

Receptors—Quality of the Used Resource in the High Plains Aquifer

Chapter 3 of

Water-Quality Assessment of the High Plains Aquifer, 1999–2004

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Chapter 3. Receptors—Quality of the Used Resource in the High Plains Aquifer

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Introduction

In this chapter, the primary ground-water receptors (users) considered include humans and irrigated crops. Irrigated crops are the receptor receiving the largest amount of water from the High Plains aquifer (fig. 8). Thus, the used resource is defined as water produced from domestic, public-supply, and irrigation wells. This chapter summarizes water-quality conditions that might be encountered by humans and irrigated crops through their use of water from those well types. Livestock may also use water from those wells to some extent; therefore, they represent a third receptor for which the following water-quality summary may have relevance.

Study Design

Data from the major-aquifer study well networks were used to assess the water quality of domestic wells. Details of the major-aquifer study design, sample collection, and sample analysis can be found in Pope and others (2001), Becker and others (2002), Fahlquist (2003), and Stanton and Qi (2007). In the NHP, samples were collected from 2002 to 2004. In the CHP, samples were collected in 1999. In the SHP, samples were collected in 2001.

The HPGW study sampled only a small number of public-supply and irrigation wells (Bruce and Oelsner, 2001). Thus, that data set was supplemented with data collected during other USGS sampling efforts or by selected Federal or State agencies (Litke, 2001) to provide sufficient data distribution and allow regional comparison of water-quality data from public-supply and irrigation wells. Some of those data have limitations, such as a small number of analyzed constituents or larger laboratory reporting levels, but they are still useful for expanding the areal coverage of water-quality conditions for those well types. Only constituents that have sufficient areal coverage to allow this regional comparison are discussed in the following sections on water quality in public-supply and irrigation wells.

Analyses reported here for domestic and public-supply wells are for untreated ground water and not “finished” water produced by municipal drinking-water treatment plants or in-home treatment systems. Treatment by municipal plants or

in-home systems may result in water that is chemically different from that described in this chapter. Water-quality data from the domestic and public-supply wells are compared to USEPA MCLs and secondary drinking-water standards (SMCLs), which technically are applicable only to public-supply systems (U.S. Environmental Protection Agency, 2006). Although individual States might have standards that are more restrictive, the USEPA standards provide a reasonable framework for comparing data between States. The quality of water from irrigation wells is evaluated relative to generally accepted indicators of crop tolerance (Rhoades and others, 1992; Ayers and Westcot, 1994).

Quality of Water from Domestic Wells

Water-quality conditions reported for domestic wells in this study are based on samples collected from 307 randomly distributed private domestic wells as part of the major-aquifer studies (table 4 and fig. 58). As discussed previously in this report, the High Plains study area was stratified on the basis of hydrogeologic unit (fig. 10A). Within each studied hydrogeologic unit, domestic wells were chosen from a set of candidate wells, generally within a 4-mi radius of randomly selected sampling sites that represent equal-area subsections of the major hydrogeologic units (Scott, 1990). This stratified random site-selection process, coupled with the substantial variation in well depths and low pumping volumes for the domestic wells, makes the results of this sampling effort a reasonable indicator of the broad range of ambient water-quality conditions within each hydrogeologic unit. It is likely that the range of observed water-quality conditions bracket the conditions expected in most domestic wells in those hydrogeologic units.

Field Measurements

Prior to collecting samples from each domestic well, water-quality field measurements were made to document stable sampling conditions in the pumping wells and to measure properties that would likely change during transport of samples to the laboratory for analysis. Those measurements

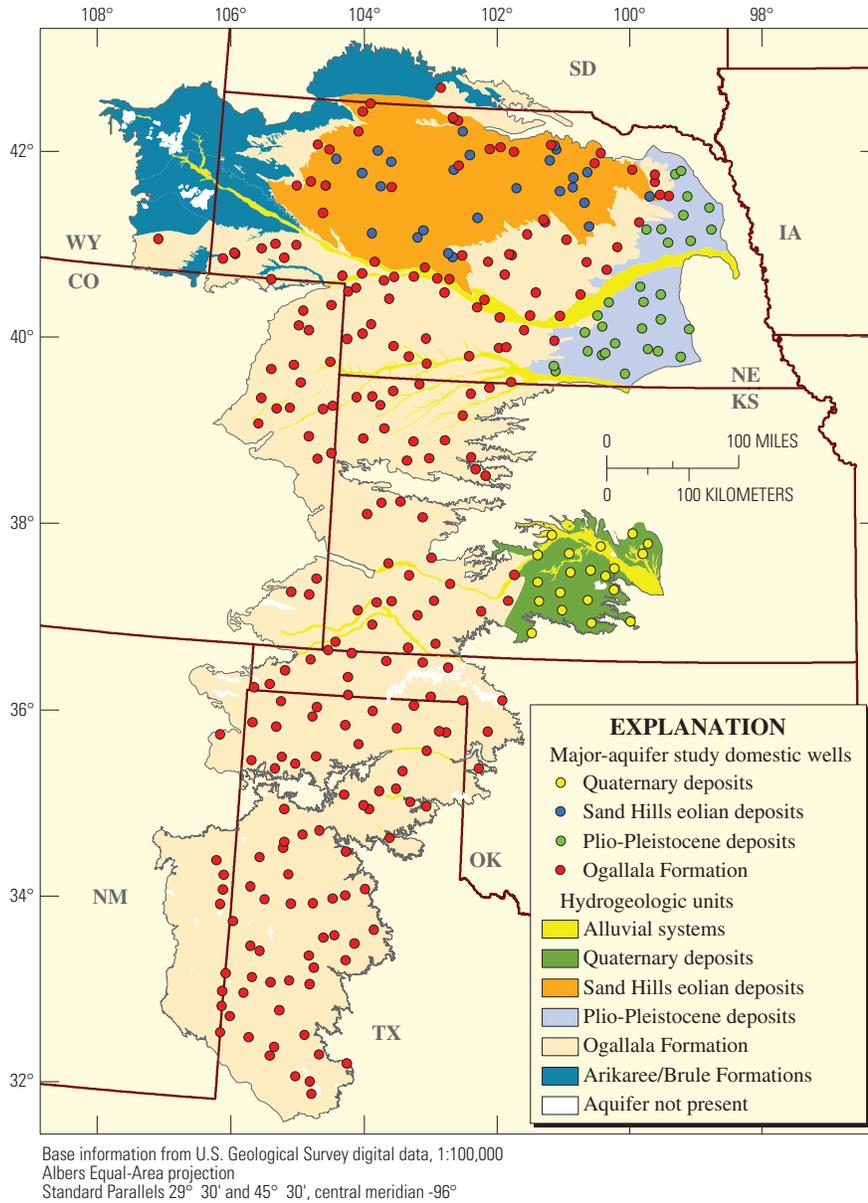


Figure 58. Location of domestic (major-aquifer study) wells sampled for the High Plains Regional Ground-Water study. Locations for domestic wells sampled in the alluvial system of the Platte River are not shown, but data are discussed by Stanton and Qi (2007).

included pH, dissolved oxygen, water temperature, specific conductance, and, in the case of low dissolved oxygen, hydrogen sulfide. Those water properties are general indicators of the quality of water for human consumption. Table 10 summarizes values for pH, dissolved oxygen, and specific conductance, by hydrogeologic unit, for domestic wells sampled during this study. Due to the fact that the hydrogeologic units of the High Plains aquifer generally are well oxygenated, measurements of hydrogen sulfide were rarely required and the

median hydrogen sulfide concentration in all hydrogeologic units was less than the detection level of 0.01 mg/L.

Only one of the field properties, pH, has an applicable USEPA drinking-water standard, a nonenforceable SMCL of between 6.5 and 8.5 standard pH units. Of the 307 domestic-well samples, only one had a pH value outside the recommended range of values (6.4 in the Quaternary deposits) (table 10). Water from each hydrogeologic unit generally was well oxygenated (dissolved oxygen concentration greater than

Table 10. Summary of values for selected field properties in water samples from domestic wells in the High Plains aquifer.

[NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; Min., minimum; Med., median; Max., maximum; <, less than; n, number of samples]

	pH, in standard units			Dissolved oxygen, in milligrams per liter			Specific conductance, in microsiemens per cen- timeter at 25° Celsius		
	Min.	Med.	Max.	Min.	Med.	Max.	Min.	Med.	Max.
Sand Hills eolian deposits (NHP), n=27	6.7	7.4	8.0	< 0.5	2.2	8.1	83	181	1,330
Plio-Pleistocene deposits (NHP), n=30	7.0	7.2	7.9	< .5	3.1	8.4	254	620	1,180
Ogallala Formation (NHP), n=114	7.0	7.6	8.4	< .5	7.4	9.5	79	401	904
Quaternary deposits (CHP), n=20	6.4	7.3	7.6	< .5	5.1	7.3	173	490	1,760
Ogallala Formation (CHP), n=67	7.3	7.6	8.3	< .5	6.3	8.5	335	509	1,640
Ogallala Formation (SHP), n=49	6.7	7.3	7.7	< .5	5.6	9.3	455	847	4,090

or equal to 0.5 mg/L); however, some samples had small dissolved-oxygen concentrations that are indicative of reducing conditions. Samples from the Sand Hills eolian deposits had the smallest median concentration of dissolved oxygen. As discussed in Chapter 2, those sediments apparently contain relatively large concentrations of electron-donor materials that are capable of generating oxygen-reducing conditions. Small dissolved-oxygen concentrations can have important implications with respect to the persistence of contaminants such as nitrate in ground water (Chapter 2). Each hydrogeologic unit also had a few large specific-conductance values, indicating that elevated concentrations of dissolved solids could be a drinking-water issue. Median values of specific conductance in water from the Ogallala Formation systematically increased from north to south in the High Plains (table 10).

Major Ions

Major dissolved ions in High Plains ground water generally are controlled by aquifer mineralogy and the residence time of ground water in the system. However, human activities can also affect the measured major-ion concentrations by changing recharge chemistry, by increasing vertical mixing in the aquifer, or by other processes (Chapters 1 and 2). Natural waters commonly are categorized by water type based on the relative percentage of major ions in the sample. Understanding the type of water produced from an aquifer can be valuable information when making decisions about treatment options related to drinking-water supplies. Water types in the Ogallala Formation are illustrated in the trilinear diagram in figure 59. The diagram highlights the variability in major-ion chemistry within the Ogallala Formation. Water samples from the NHP were predominantly of a calcium-bicarbonate type. In contrast, water samples from the SHP showed greater variability but could be broadly classified as mixed-ion type waters.

The composition of water samples from the CHP tended to be intermediate between those from the NHP and SHP. The shift in major-ion water types from north to south is related to a number of differences between the subregions, including differences in underlying bedrock geology, climate, aquifer mineralogy, land use/land cover, and hydrology (Chapters 1 and 2).

The major ions chloride and sulfate, as well as dissolved solids, have SMCLs that relate primarily to taste, hardness, and mineral precipitation or corrosive concerns. Maximum concentrations of chloride, sulfate, and dissolved solids in the water samples equaled or exceeded the SMCLs in several of the hydrogeologic units. Median concentrations, however, did not equal or exceed the SMCLs in any of the units, except for dissolved solids in the SHP Ogallala Formation domestic wells (table 11). The fact that water from the Ogallala Formation in the SHP had a median concentration of dissolved solids that exceeded the SMCL focuses some concern on water quality in the southern High Plains and highlights the general north-to-south increase in concentrations of several of the major ions. The Ogallala Formation in the SHP had smaller saturated thicknesses than many other units in the High Plains aquifer (fig. 11), and regional climate gradients in the High Plains support higher evapotranspiration rates in the south (figs. 2 and 3). Those conditions, coupled with the fact that some bedrock units underlying the SHP (and parts of the CHP) have ground water with large mineral contents that could contribute dissolved solids to the bottom of the aquifer (Chapter 2), contribute to the observed regional differences in major-ion chemistry. Superimposed on those largely natural factors are regional differences in land-use/land cover that affect recharge chemistry (Chapter 1).

The presence of individual major ions in domestic drinking water generally does not pose a specific serious health risk to humans. Fluoride is the only major ion in High Plains

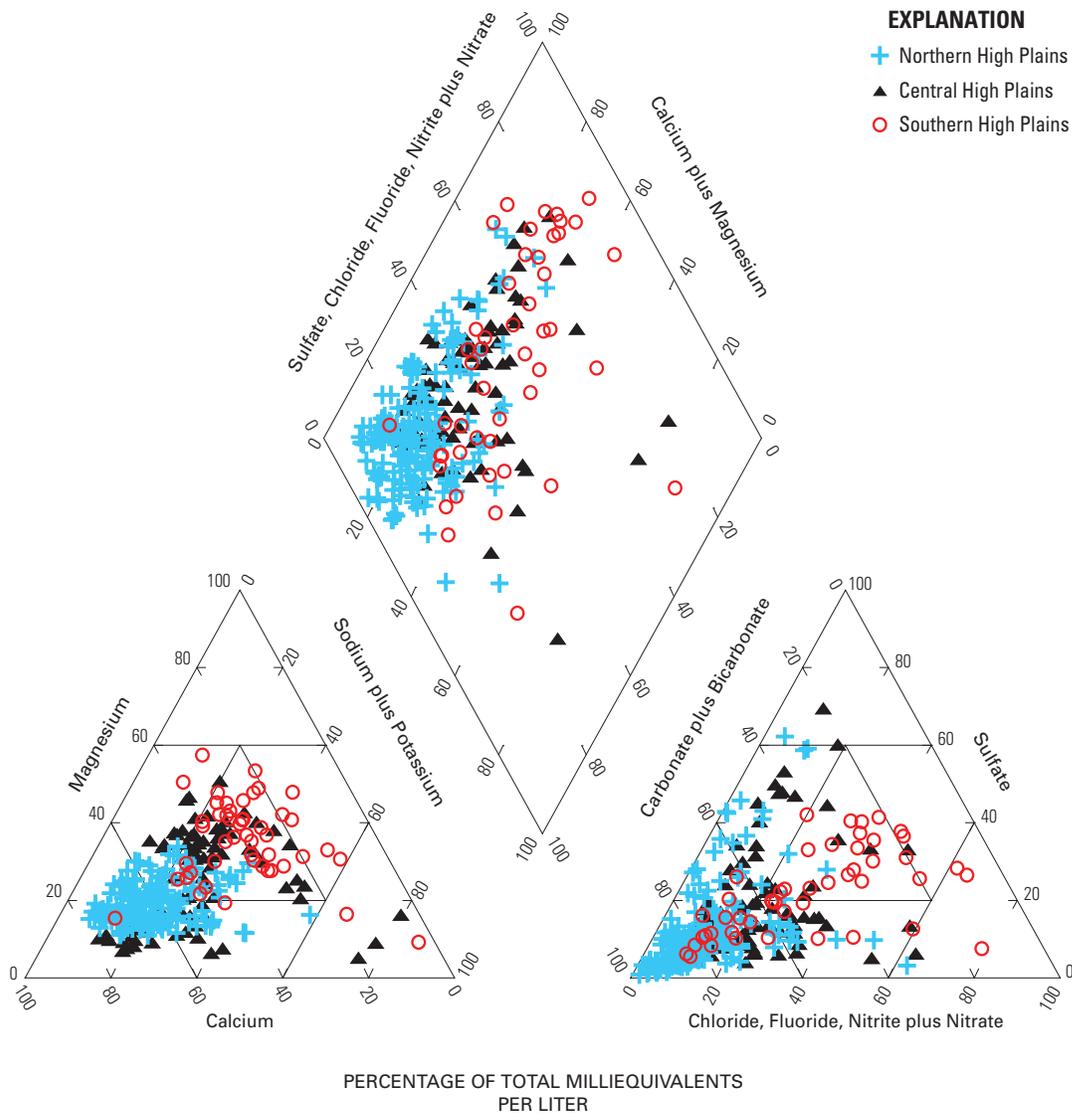


Figure 59. Trilinear diagram showing relations between major ions in water samples collected from domestic wells in the Ogallala Formation, by subregion.

