sets of data come from the same population. Because the Mann-Whitney test is nonparametric, it is resistant to the effects of extreme outliers in either of the groups compared. The *p*-value represents the level of confidence at which the two groups being tested are thought to come from different populations. For example, a *p*-value of 0.05 indicates there is a 95-percent confidence level that the groups being compared are different; a *p*-value of 0.10 indicates a 90-percent confidence level that the groups are different, and so on.

The first pair of boxplots in figure 14 compares the approximate number of years that the fields adjacent to the sampled wells had been irrigated. Due to changes in ownership of these fields and incomplete records, the year in which irrigation water was first applied to these fields was not available for all sampling sites. The approximate year that water was first applied to each field was provided by the current landowners for all 9 unaffected wells and for 17 of 21 affected wells. The data were not weighted depending on whether the fields historically were flood/furrow irrigated, sprinkler irrigated, or a combination; however, some of the fields in this study were never flood irrigated.

A correlation is observed between the number of years a site was irrigated and whether the ground water was affected by irrigated agricultural activities. The *p*-value indicates an 84-percent confidence level that the agriculturally affected wells had a longer history of irrigation than the unaffected sites. An 84-percent confidence level is generally not considered statisti-

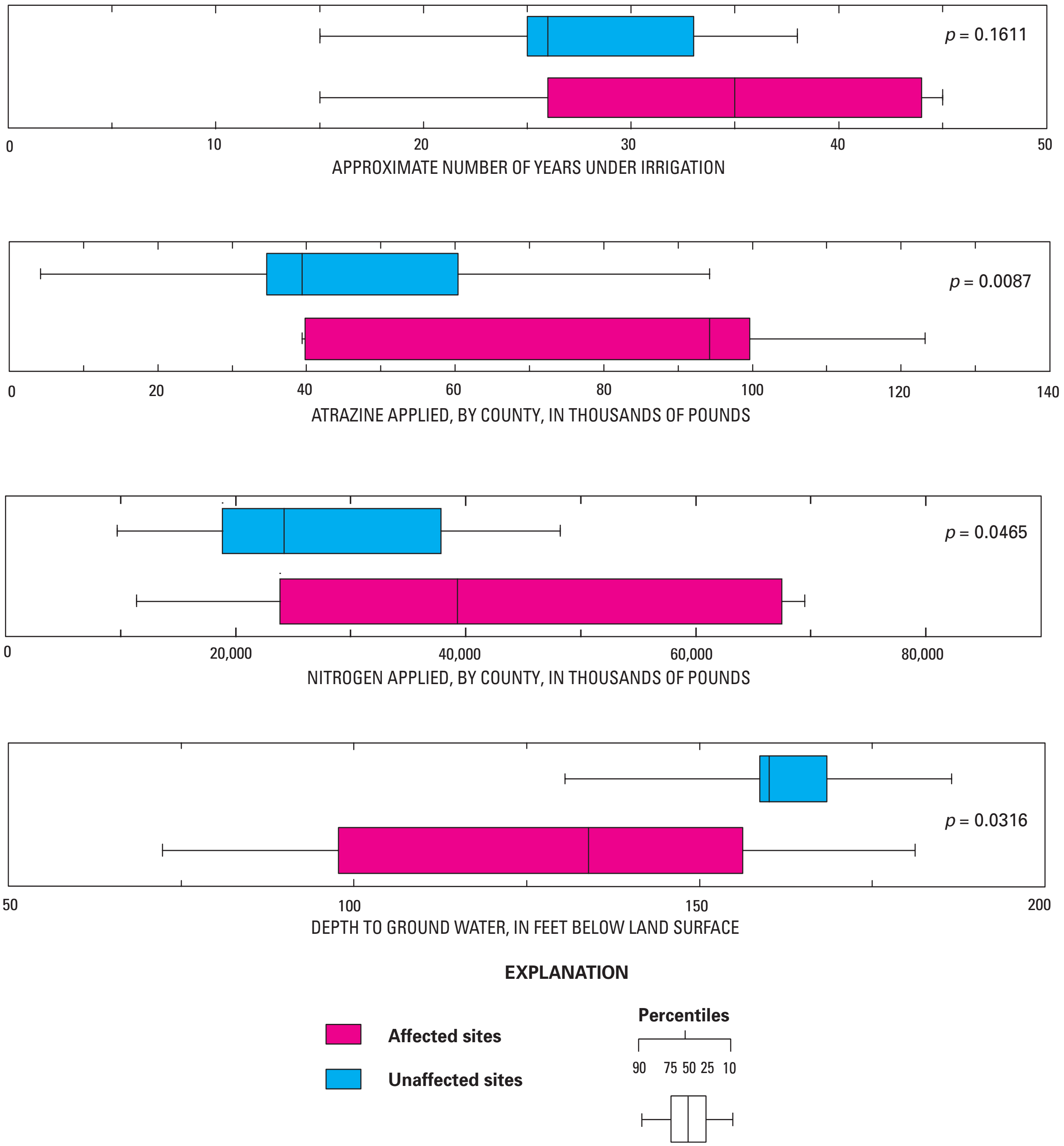


Figure 14. Comparison between sites affected and unaffected by agricultural land use and for selected factors that might contribute to aquifer vulnerability in the central High Plains

cally definitive but may indicate that ground water beneath areas of long-term irrigation is vulnerable to water-quality effects from this agricultural land-use practice.

Data generated by this study indicate that there is better than a 95-percent confidence level (*p* less than 0.05) that counties that apply large amounts of nitrogen and(or) atrazine to crops will have relatively large concentrations of nitrate and(or) atrazine or deethylatrazine present in ground-water samples (second and third box-plot pairs in fig. 14). Although the application rates only were available at the county-level scale, the correlations between these regional application rates and effects on ground-water quality were strong.

The final pair of boxplots in figure 14 indicate the importance of depth-to-water on the effect of agricultural activities on ground-water quality. Smaller depth to water in this study was strongly correlated (about a 97-percent confidence level) with water samples determined to be affected by agricultural activities. However, as previously mentioned, the water level in one of the affected wells exceeded 180 ft below land surface.

Summary and Conclusions

In 1999 and 2000, 30 water-table monitoring wells were installed near irrigated agricultural fields in the central High Plains of Colorado, Kansas, New Mexico, Oklahoma, and Texas to evaluate the effect of irrigated agriculture on recently recharged ground-water quality. The wells were located adjacent to irrigated fields in areas where the depth to ground water was 200 ft or less. Each well was constructed with a short (usually 10 ft long) well screen placed just below the water table. Each well was sampled once during 1999–2000 and the samples were analyzed for more than 100 water-quality constituents.

Water-quality data from the sampled wells indicate that 70 percent of the ground-water samples (21 of 30) were affected by agricultural land use. Nitrate concentrations in water samples exceeded the estimated maximum paleorecharge concentration of 3.5 mg/L as nitrogen in samples from 19 of 30 wells. The pesticide atrazine and its metabolite, deethylatrazine, were detected in samples from 20 and 21 of 30 wells, respectively. Atrazine and deethylatrazine were detected in all water samples that contained other pesticide compounds. Every water sample that had detectable deethylatrazine also had a nitrate concentration larger than 3.45 mg/L as nitrogen with the exception of one sample from a low-dissolved-oxygen environment that indicated the probable effects of microbial denitrification. This denitrified sample had the smallest nitrate concentration measured in any of the 30 water samples collected. Tritium data, which provide the relative age of each ground-water sample, indicate that every sample containing pesticides had at least some component of recently recharged (post-1952) water, including the denitrified sample. The 21 water samples with detectable pesticides, large nitrate concentrations (with the exception of the sample affected by denitrification), and tritium concentrations indicating recent recharge are considered to be affected by the overlying irrigated agricultural setting.

Two water samples contained enough tritium to have some component of recent recharge (2.2 and 3.2 pCi/L) but did not contain any detectable pesticides. The nitrate concentrations in these samples were 3.08 and 2.85 mg/L, respectively. Although the nitrate concentrations in these water samples were slightly larger than the 2.5-mg/L median paleorecharge concentration, the lack of detectable pesticides and relatively small tritium concentrations suggest that these samples were unaffected by agricultural land use. The remaining seven samples contained low concentrations of nitrate and tritium and no detectable pesticides. A total of nine water samples collected for this study were considered unaffected by agricultural land-use activities.

Nitrogen isotope ratios indicated the possible source of nitrate detected in ground-water samples. The nine water samples that were unaffected by agricultural land use had nitrogen isotope ratios typical of a natural organic soil-nitrogen source. The 21 water samples that were affected by agricultural activities had a range of isotopic ratios: 13 samples had ratios indicative of a commercial fertilizer source of nitrate (probably anhydrous ammonia), 4 samples had isotopic ratios indicative of an animal waste source (probably manure as fertilizer), and the 4 remaining samples, though they contained nitrate, tritium, and pesticides, had isotopic ratios in the soil-nitrogen range. One of these four affected samples with isotope ratios in the soil-nitrogen range showed the effects of denitrification, which would increase the isotopic ratio and shift it into the soil-nitrogen range. The other three affected samples with isotope ratios in the soil-nitrogen range might represent a mixture of two or more sources of nitrogen.