Table 11. Summary of concentrations of selected major ions and dissolved solids in water samples from domestic, public-supply, and irrigation wells in the High Plains aquifer.

[MCL, Maximum Contaminant Level; SMCL, Secondary Maximum Contaminant Level; mg/L, milligrams per liter; Med., median concentration; Max., maximum concentration; %, percent; ≥, greater than or equal to; NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; n, number of samples]

Hydrogeologic unit	Chloride SMCL = 250 mg/L			Fluoride MCL = 4 mg/L SMCL = 2 mg/L			Sulfate SMCL = 250 mg/L			Dissolved solids SMCL = 500 mg/L		
	Med.	Max.	≥ SMCL (%)	Med.	Max.	≥ MCL (%)	Med.	Max.	≥ SMCL (%)	Med.	Max.	≥ SMCL (%)
Domestic wells												
Sand Hills eolian deposits (NHP), n=27	0.9	33.1	0.0	0.3	1.1	0.0	3.2	196	0.0	159	964	3.7
Plio-Pleistocene deposits (NHP), n=30	9.3	37.6	0	.3	.9	0	42.5	273	6.7	413	808	30
Ogallala Formation (NHP), n=114	4.3	127	0	.5	1.8	0	13.6	265	.9	279	695	3.5
Quaternary deposits (CHP), n=20	20.5	351	5.0	0.3	0.5	0	18.3	288	5.0	311	1,060	21
Ogallala Formation (CHP), n=67	16.5	259	1.5	1.1	4.0	1.5	37.9	430	4.5	328	1,060	14
Ogallala Formation (SHP), n=48	66.0	917	15	2.4	7.0	25	83.6	603	21	534	2,540	58
Public-supply wells												
Plio-Pleistocene deposits (NHP), n=9	9.9	34.2	0	.3	.4	0	45.0	223	0	371	670	11
Ogallala Formation (NHP), n=17	20.0	80.5	0	.7	1.8	0	26.0	980	6.7	339	959	18
Ogallala Formation (CHP), n=29	18.4	96.1	0	.7	2.4	0	37.9	523	3.4	312	991	17
Ogallala Formation (SHP), n=21	43.3	587	4.8	2.9	5.5	20	72.7	460	9.5	459	1,361	48
Irrigation wells												
Ogallala Formation (NHP), n=13	4.4	12.0	0	.6	1.9	0	17.0	26.0	0	274	408	0
Ogallala Formation (CHP), n=34	25.2	550	3.0	1.0	5.0	2.9	67.0	491	15	398	1,200	36
Ogallala Formation (SHP), n=30	53.7	735	10	2.4	6.0	20	74.8	817	10	478	2,550	48

ground water that has an enforceable standard (MCL). The fluoride MCL of 4.0 mg/L is designed to protect against possible bone disease resulting in pain, weakening, or tenderness of the bones (U.S. Environmental Protection Agency, 2006). Although fluoride is sometimes added to drinking water to promote strong teeth in children, larger fluoride concentrations can lead to mottling of teeth. The USEPA established an SMCL of 2.0 mg/L for fluoride in publicly supplied drinking water in an effort to reduce that undesirable cosmetic effect. Fluoride concentrations in water samples from all but two hydrogeologic units of the High Plains aquifer were below the SMCL and MCL concentrations (table 11). One of 67 samples in domestic wells from the CHP Ogallala Formation had a fluoride concentration of 4.0 mg/L, and fluoride concentrations in 7 of the samples equaled or exceeded the SMCL. Twelve of 48 samples from the SHP Ogallala Formation had fluoride concentrations that equaled or exceeded the MCL, and 30 samples had concentrations that equaled or exceeded the SMCL (Fahlquist, 2003). One sample from the SHP did not have fluoride data.

Most of the MCL exceedances for fluoride in the SHP were in the southern part of the study area. Ground water in that part of the SHP also had larger concentrations of dissolved solids than ground water in the northern part of the SHP. Nativ and Smith (1987) and Reeves and Miller (1978) suggested that elevated concentrations of dissolved solids in the southern part of the SHP could be related to leakage from saline lakes in that area and to upwelling of brackish ground water from underlying formations. It is not clear whether elevated fluoride concentrations in the southern SHP also were related to those processes. Saline lakes also are present in the westernmost part of the Sand Hills eolian deposits (Gosselin and others, 1994), and water from the one domestic well sampled in that area had a dissolved-solids concentration six times larger than the median concentration for samples from the Sand Hills (table 11). That sample did not have an elevated fluoride concentration, but it did have elevated concentrations of several major ions and trace elements such as arsenic and uranium.

Trace Elements and Radon

Trace elements are dissolved constituents that, because of their low solubility or small crustal abundances, generally occur in natural waters at concentrations less than 1 mg/L. Twenty-two trace elements were analyzed in water samples collected from the domestic wells. Nine of them have MCLs—antimony, arsenic, barium, beryllium, cadmium, chromium, selenium, thallium, and uranium (U.S. Environmental Protection Agency, 2006). Five of them have SMCLs—aluminum, iron, manganese, silver, and zinc (U.S. Environmental Protection Agency, 2006). All of those constituents have natural sources, but some also can be derived from anthropogenic sources such as pesticides (for example,

arsenic) or materials used for well construction and household plumbing (for example, aluminum and zinc).

Each of the 22 trace elements, with the exception of antimony, beryllium, cadmium, and silver, was detected at least once in the 307 water samples collected from domestic wells. Cobalt was in one sample—the same sample from the westernmost Sand Hills eolian deposits that had an elevated concentration of dissolved solids. Lead was detected in only five samples (at concentrations ranging from 1.18 to 4.55 $\mu\text{g/L}$)—in one sample from the NHP Ogallala Formation, in two samples from the CHP Ogallala Formation, and in two samples from the SHP Ogallala Formation. The detections of lead could be related to materials used in plumbing of the wells.

Of the more frequently detected trace elements, only aluminum, arsenic, iron, manganese, selenium, and uranium concentrations equaled or exceeded an MCL or SMCL. One sample from the Sand Hills eolian deposits had an aluminum concentration that exceeded the 50- $\mu\text{g/L}$ SMCL, and two samples from the Plio-Pleistocene deposits had selenium concentrations that exceeded the selenium MCL of 50 $\mu\text{g/L}$. Only arsenic, iron, manganese, and uranium concentrations equaled or exceeded drinking-water standards in samples from more than one of the assessed hydrogeologic units. Concentration data for those four trace elements are summarized in table 12, and the spatial distribution of arsenic concentrations is illustrated in figure 60. Arsenic and uranium concentrations in particular present a concern regarding human exposure because they were frequently detected in many of the hydrogeologic units.

Arsenic concentrations equaled or exceeded the 10- $\mu\text{g/L}$ MCL in at least one water sample from all hydrogeologic units with the exception of the CHP Ogallala Formation (table 12 and fig. 61). The Sand Hills eolian deposits and the SHP Ogallala Formation had detectable (greater than or equal to 1 $\mu\text{g/L}$) concentrations of arsenic in every domestic-well sample, and every other hydrogeologic unit had at least a 75-percent detection frequency. The sources of arsenic in the High Plains aquifer are not well understood. Gosselin and others (2006), Stanton and Qi (2007) and McMahon and others (2007) proposed that arsenic in NHP ground water was mainly related to natural sources such as marine shale in underlying bedrock units, volcanic ash deposits in the aquifer, iron oxide grain coatings on aquifer sediments, and pyrite in the aquifer. One or more of those potential natural sources is common in each of the hydrogeologic units, which may explain the nearly ubiquitous occurrence of arsenic in High Plains ground water. Saline lakes in the southern part of the SHP and in the westernmost Sand Hills eolian deposits also may be natural sources of arsenic (Scanlon, 2006; Stanton and Qi, 2007). In the SHP, all of the arsenic MCL exceedances occurred in the southern part of the study area (fig. 60), which is where the lakes are located. Similarly, the sample from the westernmost Sand Hills eolian deposits that had an elevated dissolved-solids concentration also had an arsenic concentration (55.6 $\mu\text{g/L}$) that is 11 times larger than the median arsenic concentration in the Sand Hills

Table 12. Summary of concentrations of selected trace elements in water samples from domestic, public-supply, and irrigation wells in the High Plains aquifer.

[NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; <, less than; ≥, greater than or equal to; Min., minimum; Med., median; Max., maximum; MCL, Maximum Contaminant Level; SMCL, Secondary Maximum Contaminant Level; %, percent; n, number of samples; µg/L, micrograms per liter; --, no data]

Hydrogeologic unit	Arsenic (MCL = 10 µg/L)			Iron (SMCL = 300 µg/L)			Manganese (SMCL = 50 µg/L)			Uranium (MCL = 30 µg/L)		
	Med.	Max.	≥MCL (%)	Med.	Max.	≥SMCL (%)	Med.	Max.	≥SMCL (%)	Med.	Max.	≥MCL (%)
Domestic wells												
Sand Hills eolian deposits (NHP), n=27	4.90	55.6	15	0	412	3.7	< 3	298	22	< 1	91.9	3.7
Plio-Pleistocene deposits (NHP), n=30	3.65	21.1	10	0	2,710	23	< 3	1,370	30	3.86	57.4	6.7
Ogallala Formation (NHP), n=114	5.80	15.9	6.1	0	460	.9	< 3	655	11	6.09	30.5	.9
Quaternary deposits (CHP), n=20	1.35	243	5.0	0	2,580	5.0	< 3	360	10	< 1	12.6	0
Ogallala Formation (CHP), n=67	2.10	9.7	0	0	38	0	< 3	85.9	1.5	7.24	30.7	1.5
Ogallala Formation (SHP), n=48	6.50	107	29	0	58	0	< 3	671	8.3	6.92	18.2	0
Public-supply wells												
Plio-Pleistocene deposits (NHP), n=8	7	15	12	--	--	--	--	--	--	4.4	7.7	0
Ogallala Formation (NHP), n=15	8	20	20	--	--	--	--	--	--	--	--	--
Ogallala Formation (CHP), n=26	2	9	0	--	--	--	--	--	--	9.9	17.8	0
Ogallala Formation (SHP), n=20	6.5	28	20	--	--	--	--	--	--	--	--	--
Irrigation wells												
Ogallala Formation (NHP), n=7	6	18	14	--	--	--	--	--	--	--	--	--
Ogallala Formation (CHP), n=20	2	5	0	--	--	--	29.8	72.0	13	--	--	--
Ogallala Formation (SHP), n=23	8	59	43	--	--	--	1.3	195	7.1	--	--	--

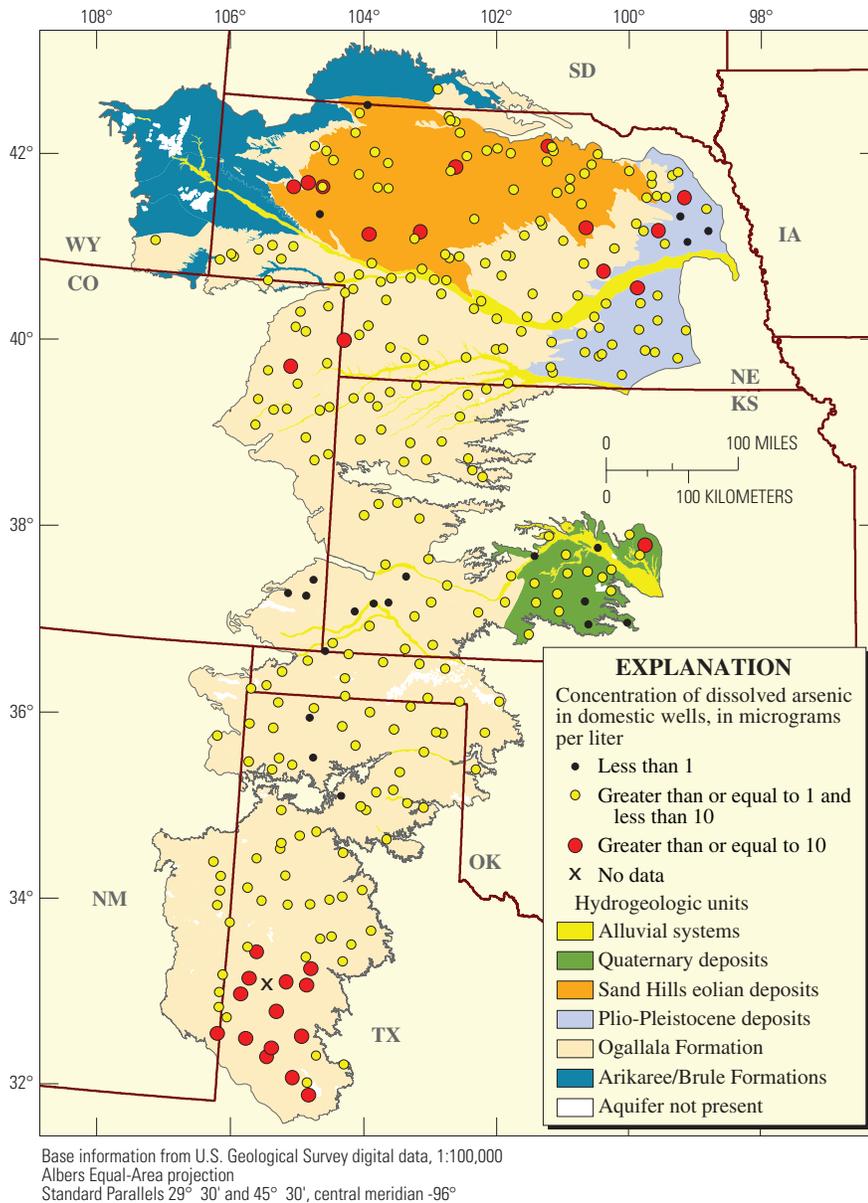


Figure 60. Arsenic concentrations in water samples collected from domestic wells in the High Plains aquifer.