A number of land-use and hydrogeologic factors might control the relative effect of agricultural activities on ground-water quality. The relative magnitude of five selected factors were correlated with water-quality samples determined to be either affected (21 samples) or unaffected (9 samples) by irrigated agricultural. Data for the percentage of irrigated land within 500 meters of each well, the number of years the land near each well was irrigated, the amount of atrazine and nitrogen applied in the county where the well was located, and the depth to ground water were compared between the two subsets of sites. The difference in percentage of irrigated land between affected and unaffected sites was not found to be statistically significant. Although irrigated agriculture probably has affected the water quality at 70 percent of the sites sampled, the percentage of irrigated land associated with a well did not predict agricultural effects on ground-water quality. Because of uncertainties in delineating local ground-water flow directions, irrigation density was summarized for a circular buffer around each well rather than determining irrigation density for upgradient areas directly contributing recharge to the sampled wells. Correlations between the density of irrigated agriculture and the concentration of water-quality constituents may have been weakened by not limiting irrigation-density analysis to upgradient areas.

The data indicate some relation between the number of years irrigation had been taking place at a sampling site and whether ground-water quality was affected by the land-use activities. It appears (at an 84-percent confidence level) that sites with longer irrigation histories were more likely to show water-quality effects. Additionally, counties with larger application rates of atrazine and nitrogen, and well sites with smaller depths to ground water, correlated strongly (greater than a 95-percent confidence level) with water samples affected by agricultural activities.

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Supplemental Information

Table 8. Median percent recoveries for individual compounds in pesticide field-spike mixtures in the central High Plains agricultural land-use study, 1999–2000

Compound	Percent recovery	Compound	Percent recovery
Carbaryl	168	Fonofos	100
Methylazinphos	149	Methyl parathion	99
Carbofuran	146	Pebulate	99
Atrazine	132	Butylate	98
Terbacil	129	Alpha-BHC	96
Tebuthiuron	125	Ethoprop	96
Propanil	116	Molinate	94
Linuron	113	Triallate	93
2,6-diethylaniline	112	Chlorpyrifos	91
Cyanazine	109	Parathion	91
Propachlor	108	Dieldrin	88
DCPA	106	Ethalfluralin	84
Metolachlor	106	Terbufos	84
Prometon	106	Trifluralin	79
Simazine	103	Pendimethalin	78
Thiobencarb	103	Benfluralin	76
Acetochlor	103	Phorate	76
Pronamide	103	Propargite	76
Lindane	103	Deethylatrazine	70
Napropamide	103	p,p’-DDE	65
EPTC	102	Disulfoton	63
Alachlor	101	Permethrin	61
Malathion	101		
Diazinon	101		
Metribuzin	101		

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000

[µS/cm, microsiemens per centimeter at 25°C; Deg. C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; <, less than; >, greater than; E, estimated; --, no data; G, gallon; min, minute; mm, millimeters; Hg, mercury; NGVD, National Geodetic Vertical Datum of 1929; ESA, ethanesulfonic acid; OA, oxanilic acid; N, nitrogen; P, phosphorus; NO_3, nitrate as nitrogen; pCi/L, picocuries per liter]

Site number (fig. 7)	Site identification	Date	Time	Water level (feet)	Depth of well (feet)	Elevation of land surface (feet above NGVD)	Turbidity (NTU)	Air pressure (mm of Hg)	Dissolved oxygen (mg/L)	pH, field (standard units)	Specific conductance (µS/cm at 25°C)
1	363518101515101	09/12/00	1000	186.85	198.00	3,460	42	675	7.9	7.5	611
2	364846102161201	09/17/00	1000	160.00	181.72	3,965	3.5	661	7.4	7.7	819
3	371303102003001	09/14/00	1700	96.70	113.18	3,623	1.2	673	7.4	7.5	948
4	374750101553501	08/09/00	0900	159.55	178.00	3,442	47	673	1.1	7.7	652
5	384422101434201	07/14/00	1200	186.48	199.00	3,655	6.6	675	7.3	7.8	385
6	374005101433501	08/08/00	0800	173.27	198.18	3,266	330	676	4.6	7.6	610
7	371909101413101	09/16/00	1000	181.70	196.60	3,324	180	677	7.9	7.7	1,100
8	370130101180904	09/14/00	0800	132.80	145.00	3,100	37	681	7.7	7.8	622
9	375734100452301	02/02/99	1130	122.69	133.00	2,877	--	694	6.5	7.0	1,640
10	383334101131301	08/08/00	1500	163.37	174.50	3,217	24	676	5.6	7.7	545
11	383803101084701	07/13/00	1100	171.34	182.00	3,181	2.0	688	5.1	7.4	548
12	381201100495101	07/11/00	1200	121.21	139.00	2,920	5.3	689	5.5	7.0	1,220
13	375855100484001	06/27/00	1200	70.45	94.00	2,853	2.0	697	5.1	6.8	3,770
14	375106100544301	09/26/00	1400	177.07	193.20	2,921	14	689	7.0	7.6	470
15	374625100490701	06/29/00	1100	151.37	170.00	2,890	3.4	695	7.2	6.9	996
16	374412100453201	07/10/00	1100	151.77	155.50	2,844	180	689	0.6	7.4	867
17	372511100155601	09/27/00	0900	12.99	31.10	2,520	0.57	700	5.6	7.3	1,450
18	373346100005701	09/27/00	1400	137.74	157.32	2,580	5.0	698	3.9	7.6	504
19	373904099545701	09/28/00	1300	99.16	115.00	2,520	5.1	699	7.6	7.4	607
20	374220100422501	06/28/00	1100	164.12	190.00	2,797	1.2	697	6.7	6.9	774
21	374642100291701	06/30/00	1200	137.70	149.00	2,740	2.1	695	6.2	7.2	556
22	375502100363601	09/26/00	1000	174.87	187.40	2,857	>1,000	690	6.7	7.9	705
23	360159103044401	09/11/00	1500	169.64	179.80	4,463	1.4	646	7.0	7.3	498
24	371728101311401	09/15/00	1100	133.69	158.00	3,190	3.8	685	7.4	7.4	1,120
25	370941101540001	09/16/00	1300	99.81	113.30	3,531	1.0	673	5.6	7.8	1,380
26	375251101135301	08/11/00	1000	92.18	105.81	3,019	5.7	685	7.7	7.3	1,660
27	380256101035901	08/10/00	0800	150.89	162.20	2,978	65	686	6.2	7.2	1,100
28	383936101120801	07/12/00	1500	156.16	173.50	3,216	9.1	686	5.8	7.4	580
29	373234099430201	09/25/00	1300	134.40	149.00	2,470	1.3	705	7.0	7.7	460
30	374430100093801	09/28/00	0900	92.24	108.50	2,595	6.0	699	7.8	7.4	792

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000—Continued

[µS/cm, microsiemens per centimeter at 25°C; Deg. C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; <, less than; >, greater than; E, estimated; --, no data; G, gallon; min, minute; mm, millimeters; Hg, mercury; NGVD, National Geodetic Vertical Datum of 1929; ESA, ethanesulfonic acid; OA, oxanilic acid; N, nitrogen; P, phosphorus; NO_3, nitrate as nitrogen; pCi/L, picocuries per liter]

Site number (fig. 7)	Water temperature (Deg. C)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Alkalinity, field (mg/L as $CaCO_3$)	Bromide, dissolved (mg/L)	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Sulfate, dissolved (mg/L)
1	18.0	43.7	30.4	5.38	25.6	146	0.55	69.5	2.4	36.5	46.2
2	19.3	56.7	54.2	5.73	26.0	166	0.71	69.1	2.2	37.2	149
3	18.2	57.5	63.0	6.37	43.8	205	0.60	70.8	2.2	32.1	152
4	19.0	76.5	21.1	6.29	26.0	168	0.15	10.5	0.7	64.5	151
5	18.3	37.1	14.2	4.63	23.8	154	0.11	7.46	1.3	28.5	38.6
6	17.0	55.5	22.7	5.03	31.3	112	0.17	6.30	1.2	18.2	122
7	15.8	86.6	53.3	5.73	47.6	130	1.43	113	2.4	24.4	202
8	17.0	38.5	11.5	8.42	74.8	216	0.15	18.0	0.5	28.9	60.2
9	12.1	145	69.6	8.89	81.6	340	0.25	101	0.7	46.8	163
10	16.0	46.7	20.6	6.70	28.1	97	0.19	23.0	2.4	56.8	59.2
11	18.6	61.5	25.1	4.76	18.2	234	0.15	11.8	1.2	34.6	31.9
12	19.5	113	43.5	8.88	105	202	0.53	70.2	2.1	56.9	209
13	18.9	410	220	14.9	503	325	1.38	223	0.7	38.6	2,360
14	18.0	64.7	9.04	3.09	17.9	152	0.08	9.36	0.4	20.7	25.7
15	17.4	121	17.4	4.35	66.6	206	0.46	104	0.3	22.0	105
16	17.3	126	22.0	6.77	27.5	145	0.23	13.0	0.5	10.8	324
17	15.0	127	39.9	4.65	163	363	0.32	40.3	1.8	49.5	344
18	17.5	63.3	19.7	3.97	8.98	198	0.20	31.5	0.7	29.7	14.1
19	16.0	77.9	15.3	4.49	22.1	234	0.13	22.8	0.3	28.0	28.4
20	17.9	97.3	14.8	1.99	52.2	250	0.18	30.3	0.3	22.9	64.2
21	20.0	79.8	12.8	3.70	25.0	180	0.10	24.6	0.4	22.6	24.5
22	15.0	83.3	29.2	4.93	21.0	156	0.27	22.8	0.8	35.3	161
23	18.7	48.3	22.2	4.57	38.7	188	0.20	19.4	1.1	24.3	78.0
24	18.0	84.4	63.0	7.06	62.4	262	0.31	47.6	1.4	30.9	272
25	16.8	86.9	78.0	11.9	82.6	182	1.19	132	2.1	22.5	343
26	17.5	226	35.4	4.75	102	127	0.31	55.3	0.4	17.2	609
27	21.0	129	43.1	7.22	46.5	252	0.54	54.3	0.6	29.7	218
28	17.8	57.8	21.0	10.3	32.1	178	0.23	27.6	1.6	30.7	64.9
29	16.6	71.3	12.1	3.66	9.33	202	0.07	7.79	0.4	31.0	10.6
30	16.0	108	16.1	5.70	25.8	262	0.11	35.5	0.3	26.8	42.2