(table 12). A possible anthropogenic source of arsenic in the SHP could be the historical use of arsenic acid as a cotton defoliant along with the application of arsenical pesticides or other arsenic-bearing fertilizers (Scanlon, 2006). However, based on a study of land-use/land-cover distribution, arsenic profiles in the unsaturated zone, and the correlation of arsenic with other naturally occurring elements like vanadium and fluoride in the SHP Ogallala Formation, Scanlon (2006) concluded that surface application of arsenic was not the primary source of arsenic to ground water in that area. As discussed in Chapter 2, an anthropogenic *process* that could produce elevated arsenic concentrations in ground water is the production of dissolved solids in agricultural recharge. An increase in dissolved solids in recharge could mobilize natural arsenic adsorbed to sediments (Welch and others, 2000; Smedley and Kinniburgh, 2002; Jurgens and others, 2005). More work is

needed to understand the sources of arsenic in the High Plains, particularly in the SHP where exceedances of the arsenic MCL occurred most frequently.

Uranium also is a trace element of potential concern due to its widespread occurrence in the High Plains aquifer (table 12). The concentration of uranium in at least one water sample from each of four hydrogeologic units equaled or exceeded the 30- $\mu\text{g/L}$ MCL (table 12), although the overall frequency of those exceedances was small. The single largest concentration (91.9 $\mu\text{g/L}$) was measured in the water sample from the westernmost Sand Hills eolian deposits that also had an elevated dissolved-solids concentration. Böhlke and others (2007), Stanton and Qi (2007), and McMahon and others (2007) discuss several additional sources for uranium in High Plains ground water, including uranium-enriched irrigation water from streams and phosphate fertilizers applied as agricultural

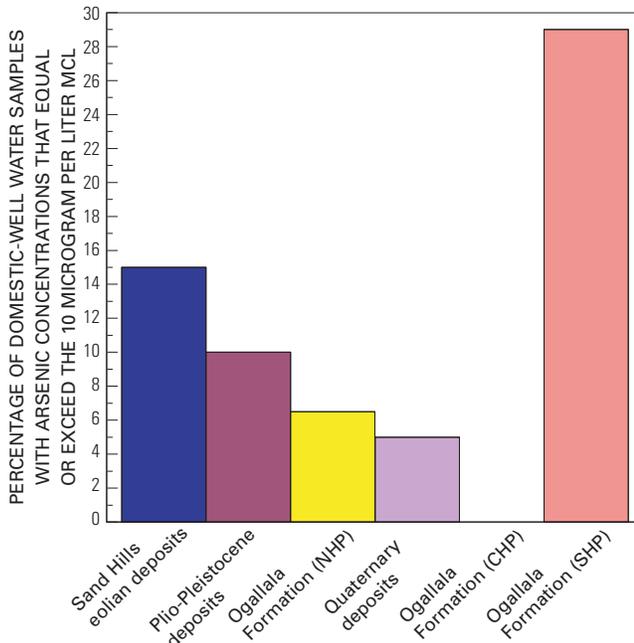


Figure 61. Percentage of water samples collected from domestic wells in the High Plains aquifer with arsenic concentrations that equalled or exceeded the 10-microgram per liter Maximum Contaminant Level (MCL), by hydrogeologic unit in the NHP, northern High Plains; CHP, central High Plains; and SHP, southern High Plains.

amendments. Furthermore, irrigation pumping in the alluvial systems and in the Ogallala Formation near streams can cause uranium-enriched surface water to enter the aquifer and mix with regional ground water (Chapter 2).

Iron and manganese are not regulated due to human health concerns but more from esthetic effects such as taste, color, and staining. Iron concentrations equalled or exceeded the 300- $\mu\text{g/L}$ SMCL in at least one sample from every hydrogeologic unit with the exception of the Ogallala Formation in the CHP and SHP (table 12). Manganese concentrations equalled or exceeded the 50- $\mu\text{g/L}$ SMCL in at least one sample from every hydrogeologic unit (table 12). The occurrence of elevated iron and manganese concentrations in ground water is typically associated with reducing conditions, and concentrations of dissolved iron and manganese in the High Plains aquifer were significantly larger in water containing less than 0.5 mg/L dissolved oxygen than in more oxygenated water ($p < 0.001$, Mann-Whitney test). Although ground water in the High Plains aquifer generally is well oxygenated (table

10), locally reducing conditions can develop where electron donors are relatively abundant, such as near clay/sand contacts, near buried soil horizons, or in ground-water/surface-water mixing zones.

Radon activities in ground water are not regulated, but one of two proposed standards would set the radon MCL at 300 picoCuries per liter (pCi/L) (U.S. Environmental Protection Agency, 2007). A summary of radon activities in water samples from the domestic wells is listed in table 13. Twenty-three to 79 percent of the samples had radon activities that were greater than or equal to 300 pCi/L. Radon activities in samples from the Ogallala Formation in the CHP and SHP exceeded 300 pCi/L most frequently, and activities in samples from the Sand Hills eolian deposits exceeded 300 pCi/L the least frequently.

Nitrate

Nitrite and nitrate are the only nitrogen species that were sampled as part of the HPGW study for which MCLs have been established. The MCLs for nitrite and nitrate are 1 and 10 mg/L as N, respectively (U.S. Environmental Protection Agency, 2006). None of the water samples from domestic wells had nitrite concentrations that equalled or exceeded the MCL, and only 7 of the 307 samples contained nitrite above its common assessment level of 0.01 mg/L as N. Thus, nitrite will not be discussed further in this chapter. Similarly, ammonium, which can be oxidized to nitrite or nitrate in the presence of oxygen, was detected above its common assessment level of 0.04 mg/L as N in only 22 of 307 samples. The maximum ammonium concentration in those 22 samples was 1 mg/L as N. Thus, ammonium will not be discussed further in this chapter either. Nitrate concentrations in this study were reported as nitrite plus nitrate, but because nitrite accounted

Table 13. Summary of radon activities in water samples from domestic wells in the High Plains aquifer.

[NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; \geq , greater than or equal to; %, percent; n, number of samples; pCi/L, picoCuries per liter]

Hydrogeologic unit	Radon activity (pCi/L)		
	Median	Maximum	≥ 300 pCi/L (%)
Sand Hills eolian deposits (n=27)	230	390	23
Plio-Pleistocene deposits (n=30)	280	900	45
Ogallala Formation, NHP (n=114)	320	1,640	58
Quaternary deposits (n=20)	265	590	40
Ogallala Formation, CHP (n=67)	470	2,950	79
Ogallala Formation, SHP (n=48)	430	1,450	70

for less than 1 percent of the reported nitrite plus nitrate concentration, those summed concentrations will be referred to as nitrate concentrations for the remainder of this chapter.

Nitrate in drinking water is a human health concern because of its potential to cause methemoglobinemia (blue-baby syndrome) in infants, a sometimes fatal illness related to impairment of the oxygen-carrying ability of the blood (U.S. Environmental Protection Agency, 2006). Other HPGW studies summarized in Chapters 1 and 2 indicate that natural background nitrate concentrations in the High Plains aquifer are between about 2.5 and 4.0 mg/L as N. For the purposes of this chapter, nitrate concentrations greater than 4.0 mg/L as N are considered to have some component of anthropogenic nitrate.

A summary of nitrate concentrations in water samples collected from domestic wells in the High Plains aquifer is provided in table 14, and the spatial distribution of nitrate concentrations is illustrated in figure 62. As with several of the other water-quality properties and constituents, regional differences in nitrate concentrations are apparent. Hydrogeologic units in the CHP and SHP had fewer samples with concentrations less than the common assessment level of 0.06 mg/L as N and more samples with concentrations greater than 4.0 and 10 mg/L as N than units in the NHP. That spatial pattern in nitrate concentrations is opposite to the pattern that was observed for nitrate concentrations in recently recharged water beneath irrigated cropland, where concentrations decreased significantly from north to south in the High Plains (table 6 and fig. 19; Chapter 1). Some of the small nitrate concentrations in domestic-well samples from hydrogeologic units to the north may be attributed to denitrification in those areas where dissolved-oxygen concentrations were also small (Chapter 2). In the Sand Hills eolian deposits and Plio-Pleistocene deposits of the NHP, 22 and 33 percent, respectively, of domestic-well samples had dissolved-oxygen concentrations less than 0.5 mg/L (table 14), which is considered to be the general threshold value for the onset of denitrification (Chapelle and others, 1995). In the NHP Ogallala Formation, 8.3 percent of the samples had dissolved-oxygen concentrations less than 0.5 mg/L. In contrast, only 1.3 to 10 percent of the samples from the CHP and SHP had dissolved-oxygen concentrations less than 0.5 mg/L. Some other important factors to consider in explaining the spatial pattern in nitrate concentrations are well-screen depth below the water and the amount of vertical mixing in the aquifer caused by pumping. Nitrate concentrations in areas of the aquifer that were not heavily pumped are expected to decrease substantially with depth below the water table because deeper water may be several thousand years old (figs. 43 and 45A, Chapter 2). Intensive well pumping for irrigation or public supply, however, can vertically mix water and accelerate the movement of recent recharge, which presumably contains relatively large nitrate concentrations, deeper into the aquifer (fig. 45B, Chapter 2). That mixing phenomenon is most pronounced in areas with small saturated thickness, high density of irrigation or public-supply wells, and a lack of fine-grained confining layers to isolate deep water-bearing layers from surface contamination.

In general, those conditions appear to be more common in the SHP than the NHP. An additional factor to consider is depth to water below land surface and chemical transit time to the water table (Chapter 1). All of the domestic-well samples that exceeded the nitrate MCL were from wells where the depth to water was less than 200 ft. This observation is consistent with the findings reported by McMahon (2000) in which the effects of irrigated agriculture on ground-water quality in the High Plains aquifer were generally more pronounced in areas with depth to water of less than 200 ft.

Domestic wells in the High Plains aquifer generally supplied high-quality drinking water with respect to nitrate. Only the Quaternary deposits in the CHP and the SHP Ogallala Formation had more than 10 percent of their water samples equal or exceed the nitrate MCL (table 14). None of the water samples from the Plio-Pleistocene deposits in the NHP equaled or exceeded the MCL. Overall, only 5 percent of the samples from domestic wells had nitrate concentrations that equaled or exceeded the MCL.

Pesticides

Each water sample was analyzed for at least 47 pesticide compounds, 44 of which were common to all 307 samples. This section of the chapter focuses on those 44 compounds so that comparisons between the hydrogeologic units can be made. Information about the other compounds is available in the reports by Pope and others (2001), Becker and others (2002), Fahllquist (2003), and Stanton and Qi (2007). At least one of the 44 pesticide compounds was detected in each of the assessed hydrogeologic units, with detection frequencies ranging from 10 to 40 percent (table 15). The spatial distribution of those detections is illustrated in figure 63. The largest detection frequencies occurred in the Plio-Pleistocene deposits, Quaternary deposits, and SHP Ogallala Formation (figs. 63 and 64). In the case of the Plio-Pleistocene and Quaternary deposits, relatively wet climatic conditions (fig. 3) may have supported faster recharge rates compared to drier regions of the High Plains. Depths to water in the Quaternary deposits were also relatively small (table 15), which could result in shorter pesticide-compound transit times to the water table than in areas with larger depths to water (Chapter 1). The common occurrence of pesticide compounds in the SHP (table 15), despite the dry climate (fig. 3) and large depths to water (table 15), may be related to the relatively shallow well-screen depths below the water table (table 15) and possibly focused recharge through playas that are common in the SHP (Scanlon and Goldsmith, 1997; Chapter 1). The smallest detection frequencies occurred in the Sand Hills eolian deposits and in the NHP Ogallala Formation. The small detection frequency in the Sand Hills is consistent with the overall lack of agriculture in that area (fig. 5A). The small detection frequency in the NHP Ogallala Formation may be due in part to relatively large well-screen depths below the water table in that unit. The median screen depth below the water table in the NHP

Table 14. Summary of concentrations of nitrate in water samples from domestic, public-supply, and irrigation wells in the High Plains aquifer.

[NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; <, less than; >, greater than; ≥, greater than or equal to; 0.06, common assessment level; n, number of samples; *, not all wells had depth information; mg/L as N, milligrams per liter as nitrogen; --, no data]

Hydrogeologic unit	Nitrate concentration (mg/L as N)			Percentage of samples with nitrate concentra- tions < 0.06 mg/L as N	Percentage of samples with nitrate concentra- tions > 4 and < 10 mg/L as N	Percentage of samples with nitrate concentra- tions ≥ 10 mg/L as N	Median depth to water table, in feet	Median depth of well- screen midpoint below wa- ter table, in feet	Percentage of samples with dis- solved oxygen concentra- tions < 0.5 mg/L
	Minimum	Median	Maximum						
Domestic wells									
Sand Hills eolian deposits (NHP), n=27	< 0.06	0.73	11.0	22	15	3.7	18	77	22
Plio-Pleistocene deposits (NHP), n=30	< .06	1.92	6.65	23	20	0	90	83	33
Ogallala Formation (NHP), n=114	< .06	2.21	11.6	6.1	14	2.6	77	100	8.3
Quaternary deposits (CHP), n=20	< .06	6.16	14.8	5.0	50	15	30	45	10
Ogallala Formation (CHP), n=67	.85	2.29	20.3	0	19	4.5	158	76	1.3
Ogallala Formation (SHP), n=49	.18	2.94	19.5	0	31	12	134	50	2.1
Public-supply wells									
Plio-Pleistocene deposits (NHP), n=11	< .06	4.34	12.7	27	45	9.1	--	--	--
Ogallala Formation (NHP), n=26	< .06	2.70	15.4	3.8	27	7.7	--	--	--
Ogallala Formation (CHP), n=29	.81	2.74	8.94	0	17	0	--	--	--
Ogallala Formation (SHP), n=28	.46	2.89	9.02	0	28	0	--	--	--
Irrigation wells									
Plio-Pleistocene deposits (NHP), n=8	1.4	3.3	6.7	0	38	0	84*	74*	--
Ogallala Formation (NHP), n=17	1.2	2.1	18.3	0	5.9	5.9	106*	98*	--
Ogallala Formation (CHP), n=34	1.2	2.6	19.0	0	26	5.9	196*	90.5*	--
Ogallala Formation (SHP), n=28	0.5	2.6	11.4	0	18	3.6	158*	38*	--

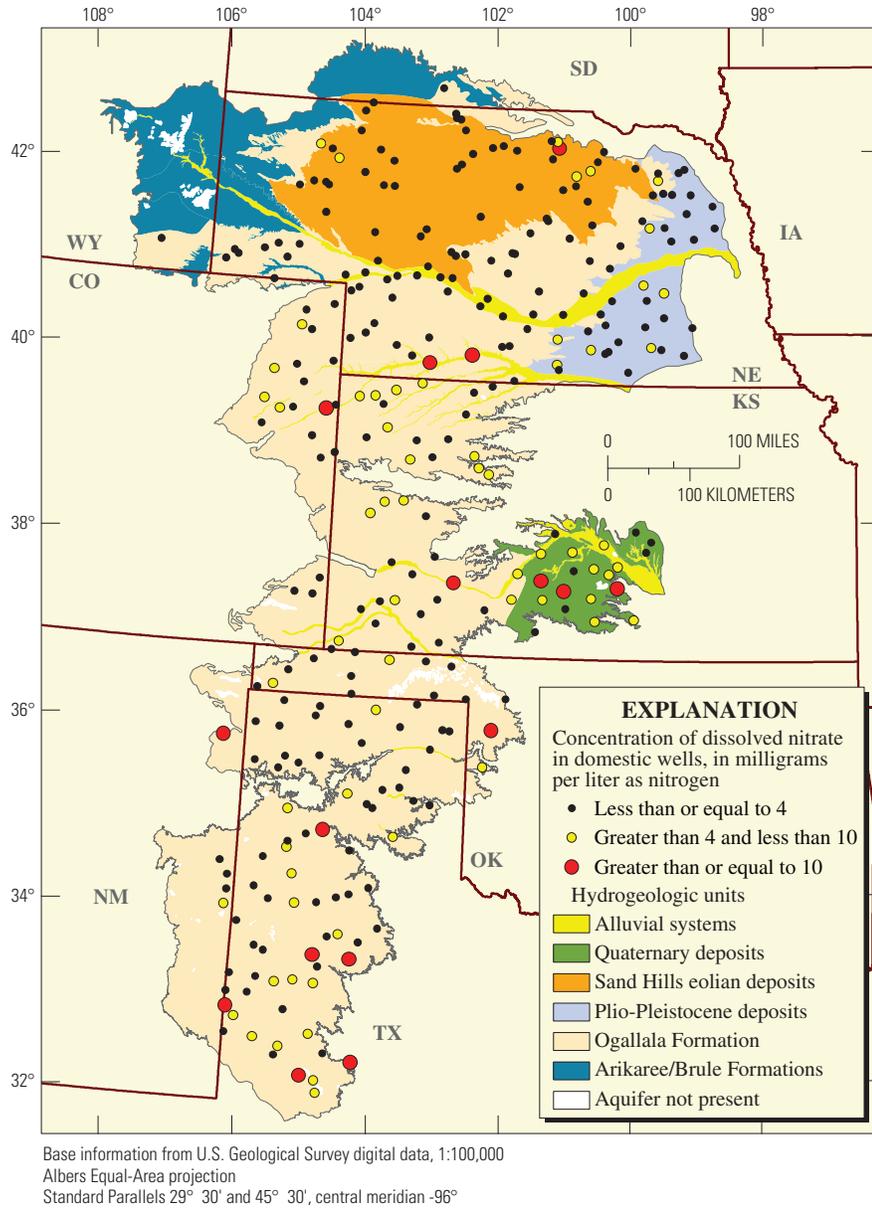


Figure 62. Nitrate concentrations in water samples collected from domestic wells in the High Plains aquifer.

Table 15. Summary of pesticide compound detections in water samples from domestic and public-supply wells in the High Plains aquifer. For domestic wells, only those compounds common to all hydrogeologic units were compared. For public-supply wells, only data for atrazine and deethylatrazine were available for all samples.

[NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; $\mu\text{g/L}$, micrograms per liter; MCL, Maximum Contaminant Level; n, number of samples; --, no data]

Hydrogeologic unit	Detection frequency, in percent	Range of reported concentrations, $\mu\text{g/L}$	Pesticide compound with largest concentration	Number of MCL exceedances	Median depth to water table, in feet	Median depth of well-screen midpoint below water table, in feet
Domestic wells						
Sand Hills eolian deposits (NHP), n=27	15	0.006 – 0.190	Deethylatrazine	0	18	77
Plio-Pleistocene deposits (NHP), n=30	30	.007 – .232	Atrazine	0	90	83
Ogallala Formation (NHP), n=108	10	.006 – 1.38	Atrazine	0	77	100
Quaternary deposits (CHP), n=20	40	.006 – .179	Atrazine	0	30	45
Ogallala Formation (CHP), n=67	19	.006 – 1.88	Deethylatrazine	0	158	76
Ogallala Formation (SHP), n=49	33	.007 – .234	Deethylatrazine	0	134	50
Public-supply wells						
Plio-Pleistocene deposits (NHP), n=9	78	.03 – .31	Atrazine	0	--	--
Ogallala Formation (NHP), n=5	60	.04 – .13	Atrazine	0	--	--
Ogallala Formation (CHP), n=13	31	.02 – 1.23	Atrazine	0	--	--
Ogallala Formation (SHP), n=6	17	.03	Atrazine	0	--	--

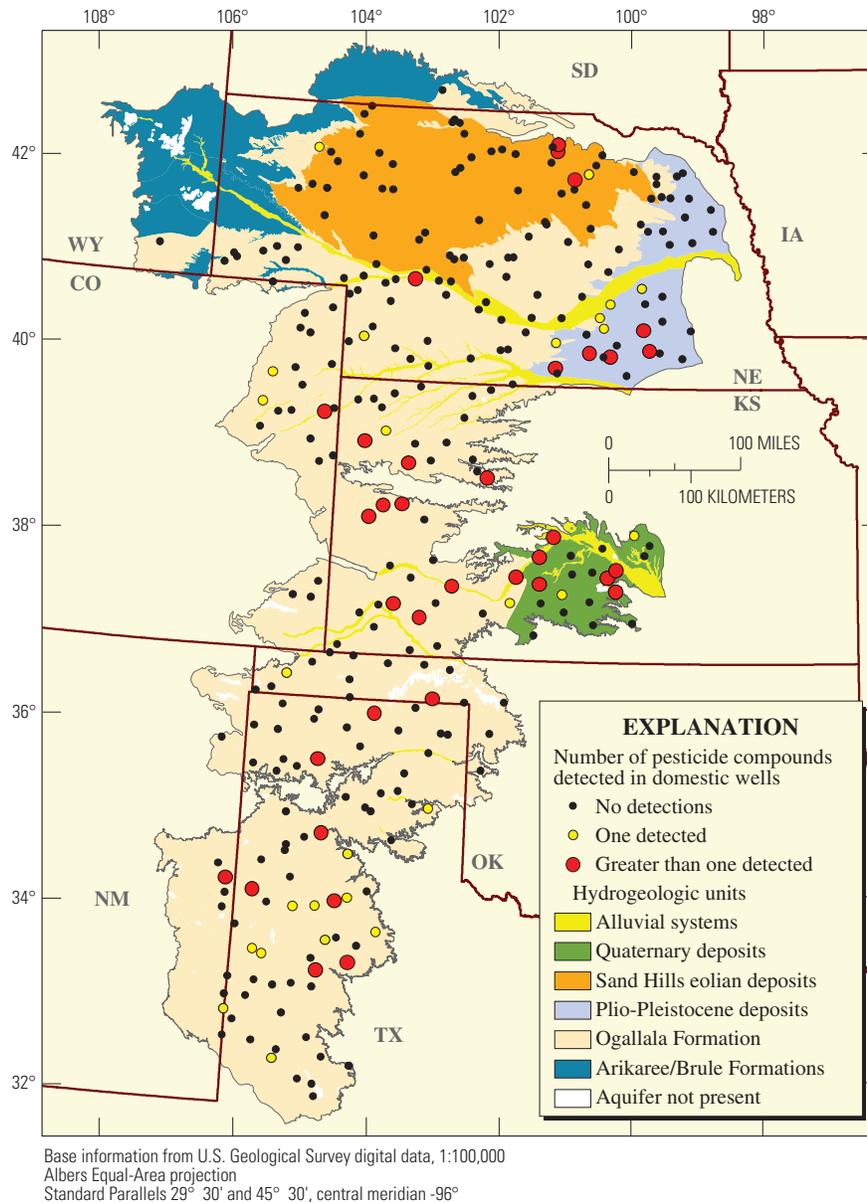


Figure 63. Pesticide-compound detections in water samples collected from domestic wells in the High Plains aquifer.

Ogallala Formation was 100 ft compared to median depths of 45 to 83 ft in the other units (table 15). Overall, pesticide-compound concentrations decreased substantially with depth below the water table in the High Plains aquifer (fig. 43), so water from deeper wells generally is expected to have fewer pesticide detections than water from shallower wells (Chapter 2). In general, results from this assessment indicate that the occurrence of pesticide compounds in water from domestic wells was dependent on land use/land cover, climate, depth

to water, and well-screen depth below the water table, among other factors.

All of the pesticide-compound concentrations detected were smaller than 2 µg/L, and none of them equaled or exceeded an MCL (table 15), although only 2 of the 12 detected compounds had MCLs. Of the 12 detected compounds, 8 are herbicides and 4 are insecticides (fig. 64). Atrazine, a commonly used corn herbicide, or its degradation product deethylatrazine were the most frequently detected compounds in each of the hydrogeologic units. Furthermore,

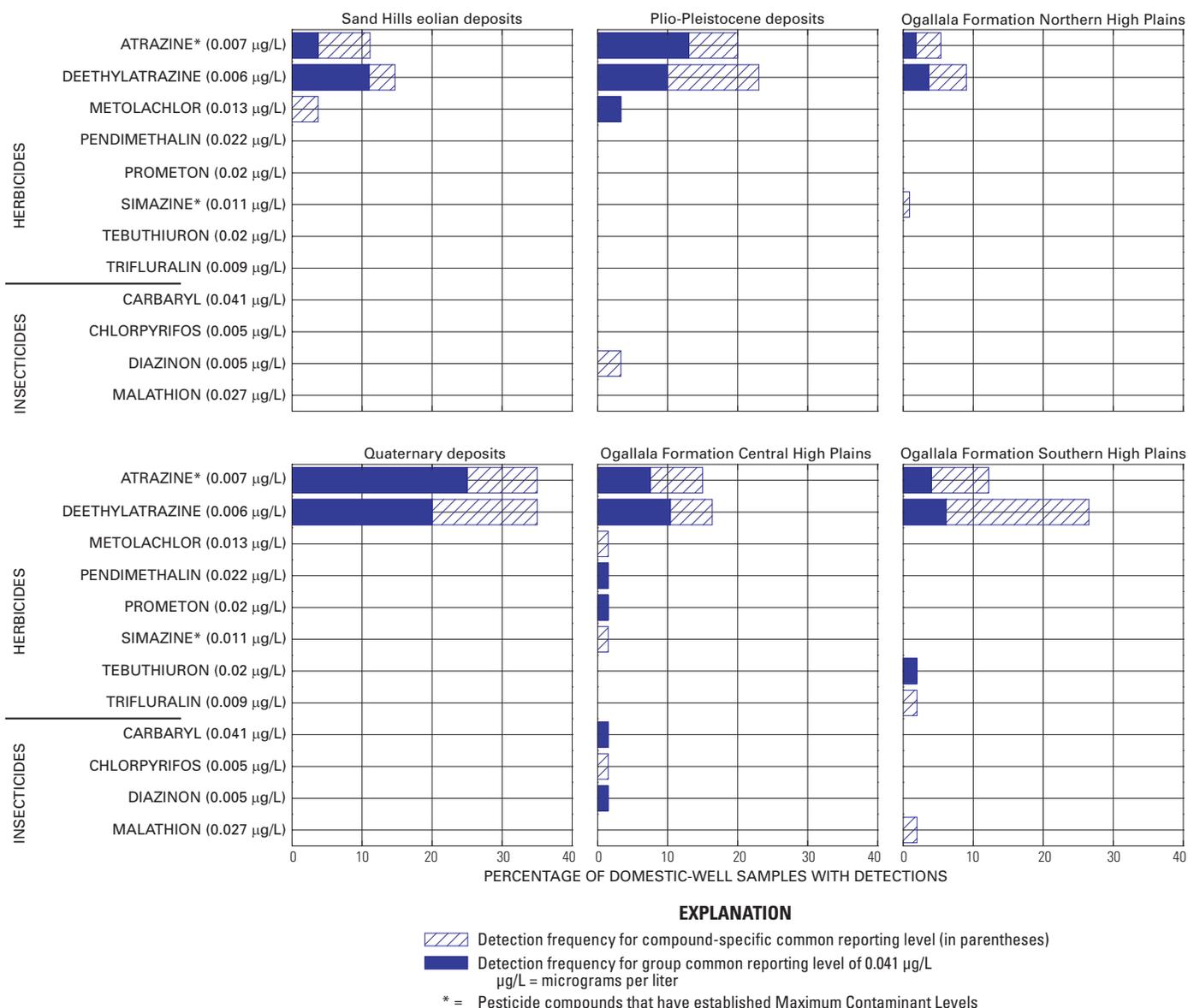


Figure 64. Pesticide compounds detected most frequently in water samples collected from domestic wells in the High Plains aquifer. Only those compounds common to all hydrogeologic units were compared.

one or the other of those compounds had the largest concentration in each hydrogeologic unit (table 15). Two of the compounds detected only in the SHP Ogallala Formation, malathion and trifluralin, are commonly used cotton insecticides and herbicides, respectively. Several of the compounds detected in water samples from the domestic wells also were detected in water from the agricultural land-use study wells nested within the major-aquifer studies (figs. 23 and 64), indicating that irrigated cropland probably was a source for at least some of the pesticide compounds detected in water samples from the domestic wells. Nine of the 12 most frequently

detected pesticide compounds in High Plains ground water were among the 14 most commonly detected compounds in the Nation's ground water underlying agricultural land-use areas (Gilliom and others, 2006). That group of compounds is characterized by extensive agricultural use and relatively high mobility and (or) persistence in the environment.