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000—Continued

[µS/cm, microsiemens per centimeter at 25°C; Deg. C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; <, less than; >, greater than; E, estimated; --, no data; G, gallon; min, minute; mm, millimeters; Hg, mercury; NGVD, National Geodetic Vertical Datum of 1929; ESA, ethanesulfonic acid; OA, oxanilic acid; N, nitrogen; P, phosphorus; NO_3, nitrate as nitrogen; pCi/L, picocuries per liter]

Site number (fig. 7)	Dissolved solids (mg/L)	Ammonium, dissolved (mg/L as N)	Ammonium plus organic nitrogen, dissolved (mg/L as N)	Nitrate plus nitrite, dissolved (mg/L as N)	Nitrite, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Orthophosphate, dissolved (mg/L as P)	Carbon, organic, dissolved (mg/L)	Iron, dissolved
1	373	<0.02	<0.10	3.48	<0.010	<0.050	<0.01	0.7	<30
2	542	<0.02	0.13	3.08	<0.010	<0.050	<0.01	14.5	<10
3	624	<0.02	0.13	9.27	<0.010	0.006	<0.01	4.2	<10
4	493	<0.02	<0.10	2.85	<0.010	0.008	<0.01	0.4	33
5	277	0.03	<0.10	2.36	<0.010	<0.050	0.02	1.2	<10
6	400	<0.02	<0.10	3.07	<0.010	0.047	0.01	0.8	<10
7	720	<0.02	0.17	14.9	0.016	0.022	<0.01	3.0	<10
8	388	0.53	0.66	3.75	0.091	0.018	<0.01	0.8	<10
9	1,060	<0.02	0.65	54.4	<0.010	0.009	0.02	--	<10
10	374	<0.02	0.20	3.42	<0.010	0.012	<0.01	1.5	<10
11	382	<0.02	0.11	8.31	<0.010	<0.050	<0.01	2.9	<10
12	1,040	<0.02	0.35	61.1	<0.010	<0.05	<0.01	2.6	<10
13	4,510	0.03	0.23	9.60	<0.010	0.016	0.01	2.4	<30
14	300	<0.02	<0.10	11.6	<0.010	0.015	0.01	6.5	<10
15	680	<0.02	0.20	24.1	<0.010	0.007	<0.01	1.9	<10
16	675	<0.02	0.10	0.25	0.012	<0.05	<0.01	2.5	<10
17	1,090	<0.02	0.28	21.5	<0.010	0.022	0.02	5.3	<10
18	300	<0.02	<0.10	1.27	0.011	<0.006	<0.01	6.3	10
19	380	<0.02	<0.10	6.57	<0.010	0.012	0.01	24.2	<10
20	554	<0.02	0.13	22.0	<0.010	0.007	<0.01	1.5	<10
21	396	<0.02	<0.10	19.3	<0.010	0.019	0.02	1.1	<10
22	485	<0.02	<0.10	3.21	<0.010	0.012	<0.01	0.6	<10
23	366	<0.02	<0.10	1.29	<0.010	<0.050	<0.01	0.7	<10
24	782	<0.02	<0.10	5.91	<0.010	<0.050	<0.01	1.7	<30
25	964	0.06	0.35	6.62	1.09	0.011	<0.01	3.6	<10
26	1,310	<0.02	<0.10	22.9	<0.010	0.006	0.01	1.1	<10
27	782	<0.02	0.20	15.8	0.011	0.009	<0.01	1.9	<10
28	407	<0.02	<0.10	7.56	<0.010	<0.050	<0.01	3.1	<10
29	287	<0.02	<0.10	2.71	<0.010	<0.050	<0.01	2.3	<10
30	489	<0.02	0.10	7.48	<0.010	0.032	0.03	3.0	<10

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000—Continued

[µS/cm, microsiemens per centimeter at 25°C; Deg. C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; <, less than; >, greater than; E, estimated; --, no data; G, gallon; min, minute; mm, millimeters; Hg, mercury; NGVD, National Geodetic Vertical Datum of 1929; ESA, ethanesulfonic acid; OA, oxanilic acid; N, nitrogen; P, phosphorus; NO_3, nitrate as nitrogen; pCi/L, picocuries per liter]

Site number (fig. 7)	Manganese, dissolved (µg/L)	2-6-Diethylaniline (µg/L)	Acetochlor, dissolved (µg/L)	Acetochlor, ESA (µg/L)	Acetochlor, OA (µg/L)	Alachlor, dissolved (µg/L)	Alachlor, ESA (µg/L)	Alachlor, OA (µg/L)	Alpha BHC, dissolved (µg/L)	Atrazine (µg/L)	Benfluralin (µg/L)
1	2.7	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	<0.005	<0.002
2	2.7	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	<0.001	<0.002
3	3.5	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	1.71	<0.002
4	44.2	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	<0.001	<0.002
5	3.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	<0.001	<0.002
6	45.7	<0.003	<0.002	<0.05	<0.05	<0.002	0.07	<0.05	<0.002	<0.01	<0.002
7	7.8	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.310	<0.002
8	35.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.065	<0.002
9	<3.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	5.01	<0.002
10	40.7	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	<0.010	<0.002
11	43.4	<0.003	<0.002	<0.05	<0.05	<0.002	0.16	<0.05	<0.002	E4.78	<0.002
12	5.4	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.038	<0.002
13	<3.0	<0.003	<0.002	0.47	<0.05	<0.002	<0.05	<0.05	<0.002	0.008	<0.002
14	2.5	<0.002	<0.004	<0.05	<0.05	<0.002	0.23	<0.05	<0.005	0.016	<0.010
15	<3.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.270	<0.002
16	744	<0.003	<0.010	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.117	<0.002
17	<2.2	<0.002	0.009	1.84	<0.05	<0.002	<0.05	<0.05	<0.005	0.438	<0.010
18	76.1	<0.002	<0.004	<0.05	<0.05	<0.002	<0.05	<0.05	<0.005	<0.007	<0.010
19	<3.0	<0.002	<0.004	<0.05	<0.05	0.049	0.52	0.06	<0.005	2.56	<0.010
20	<2.2	<0.003	<0.002	0.80	<0.05	<0.002	<0.05	<0.05	<0.002	1.28	<0.002
21	<3.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.050	<0.002
22	<2.2	<0.002	<0.004	<0.05	<0.05	<0.002	<0.05	<0.05	<0.005	<0.007	<0.010
23	<3.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	<0.001	<0.002
24	<3.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.128	<0.002
25	160	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.009	<0.002
26	<3.0	<0.003	<0.002	<0.05	<0.05	<0.002	<0.05	<0.05	<0.002	0.288	<0.002
27	13.2	<0.003	<0.002	<0.05	<0.05	<0.002	1.24	<0.05	<0.002	0.782	<0.002
28	4.3	<0.003	<0.002	<0.05	<0.05	<0.002	0.07	<0.05	<0.002	0.013	<0.002
29	<2.2	<0.002	<0.004	<0.05	<0.05	<0.002	<0.05	<0.05	<0.005	<0.010	<0.010
30	<2.2	<0.002	<0.004	<0.05	<0.05	<0.002	0.13	<0.05	<0.005	0.232	<0.010