About 4 to 30 percent of the samples contained at least two pesticide compounds (fig. 65). The largest mixture contained seven compounds. The most common compounds in those mixtures were atrazine and deethylatrazine. Like atrazine, several of the other measured pesticide compounds,

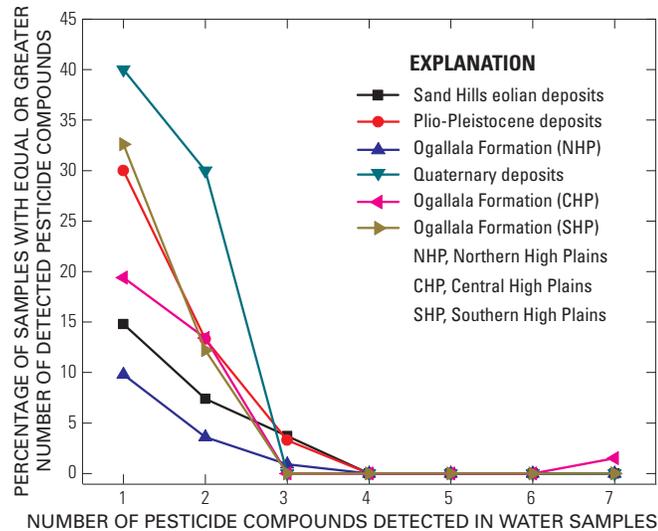


Figure 65. Frequency of occurrence of pesticide-compound mixtures in water samples collected from domestic wells in the High Plains aquifer based on a set of pesticide compounds common to all of the hydrogeologic units.

such as alachlor and metolachlor, have degradation products that have been detected in ground water (Gilliom and others, 2006). Degradation products for those compounds, however, were not among the group of 44 compounds analyzed in all of the samples. Thus, it is possible that the mixtures could be more complex than indicated in figure 65. Understanding the composition of pesticide-compound mixtures in drinking water is important because little is known about their health effects. Although the pesticide content of water from the domestic wells was small, better understanding is still needed related to the health effects of pesticide compounds that do not have MCLs and of pesticide-compound mixtures.

Volatile Organic Compounds

Each water sample was analyzed for a common set of 85 volatile organic compounds (VOCs), nine of which were detected at concentrations above common assessment levels (fig. 66). The spatial distribution of those detections is illustrated in figure 67. All detected concentrations were small, and none exceeded an MCL (table 16). Of the nine detected VOCs, 3 were trihalomethanes and 6 were solvents. The fuel hydrocarbons toluene, styrene, and 1,2,4-trimethylbenzene were detected in a few environmental samples; however, because they were also detected at similar concentrations in field-blank samples, they were not included in figure 66. Methyl *tert*-butyl ether (MTBE), a fuel hydrocarbon that is one of the most frequently detected VOCs in the Nation's ground water (Zogorski and others, 2006), was not detected in water from any of the domestic wells. Of the 16 samples

that contained a detectable VOC, only 3 of them contained more than one compound. One sample contained two VOCs: chlorobenzene and chloroform. Two samples contained three VOCs: *o*-dichlorobenzene, *p*-dichlorobenzene, chloroform and bromoform, chloroform, bromodichloromethane. As with pesticide mixtures, very little is known about the health effects of VOC mixtures at small concentrations.

The trihalomethane chloroform was the only VOC to be detected in more than two hydrogeologic units, and it was the most commonly detected VOC in three of them (fig. 66). That finding is consistent with data for domestic-well samples from across the Nation that show chloroform as being the most commonly detected VOC in water from that well type (Zogorski and others, 2006). Chloroform and other trihalomethanes such as bromoform and bromodichloromethane (fig. 66) are commonly produced during the chlorination of water and wastewater (Zogorski and others, 2006), implying that chlorinated water may be a primary source of those trihalomethanes in High Plains ground water. For example, the compounds in one of the two samples that contained a mixture of three VOCs were all trihalomethanes, indicating that sample probably contained chlorinated water. Chloroform also is used in industry as a solvent and in the manufacture of refrigerants, among other uses. Chloroform and other trihalomethanes may be produced naturally in soils and marine environments as well (Hoekstra and others, 1998; Zogorski and others, 2006).

The relatively common occurrence of chloroform in the domestic-well samples may be related in part to redox conditions in the aquifer. Chloroform and the other trihalomethanes, as well as several of the other halogenated VOCs detected in samples from the domestic wells, are relatively stable in oxic ground water. In contrast, many of the fuel hydrocarbons, such as benzene, toluene, and MTBE, are relatively unstable in oxic ground water. These redox relations, combined with the fact that water from the domestic wells was predominantly oxic (table 10), may help to explain the more common occurrence of trihalomethanes in water from the domestic wells in comparison to the fuel hydrocarbons.

Overall, the detection frequency of VOCs (5.2 percent) was about four times smaller than the detection frequency of pesticides (20 percent) in water samples from the domestic wells. That observation is consistent with the predominance of agriculture over urban land uses in the High Plains (fig. 5A), assuming that most VOC sources occur in urban settings. Zogorski and others (2006) reported positive associations between several of the commonly detected VOCs in the Nation's ground water and the density of urban land. Other positive associations were observed between VOC detections and density of septic systems (potential VOC source), wet climates (increased recharge), and shallow depths to water (shorter transit times to the water table).

The occurrence of VOCs, as well as anthropogenic nitrate and pesticide compounds, in water samples from some of the domestic wells would not be expected based on ground-water age gradients in undisturbed areas of the aquifer. For example, in areas of the Ogallala Formation that were not heavily

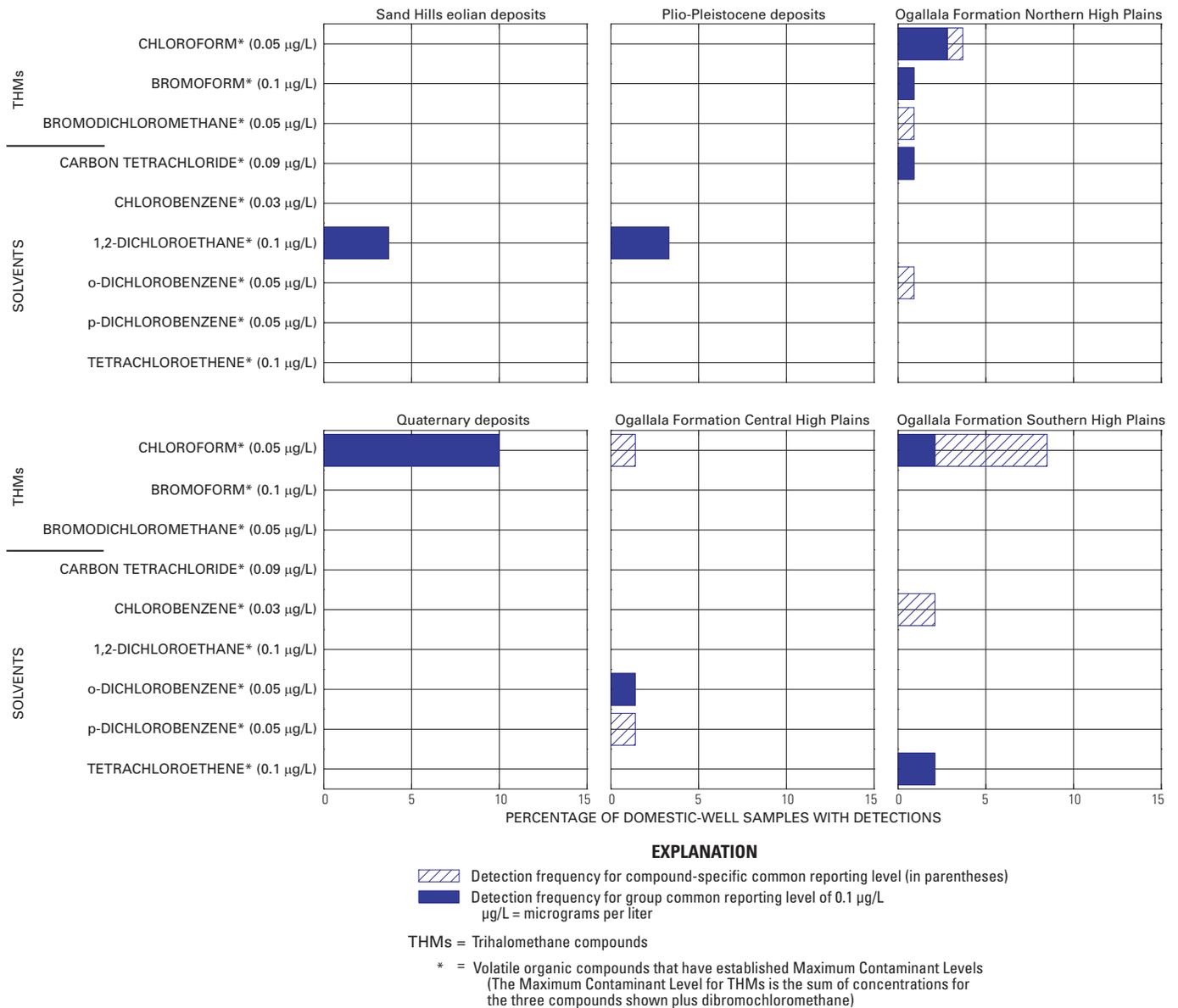


Figure 66. Volatile organic compounds detected most frequently in water samples collected from domestic wells in the High Plains aquifer. Only those compounds common to all hydrogeologic units were compared.

pumped for irrigation water or for public supply, ground-water ages increased rapidly with depth below the water table so that ages were more than 50 years (approximate maximum age of modern agricultural recharge) within 20 to 30 ft of the water table (fig. 45A, Chapter 2). Such steep age gradients are consistent with the small recharge rates in natural rangeland settings overlying the Ogallala Formation (Chapter 1). Thus, anthropogenic nitrate, pesticide compounds, and VOCs would not be expected in Ogallala ground water deeper than about 20 to 30 ft below the water table if vertical age gradients

throughout the formation were similar to those measured in parts of the formation that were not heavily pumped (fig. 45A). Samples from wells screened more than 30 ft below the water table in the Ogallala Formation represented 62 to 88 percent of the samples with anthropogenic nitrate (more than 4 mg/L as N), 77 to 100 percent of the samples with pesticide-compound detections, and 83 to 100 percent of the samples with VOC detections. This finding indicates that processes other than natural recharge probably were important for moving those chemicals vertically downward in the aquifer. Two likely