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000—Continued

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Site number (fig. 7)	Butylate (µg/L)	Carbaryl (µg/L)	Carbofuran (µg/L)	Chlorpyrifos (µg/L)	Cyanazine (µg/L)	DCPA (dacthal) (µg/L)	Deethyl-atrazine (µg/L)	Diazinon (µg/L)	Dieldrin (µg/L)	Disulfoton (µg/L)	EPTC (eptam) (µg/L)	Ethalfluralin (µg/L)
1	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.074	<0.002	<0.001	<0.02	<0.002	<0.004
2	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	<0.006	<0.002	<0.001	<0.02	<0.002	<0.004
3	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E2.10	<0.002	<0.001	<0.02	<0.002	<0.004
4	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	<0.002	<0.002	<0.001	<0.02	<0.002	<0.004
5	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	<0.002	<0.002	<0.001	<0.02	<0.002	<0.004
6	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	<0.002	<0.002	<0.001	<0.02	<0.002	<0.004
7	<0.002	<0.003	<0.003	0.007	<0.004	<0.002	E0.029	<0.002	<0.001	<0.02	<0.002	<0.004
8	<0.002	<0.003	<0.003	0.018	<0.004	<0.002	E0.012	<0.002	<0.001	<0.02	<0.002	<0.004
9	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E1.70	<0.002	<0.001	<0.02	<0.002	<0.004
10	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	<0.002	<0.002	<0.001	<0.02	<0.002	<0.004
11	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.532	<0.002	<0.001	<0.02	<0.002	<0.004
12	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.172	<0.002	<0.001	<0.02	<0.002	<0.004
13	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.049	<0.002	<0.001	<0.02	<0.002	<0.004
14	<0.002	<0.041	<0.020	<0.005	<0.018	<0.003	E0.187	<0.005	<0.005	<0.02	<0.002	<0.009
15	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.407	<0.002	<0.001	<0.02	<0.002	<0.004
16	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.074	<0.007	<0.001	<0.02	<0.002	<0.004
17	<0.002	<0.041	<0.020	<0.005	<0.018	<0.003	E0.726	<0.005	<0.005	<0.02	<0.002	<0.009
18	<0.002	<0.041	<0.020	<0.005	<0.018	<0.003	<0.006	<0.005	<0.005	<0.02	<0.002	<0.009
19	<0.002	<0.041	<0.020	<0.005	<0.018	<0.003	E1.00	<0.005	<0.005	<0.02	0.018	<0.009
20	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.549	<0.002	<0.001	<0.02	<0.002	<0.004
21	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.097	<0.002	<0.001	<0.02	<0.002	<0.004
22	<0.002	<0.041	<0.020	<0.005	<0.018	<0.003	<0.006	<0.007	<0.005	<0.02	<0.002	<0.009
23	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	<0.002	<0.002	<0.001	<0.02	<0.002	<0.004
24	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.439	<0.002	<0.001	<0.02	<0.002	<0.004
25	<0.002	<0.003	<0.030	0.012	<0.004	<0.002	E0.249	<0.002	<0.001	<0.02	<0.010	<0.004
26	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E1.20	<0.002	<0.001	<0.02	<0.002	<0.004
27	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E1.30	<0.002	<0.001	<0.02	<0.002	<0.004
28	<0.002	<0.003	<0.003	<0.004	<0.004	<0.002	E0.037	<0.002	<0.001	<0.02	<0.002	<0.004
29	<0.002	<0.041	<0.020	<0.005	<0.018	<0.003	<0.006	<0.005	<0.005	<0.02	<0.002	<0.009
30	<0.002	<0.041	<0.020	<0.005	<0.018	<0.003	E1.04	<0.005	<0.005	<0.02	<0.002	<0.009

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000—Continued

[µS/cm, microsiemens per centimeter at 25°C; Deg. C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; <, less than; >, greater than; E, estimated; --, no data; G, gallon; min, minute; mm, millimeters; Hg, mercury; NGVD, National Geodetic Vertical Datum of 1929; ESA, ethanesulfonic acid; OA, oxanilic acid; N, nitrogen; P, phosphorus; NO_3, nitrate as nitrogen; pCi/L, picocuries per liter]

Site number (fig. 7)	Ethoprop (µg/L)	Fonofos (µg/L)	Lindane (µg/L)	Linuron (µg/L)	Malathion (µg/L)	Methyl-azinphos (µg/L)	Methyl, parathion (µg/L)	Metolachlor, dissolved (µg/L)	Metolachlor, ESA (µg/L)	Metolachlor, OA (µg/L)	Metribuzin (µg/L)	Molinate (µg/L)
1	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
2	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
3	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
4	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
5	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
6	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
7	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
8	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
9	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	0.097	2.80	1.20	<0.004	<0.004
10	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
11	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	0.021	0.26	0.09	<0.004	<0.004
12	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	0.11	<0.05	<0.004	<0.004
13	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
14	<0.005	<0.003	<0.004	<0.035	<0.027	<0.050	<0.006	<0.013	0.09	<0.05	<0.006	<0.002
15	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	0.24	<0.05	<0.004	<0.004
16	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
17	<0.005	<0.003	<0.004	<0.035	<0.027	<0.050	<0.006	<0.013	0.47	<0.05	<0.006	<0.002
18	<0.005	<0.003	<0.004	<0.035	<0.027	<0.050	<0.006	<0.013	<0.05	<0.05	<0.006	<0.002
19	<0.005	<0.003	<0.004	<0.035	<0.027	<0.050	<0.006	0.679	0.92	0.62	0.017	<0.002
20	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.004	<0.05	<0.05	<0.004	<0.004
21	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
22	<0.005	<0.003	<0.004	<0.035	<0.027	<0.050	<0.006	<0.013	<0.05	<0.05	<0.006	<0.002
23	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
24	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
25	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
26	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
27	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
28	<0.003	<0.003	<0.004	<0.002	<0.005	<0.001	<0.006	<0.002	<0.05	<0.05	<0.004	<0.004
29	<0.005	<0.003	<0.004	<0.035	<0.027	<0.050	<0.006	<0.013	<0.05	<0.05	<0.006	<0.002
30	<0.005	<0.003	<0.004	<0.035	<0.027	<0.050	<0.006	<0.013	0.08	<0.05	<0.006	<0.002

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000—Continued

[µS/cm, microsiemens per centimeter at 25°C; Deg. C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; <, less than; >, greater than; E, estimated; --, no data; G, gallon; min, minute; mm, millimeters; Hg, mercury; NGVD, National Geodetic Vertical Datum of 1929; ESA, ethanesulfonic acid; OA, oxanilic acid; N, nitrogen; P, phosphorus; NO_3, nitrate as nitrogen; pCi/L, picocuries per liter]