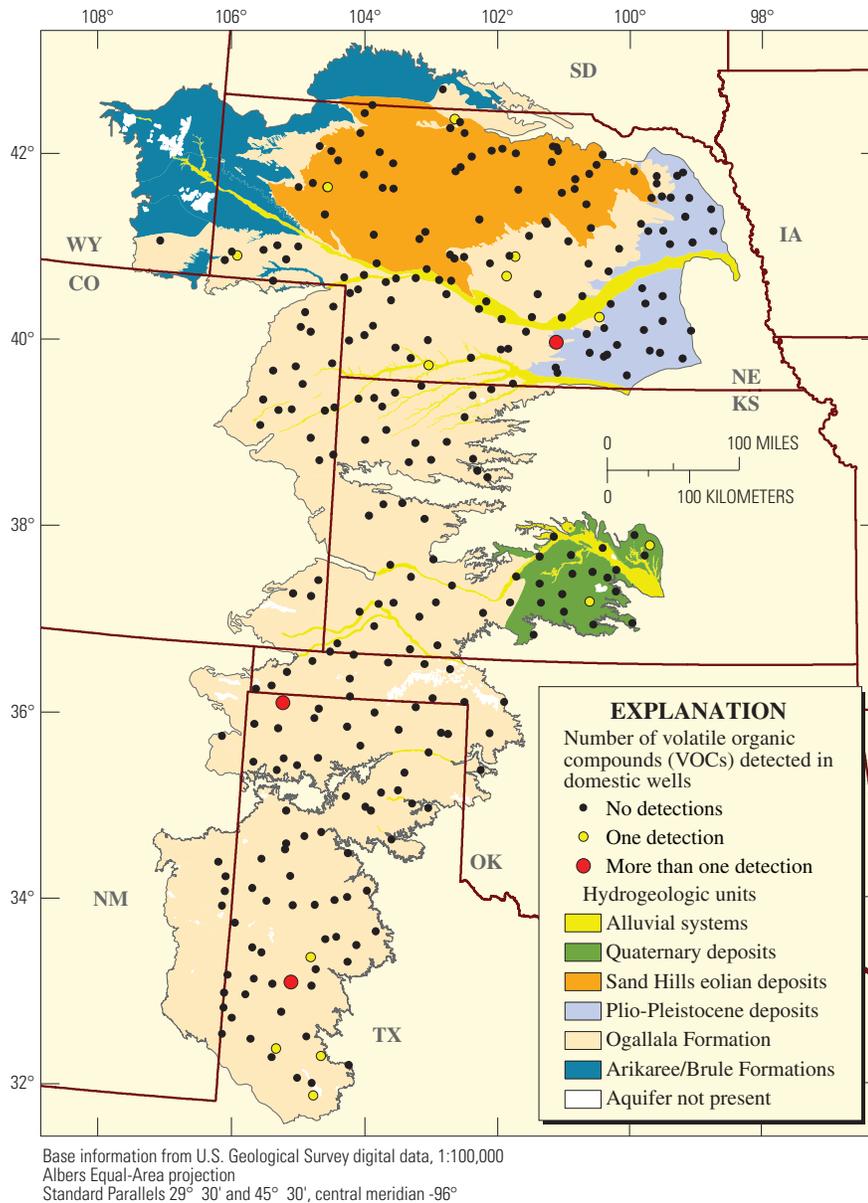


Figure 67. Volatile organic compound detections in water samples collected from domestic wells in the High Plains aquifer.

processes are increased recharge associated with irrigated agriculture (Chapter 1) and vertical mixing in the aquifer caused by well pumping or by leakage down long well screens (Chapter 2). Thus, anthropogenic activity was not only a source of contaminants to the water table, but it also appears to have enhanced their transport once they were in the aquifer. Irrigation and public-supply wells are considered to be more important than domestic wells in vertically redistributing contaminants in the aquifer because they are pumped at higher volumes and for longer periods of time, and generally have

longer well screens (Bruce and Oelsner, 2001; Landon and others, 2007; Clark and others, 2007).

Comparison of Overall Water Quality in the Hydrogeologic Units

Overall water quality from a drinking-water standpoint in the hydrogeologic units was assessed by comparing percentages of domestic-well samples in each unit that had at least

Table 16. Summary of volatile organic compound detections in water samples from domestic and public-supply wells in the High Plains aquifer. For domestic wells, only those compounds common to all hydrogeologic units were compared. For public-supply wells, only data for chloroform were available for all samples.

[NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; µg/L, micrograms per liter; MCL, Maximum Contaminant Level; n, number of samples; --, no data]

Hydrogeologic unit	Detection frequency, in percent	Range of reported concentrations, µg/L	Volatile organic compound with largest concentration	Number of MCL exceedances	Median depth to water table, in feet	Median depth of well-screen midpoint below water table, in feet
Domestic wells						
Sand Hills eolian deposits (NHP), n=27	3.7	0.8	1,2-Dichloroethane	0	18	77
Plio-Pleistocene deposits (NHP), n=30	3.3	.2	1,2-Dichloroethane	0	90	83
Ogallala Formation (NHP), n=108	5.3	.05 – .38	Bromoform	0	77	100
Quaternary deposits (CHP), n=20	10	.18 – 0.25	Chloroform	0	30	45
Ogallala Formation (CHP), n=67	1.5	.05 – 1.5	o – Dichlorobenzene	0	158	76
Ogallala Formation (SHP), n=48	10	.03 – 1.5	Chloroform	0	134	50
Public-supply wells						
Plio-Pleistocene deposits (NHP), n=8	0	--	--	0	--	--
Ogallala Formation (NHP), n=4	75	.13 – 3.0	Chloroform	0	--	--
Ogallala Formation (CHP), n=9	22	.06 – .50	Chloroform	0	--	--

one exceedance of an MCL or SMCL. The SHP Ogallala Formation had the poorest water quality on the basis of this comparison, followed by the Quaternary and Plio-Pleistocene deposits (fig. 68). The Ogallala Formation in the NHP and CHP had the best water quality. Most SMCL exceedances were for chloride, fluoride, iron, manganese, sulfate, and dissolved solids (tables 11 and 12). Most MCL exceedances were for arsenic, fluoride, nitrate, and uranium (tables 11, 12, and 14). The observed water-quality differences between hydrogeologic units are attributed to several source and transport factors such as irrigation density, nitrogen and pesticide applications, climate, depth to water, screen depth below the water table, redox conditions, and mixing, as previously discussed in this chapter.

Radon activities were not included in this assessment because no MCL has been established for radon (though an MCL of 300 pCi/L has been proposed), and concentrations of pesticide compounds and VOCs were not included because none of them exceeded a drinking-water standard. Moreover, very little is known about the health effects of low-concentration mixtures of pesticide compounds and VOCs in drinking water. If samples containing a radon activity greater than or equal to the proposed standard of 300 pCi/L, a pesticide-compound detection, or a VOC detection are included in the assessment of overall water quality, then the range in percentages of affected samples increases from 22 to 88 percent (fig. 68) to 59 to 94 percent. According to this assessment, water quality would increase according to: SHP Ogallala Formation, Plio-Pleistocene deposits, CHP Ogallala Formation,

Quaternary deposits, NHP Ogallala Formation, and the Sand Hills eolian deposits.

Water quality in the High Plains aquifer also was compared to that in other principal aquifers of the United States. Water-quality comparisons were made for some of the most commonly detected inorganic and organic constituents in the Nation’ ground water (Nolan and Stoner, 2000; Lapham and others, 2005; Gilliom and others, 2006; Zogorski and others, 2006) (Appendix 2).

Quality of Water from Public-Supply Wells

The HPGW study sampled only 23 public-supply wells in the NHP and CHP; therefore, additional data from public-supply wells sampled by other agencies were added to the database to improve the spatial coverage and increase overall sample numbers. The final dataset consisted of 101 wells located in the Plio-Pleistocene deposits and the Ogallala Formation (fig. 69). The data used for analysis of public-supply wells were limited to samples collected since 1990 to be comparable with the domestic-well data. Furthermore, only samples collected prior to treatment and prior to mixing in distribution systems were used in this analysis. Those data constraints limited the number of available samples that could be added to the database. Data from the other agencies

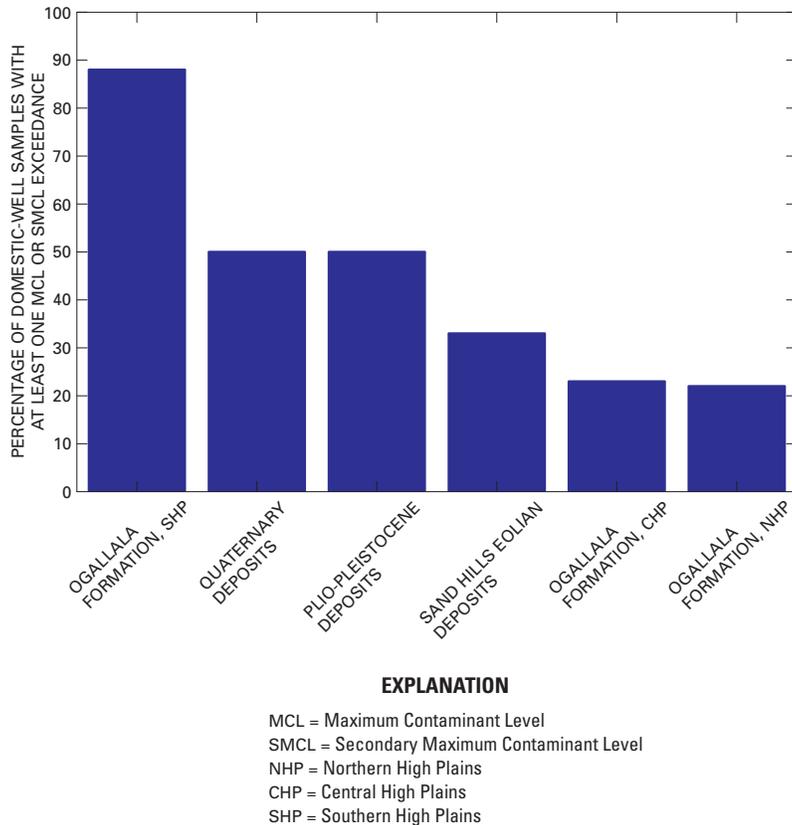


Figure 68. Comparison of overall water quality in assessed hydrogeologic units of the High Plains aquifer based on water samples collected from domestic wells.

also were limited in the number of constituents analyzed, and the laboratory reporting levels for chemical constituents often were larger than those for the domestic-well samples. Because of those limitations, the following discussion focuses only on major ions, dissolved solids, arsenic, and nitrate. Data summaries for other constituents are presented in tables 11 through 16 but are not discussed further.

The type of water produced from public-supply wells in the Ogallala Formation is summarized in figure 70. Samples from the NHP were predominantly calcium-bicarbonate or calcium-magnesium-bicarbonate type waters. Although many of the CHP samples also were calcium-magnesium-bicarbonate type waters, a number of the samples from the CHP transitioned to mixed cation-bicarbonate-chloride waters. The SHP samples were primarily mixed cation waters with increasing chloride and sulfate concentrations compared to samples from the NHP and CHP. Those north-to-south variations in major-ion chemistry are similar to what was observed in domestic-well samples (fig. 59) and are generally attributed to regional gradients in underlying bedrock geology, climate, aquifer mineralogy, land use, and possibly hydrologic features such as saline lakes, as previously discussed.

Differences in concentrations of dissolved solids, arsenic, and nitrate among the hydrogeologic units have already been assessed using the more complete dataset from domestic wells; therefore, the following paragraphs compare water quality by well type (domestic, public supply, irrigation). Only dissolved-solids concentrations exhibited a significant (p less

than or equal to 0.05) difference between well types (figs. 71 to 73), with water samples from the NHP public-supply wells containing larger concentrations than samples from the NHP domestic wells. Overall, this analysis indicates that water quality in the domestic and public-supply wells was similar from the standpoint of this limited constituent list. A similar result was obtained for those three constituents by Bruce and Oelsner (2001). In that study, 15 pairs of closely spaced domestic and public-supply wells in the Ogallala Formation were sampled for major ions, nutrients, trace elements, pesticides, VOCs, and tritium. They did find that water from public-supply wells had more pesticide detections and more tritium concentrations greater than 0.5 TU, indicating that those wells contained a larger fraction of recent recharge than the paired domestic wells. Bruce and Oelsner (2001) attributed the more frequent occurrence of pesticides and tritium in water from public-supply wells to the fact that those wells had longer screens, were pumped at higher rates, and were pumped for longer periods than the domestic wells. Each of those factors could contribute to the relatively rapid downward movement of modern recharge from the water table to the public-supply wells. The analysis of public-supply well data in this report is inconclusive with respect to that hypothesis. Nevertheless, data from the land-use (Chapter 1), regional transect (Chapter 2), and major-aquifer study wells (Chapter 3—domestic wells) strongly support the conclusion that leakage down long well screens and long-term pumping of high-capacity wells such as public-supply and irrigation wells are important mechanisms

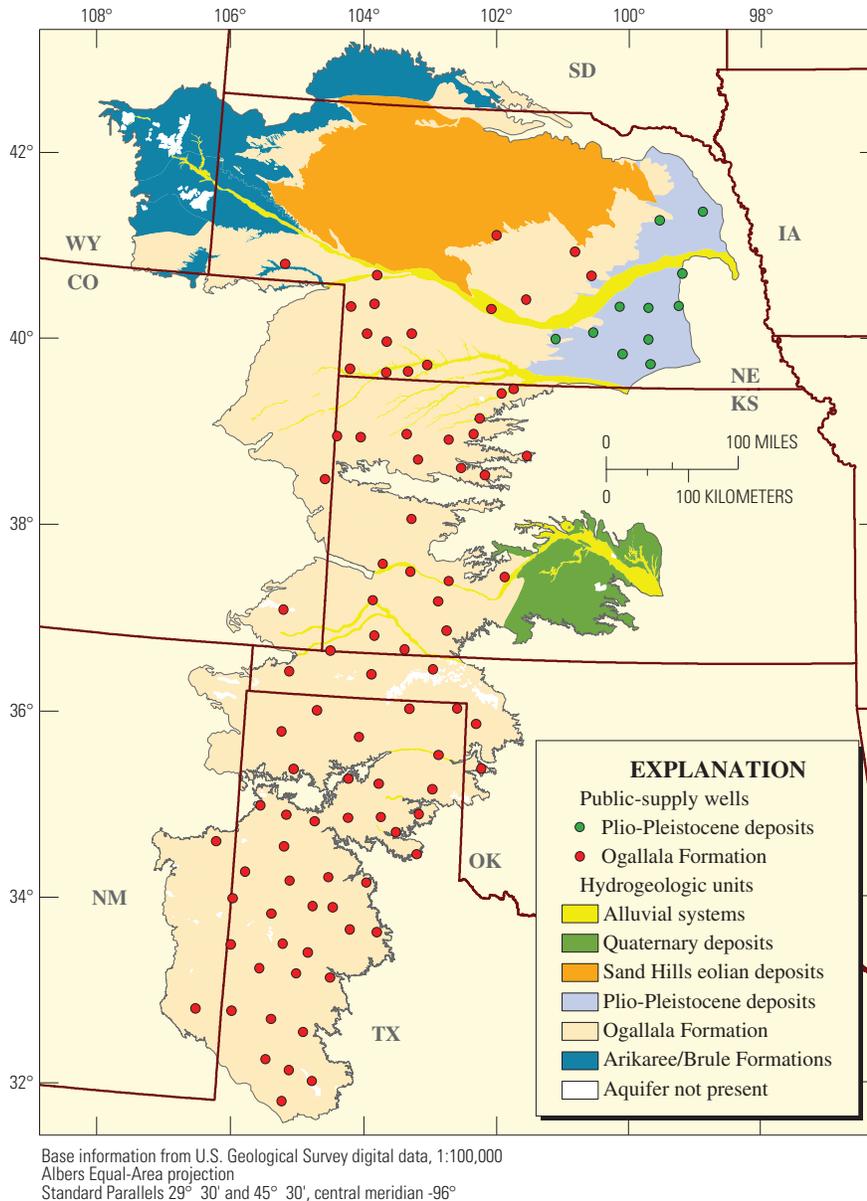


Figure 69. Location of public-supply wells sampled for the High Plains Regional Ground-Water study or by other agencies.

data collected by other agencies were assembled for 125 irrigation wells in the Plio-Pleistocene deposits and Ogallala Formation (fig. 74). Those data supplement the limited number of samples collected from six irrigation wells by the HPGW study as part of the unsaturated-zone studies (Chapter 1). Only irrigation-well data collected since 1990 were used in the analysis to be comparable with the domestic-well data. Water-quality data for the irrigation wells were subject to similar limitations as data from the public-supply wells in that the list of analyzed constituents was relatively small and laboratory reporting levels were relative large compared to those for the domestic-well data. Thus, this analysis focuses on two aspects of the data: (1) A comparison of concentrations of dissolved solids, arsenic, and nitrate between domestic, public-supply, and irrigations wells and (2) an assessment of selected water-quality data that could affect crop yield.