Site number (fig. 7)	Napromide (µg/L)	p,p' DDE (µg/L)	Parathion (µg/L)	Pebulate (µg/L)	Pendimethalin (µg/L)	Permethrin (µg/L)	Phorate (µg/L)	Prometon (µg/L)	Pronamide (µg/L)	Propachlor (µg/L)	Propanil (µg/L)
1	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
2	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
3	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
4	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
5	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
6	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
7	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
8	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
9	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
10	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
11	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
12	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
13	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
14	<0.007	<0.003	<0.007	<0.002	<0.010	<0.006	<0.011	<0.01	<0.004	<0.010	<0.011
15	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
16	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
17	<0.007	<0.003	<0.007	<0.002	<0.010	<0.006	<0.011	<0.01	<0.004	<0.010	<0.011
18	<0.007	<0.003	<0.007	<0.002	<0.010	<0.006	<0.011	<0.01	<0.004	<0.010	<0.011
19	<0.007	<0.003	<0.007	<0.002	<0.010	<0.006	<0.011	<0.01	<0.004	<0.010	<0.011
20	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
21	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
22	<0.007	<0.003	<0.007	<0.002	<0.010	<0.006	<0.011	<0.01	<0.004	<0.010	<0.011
23	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
24	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
25	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
26	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
27	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
28	<0.003	<0.006	<0.004	<0.004	<0.004	<0.005	<0.002	<0.02	<0.003	<0.007	<0.004
29	<0.007	<0.003	<0.007	<0.002	<0.010	<0.006	<0.011	<0.01	<0.004	<0.010	<0.011
30	<0.007	<0.003	<0.007	<0.002	<0.010	<0.006	<0.011	<0.01	<0.004	<0.010	<0.011

Table 9. Results of physical and chemical analyses of water samples from wells completed as part of the central High Plains agricultural land-use study, 1999–2000—Continued

[µS/cm, microsiemens per centimeter at 25°C; Deg. C, degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; <, less than; >, greater than; E, estimated; --, no data; G, gallon; min, minute; mm, millimeters; Hg, mercury; NGVD, National Geodetic Vertical Datum of 1929; ESA, ethanesulfonic acid; OA, oxanilic acid; N, nitrogen; P, phosphorus; NO_3, nitrate as nitrogen; pCi/L, picocuries per liter]

Site number (fig. 7)	Propargite (µg/L)	Simazine (µg/L)	Tebuthiuron (µg/L)	Terbacil (µg/L)	Terbufos (µg/L)	Thiobencarb (µg/L)	Triallate (µg/L)	Trifluralin (µg/L)	N-15/N-14 NO_3 fraction (ratio per mil)	Tritium total (pCi/L)	Tritium 2 sigma (pCi/L)
1	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	4.80	7	1.0
2	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	4.70	2	1.0
3	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	3.80	6	1.0
4	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	8.50	3	1.0
5	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	5.30	<1	1.0
6	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	6.60	<1	1.0
7	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	3.80	15	1.3
8	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	3.40	37	2.6
9	<0.01	0.038	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	15.80	16	1.3
10	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	7.80	<1	1.0
11	<0.01	0.033	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	10.90	24	1.9
12	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	10.50	11	1.0
13	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	6.80	24	1.6
14	<0.02	<0.011	<0.02	<0.034	<0.02	<0.005	<0.002	<0.009	2.10	11	1.0
15	<0.01	0.006	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	1.90	16	1.3
16	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	6.80	5	1.0
17	<0.02	<0.011	<0.02	<0.034	<0.02	<0.005	<0.002	<0.009	4.50	10	1.0
18	<0.02	<0.011	<0.02	<0.034	<0.02	<0.005	<0.002	<0.009	4.60	<1	1.0
19	<0.02	0.021	<0.02	<0.034	<0.02	<0.005	<0.002	<0.009	4.10	14	1.3
20	<0.01	0.023	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	3.00	16	1.3
21	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	4.40	7	1.0
22	<0.02	<0.011	<0.02	<0.034	<0.02	<0.005	<0.002	<0.009	7.80	<1	1.0
23	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	4.30	<1	1.0
24	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	4.20	7	1.0
25	<0.01	<0.005	<0.01	<0.300	<0.01	<0.002	<0.001	<0.002	9.90	4	1.0
26	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	–0.30	40	2.6
27	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	2.20	7	1.0
28	<0.01	<0.005	<0.01	<0.007	<0.01	<0.002	<0.001	<0.002	6.80	16	1.3
29	<0.02	<0.011	<0.02	<0.034	<0.02	<0.005	<0.002	<0.009	6.10	1	1.0
30	<0.02	<0.011	<0.02	<0.034	<0.02	<0.005	<0.002	<0.009	6.40	20	1.3