Water samples from irrigation wells in the CHP Ogallala Formation were the only ones to have significantly different concentrations of dissolved solids compared to samples from domestic or public-supply wells (fig. 71). In contrast, concentrations of arsenic and nitrate were not significantly different between well types in any of the assessed subregions (figs. 72 and 73). The results indicate that water quality in the domestic, public-supply, and irrigation wells was similar from the standpoint of this limited constituent list. Moreover, water types also were similar for domestic, public-supply, and irrigation wells (figs. 59, 70, and 75).

The following discussion represents a generalized assessment of selected water-quality data because many factors, not just water quality, could affect crop yield. Other factors that might affect crop yield for a particular irrigation-water quality include crop type, soil type, and stage of plant growth (U.S. Department of Agriculture, 1954; Ayers and Wescot, 1994); however, a discussion of those additional factors is beyond the scope of this report. Four factors related to crop yield are discussed: water infiltration, salinity, boron toxicity, and nitrogen credit for nitrate in irrigation water. The first three factors have the potential to reduce crop yield. The fourth factor could potentially increase crop yield and(or) reduce production costs.

for moving contaminants downward from the water table more quickly than would occur naturally in the aquifer.

Quality of Water from Irrigation Wells

Irrigated crops are the receptor that receives the largest amount of water pumped from the High Plains aquifer. The quality of water from irrigation wells can potentially have adverse or positive effects on crop yield. To evaluate the quality of ground water pumped for irrigation, water-quality

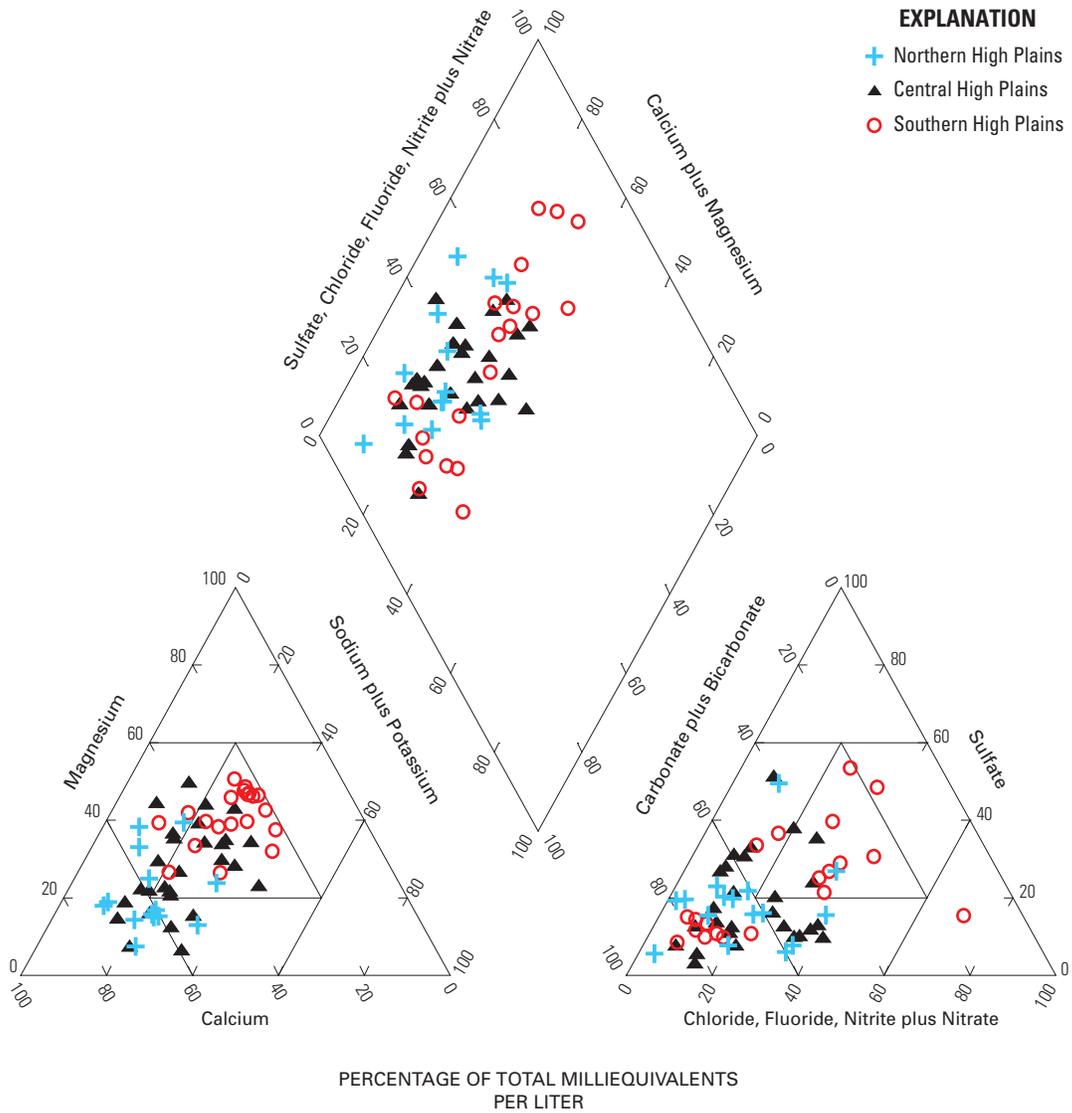
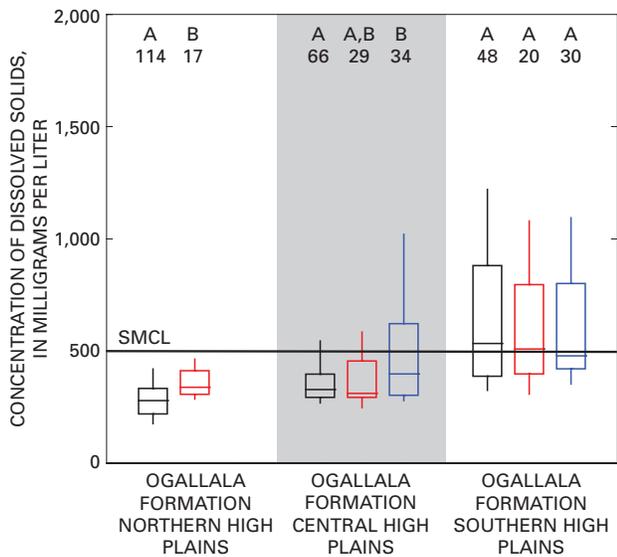


Figure 70. Trilinear diagram showing relations between major ions in water samples collected from public-supply wells in the Ogallala Formation, by subregion.

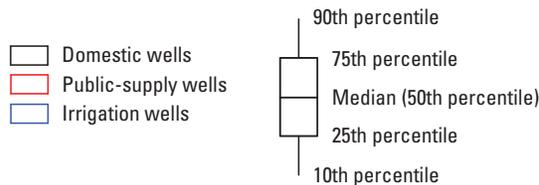
Water infiltration into soils can be affected by water quality, although other factors like soil texture and mineralogy may also be important. Reduced water infiltration can limit the amount of water available to crop roots. Salinity and sodium are important water-quality constituents that can affect infiltration. According to Ayers and Wescot (1994), low-salinity water tends to leach surface soils free of soluble minerals and salts that stabilize soil aggregates and soil structure. Without those stabilizing minerals and salts, finer soil particles disperse into pore spaces, thereby reducing rates of water infiltration. Sodium is particularly effective at dispersing finer soil particles once it has adsorbed onto the soil. A graphical tool developed by Ayers and Wescot (1994)

was used to assess the potential effect of irrigation waters from the Ogallala Formation on water infiltration (fig. 76). Their graphical approach is based on measurement of specific conductance (a measure of salinity) and sodium adsorption ratio (SAR) in irrigation water. The value of SAR depends on the concentrations of sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in solution, and it is calculated using equation 4:

$$\text{SAR} = \frac{(\text{Na}^+)}{\sqrt{0.5 \times [(\text{Ca}^{2+}) + (\text{Mg}^{2+})]}} \quad (4)$$

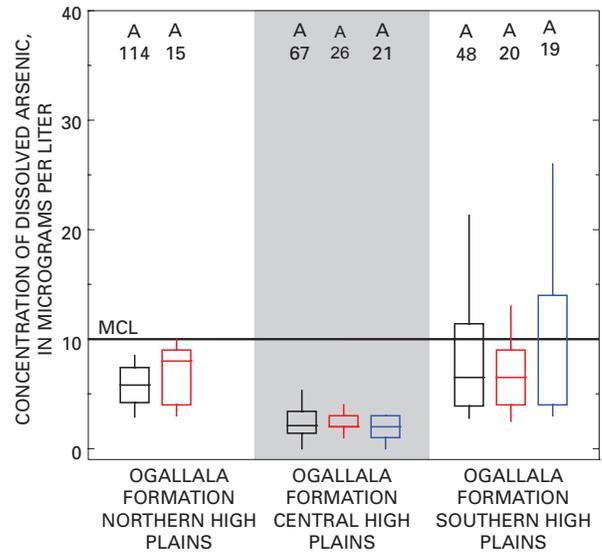


EXPLANATION

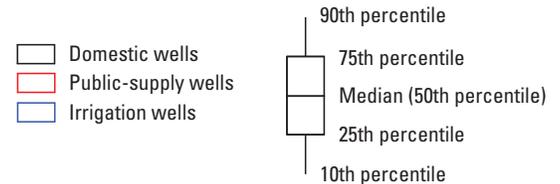


SMCL = Secondary Maximum Contaminant Level

A 114 For each subregion, well types with different letters have significantly different concentrations at $\alpha = 0.05$ (Mann-Whitney and Kruskal-Wallis tests). Comparisons only apply within subregions. Number indicates sample size.



EXPLANATION



MCL = Maximum Contaminant Level

A 114 For each subregion, well types with different letters have significantly different concentrations at $\alpha = 0.05$ (Mann-Whitney and Kruskal-Wallis tests). Comparisons only apply within subregions. Number indicates sample size.

Figure 71. Distribution of the concentrations of dissolved solids in water samples from domestic, public-supply, and irrigation wells in the Ogallala Formation, by subregion.

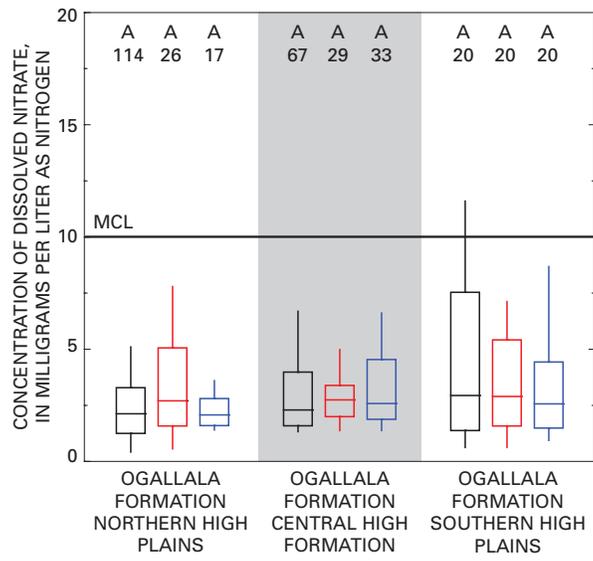
Figure 72. Distribution of the concentrations of dissolved arsenic in water samples from domestic, public-supply, and irrigation wells in the Ogallala Formation, by subregion.

According to figure 76, most of the assessed irrigation waters have the potential to slightly or moderately reduce water-infiltration rates. A smaller number of samples potentially would have no effect at all on infiltration, and only one low-conductance sample from the NHP Ogallala Formation has the potential to severely reduce infiltration.

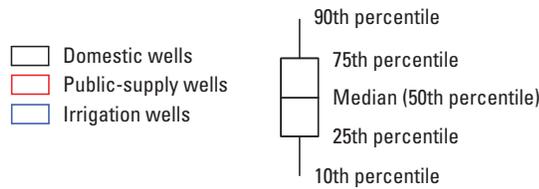
In some irrigated settings, salts in the applied water can accumulate in soil and reduce soil-water availability to crops to an extent that crop yield may be affected. The salinity classification scheme of Ayers and Wescot (1994) was used to evaluate the quality of irrigation water from the Ogallala Formation (table 17). The classification is based on concentrations of dissolved solids in irrigation water, which indicate a north-to-south increase in salinity restrictions. There were no salinity restrictions for samples from the NHP Ogallala Formation, but only 59 and 40 percent of the samples from the CHP and SHP, respectively, could be characterized as having no salinity restrictions. Forty-one and 57 percent of the samples from the

CHP and SHP, respectively, could be characterized as having slight to moderate salinity restrictions. Three percent of the SHP samples had dissolved-solids concentrations in excess of 2,000 mg/L, indicating severe salinity restrictions. Those results are consistent with data from the agricultural land-use wells (fig. 19) and from the domestic wells (table 11), which also exhibited north-to-south increases in concentrations of dissolved solids.

Unlike infiltration or salinity effects, toxicity effects related to irrigation-water quality occur within the plant itself and are not caused by a water shortage (Ayers and Wescot, 1994). Specific toxicity effects occur if certain ions in irrigation water or soil are taken up by the plants and accumulate to concentrations large enough to cause crop damage or reduced yields (Ayers and Wescot, 1994). The tolerance of crops to salinity and specific ions is dependent on several factors, including crop type. In the case of boron, small concentrations are essential for crop growth, but larger



EXPLANATION



MCL = Maximum Contaminant Level

A
114 For each subregion, well types with different letters have significantly different concentrations at $\alpha = 0.05$ (Mann-Whitney and Kruskal-Wallis tests). Comparisons only apply within subregions. Number indicates sample size.

Figure 73. Distribution of the concentrations of dissolved nitrate in water samples from domestic, public-supply, and irrigation wells in the Ogallala Formation, by subregion.

concentrations may be toxic to plants. For crops commonly grown in the High Plains (fig. 6), boron sensitivities are quite variable. Wheat is sensitive, corn is moderately tolerant, sorghum and alfalfa are tolerant, and cotton is very tolerant to boron in irrigation water. The boron toxicity classification scheme of Ayers and Wescot (1994) was used to evaluate the quality of irrigation water from the Ogallala Formation (table 17). According to that classification scheme, none of the irrigation-water samples are likely to cause boron toxicity in crops.

As discussed in Chapter 1, nitrate concentrations in recently recharged ground water beneath irrigated cropland

commonly exceeded the maximum background concentration of 4 mg/L as N (fig. 19), indicating that the aquifer was contaminated with agricultural nitrogen, most likely from fertilizer and manure sources. Nitrate above background concentrations also was present deeper in the aquifer, as indicated by data from the domestic wells (fig. 62). Nitrate in irrigation water could actually supply a substantial portion of the crop N requirement (or N “credit”), depending on the nitrate concentration and the crop (Bauder, 2001). Nitrogen credits in water samples from the irrigation wells were calculated based on the assumption that 1 acre-ft of irrigation water would be applied to the crop (table 18). (One acre-ft of irrigation water

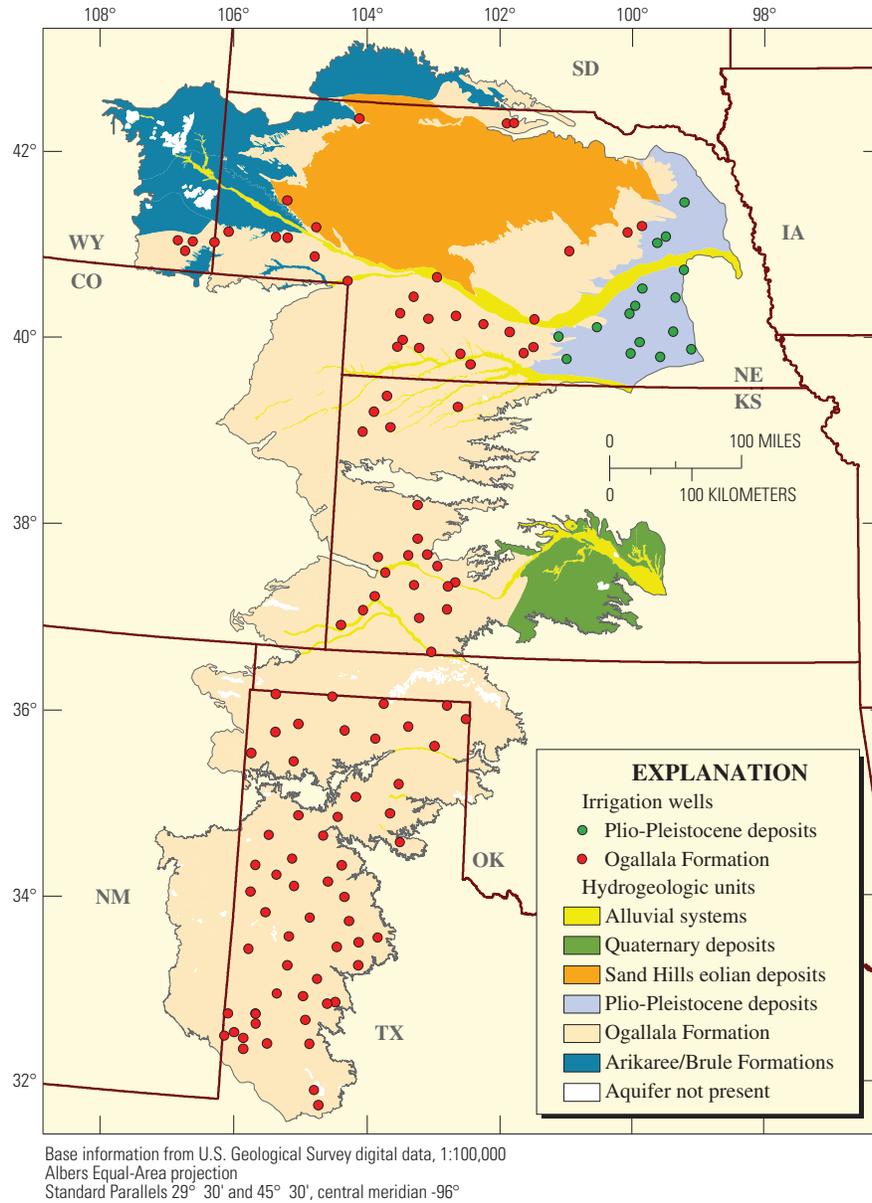


Figure 74. Location of irrigation wells sampled by other agencies.

contains 2.71 pounds of N for each milligram per liter of nitrate-nitrogen.) This approach may underestimate actual N credits because some crops such as corn typically require more than 1 acre-ft of irrigation water in the High Plains. Sixty-two to 88 percent of the irrigation-water samples contained less than 10 pounds of N per acre-ft of water (table 18). Six to 38 percent of the samples contained 10 to less than 20 pounds of N per acre-foot of water. Only a small percentage (3 to 6) of the samples contained more than 50 pounds of N per acre-foot of water. Nitrogen credits for most of the samples probably

represent less than 20 percent of the N requirement for irrigated corn in the High Plains (Shapiro and Wortman, 2003); nevertheless, the credits could be important from a water-quality perspective if producers were to reduce N applications at the land surface by a similar amount. Moreover, it is likely that nitrate concentrations deeper in the aquifer will increase over time as nitrate in the thick unsaturated zones reaches the water table (Chapter 1) and as irrigation pumping vertically redistributes nitrate in the aquifer (Chapter 2). Thus, N credits in irrigation water could increase over time.

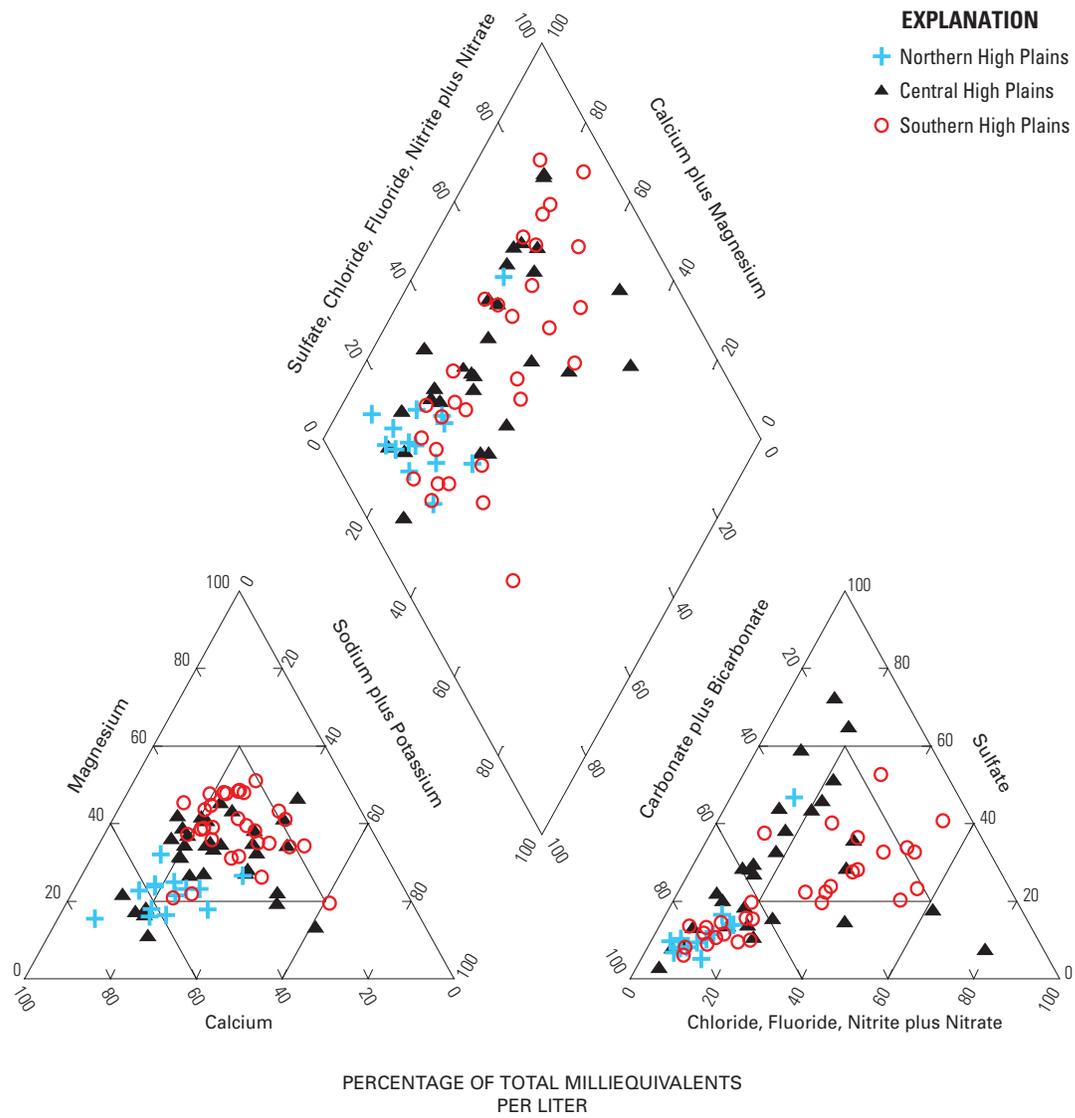


Figure 75. Trilinear diagram showing relations between major ions in water samples collected from irrigation wells in the Ogallala Formation, by subregion.

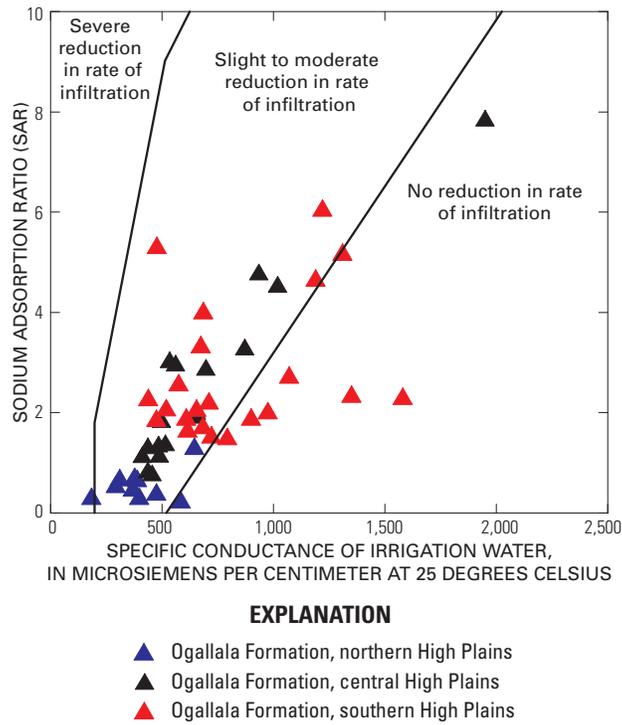


Figure 76. Relative rate of water infiltration as affected by specific conductance (salinity) and sodium adsorption ratio of irrigation water from the Ogallala Formation, by subregion (modified from Ayers and Wescot, 1994). Specific conductance is directly related to salinity.

Table 17. Salinity and boron toxicity of irrigation water from the Ogallala Formation.

[mg/L, milligrams per liter; µg/L, micrograms per liter; n, number of samples; <, less than; >, greater than]

Potential irrigation problem	General water-quality criteria ¹	Ogallala Formation (percentage of samples in each category)		
		Northern High Plains	Central High Plains	Southern High Plains
Salinity				
Dissolved solids	mg/L	n = 13	n = 34	n = 30
None	< 450	100	59	40
Slight to moderate	450 – 2,000	0	41	57
Severe	> 2,000	0	0	3
Boron toxicity				
Boron concentration	µg/L	n = 9	n = 29	n = 21
None	0 – 700	100	100	100
Slight to moderate	700 – 3,000	0	0	0
Severe	> 3,000	0	0	0

¹From Ayers and Wescot (1994).

Table 18. Nitrogen credits in irrigation water from the Plio-Pleistocene deposits and Ogallala Formation.

[One acre-foot of irrigation water contains 2.71 pounds of nitrogen for each milligram per liter of nitrate-nitrogen; <, less than; >, greater than; n, number of samples]

Hydrogeologic unit	Pounds of nitrogen per acre-foot of irrigation water (percentage of samples in each category)					
	< 10	10 to < 20	20 to < 30	30 to < 40	40 to < 50	> 50
Plio-Pleistocene deposits (n = 8)	62	38	0	0	0	0
Ogallala Formation, northern High Plains (n = 17)	88	6	0	0	0	6
Ogallala Formation, central High Plains (n = 34)	65	29	3	0	0	3
Ogallala Formation, southern High Plains (n = 28)	71	18	7	4	0	0