In cooperation with the San Antonio Water System

Quality of Groundwater at and near an Aquifer Storage and Recovery Site, Bexar, Atascosa, and Wilson Counties, Texas, June 2004–August 2008

Scientific Investigations Report 2010–5061

U.S. Department of the Interior
U.S. Geological Survey

Front cover: Cascading aerator at aquifer storage and recovery plant (photograph by Cassi L. Otero).

Back cover:

Top: Edwards production well artesia pump station (photograph by Brian L. Petri, September 2007).

Botttom: Flooding on Galvan Creek (photograph by Michael B. Nyman, June 2005).

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KEN SALAZAR, Secretary

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Suggested citation:
Otero, C.L., and Petri, B.L., 2010, Quality of groundwater at and near an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties, Texas, June 2004–August 2008: U.S. Geological Scientific Investigations Report 2010–5061, 34 p.

Acknowledgments

The authors thank McCoy, Oak Hills, Picosa, Sutherland Springs, and Three Oaks Water Supply Corporations; the Cities of Floresville, Jourdanton, Pleasanton, and Poteet; and landowner Tom Ray for granting access to wells sampled for this report.

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Conversion Factors, Datum, Water-Quality Units, and Isotope Unit Explanations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

$$°F=(1.8\times°C)+32$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Water-Quality Units

Concentrations are reported in metric units. Chemical concentrations are reported in milligrams per liter (mg/L), micrograms per liter (µg/L), and milliequivalents per liter (meq/L). Milligrams per liter and micrograms per liter are units expressing the concentration of chemical constituents in solution as weight of solute (milligrams or micrograms) per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value of milligrams per liter is equivalent to the concentration in parts per million. The numerical value of micrograms per liter is equivalent to the concentration in parts per billion. Milliequivalents per liter is a unit expressing the concentration of chemical constituents in solution as 1/1,000 the molecular weight, in milligrams, divided by the valence of one molecule of the constituent per unit volume (liter) of water.

Specific conductance is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Bacteria is reported in colonies per 100 milliliters (cols./100 mL).

Turbidity is reported in nephelometric turbidity ratio units (NTRU).

Radioactivity is reported in picocuries per liter (pCi/L).

Isotope Unit Explanations

Per mil: A unit expressing the ratio of stable-isotope abundances of an element in a sample to those of a standard material. Per mil units are equivalent to parts per thousand. Stable-isotope ratios are computed as follows (Kendall and McDonnell, 1998):

$$\delta X = \{(R_{sample} - R_{standard}) / R_{standard}\} \times 1{,}000,$$

where

δ is the "del" notation,

X is the heavier stable isotope, and

R is the ratio of the heavier, less abundant isotope to the lighter, stable isotope in a sample or standard.

The δ values for stable-isotope ratios discussed in this report are referenced to the following standard materials:

Element	R	Standard identity and reference
hydrogen	hydrogen-2/hydrogen-1	Vienna-Standard Mean Ocean Water (Fritz and Fontes, 1980)
oxygen	oxygen-18/oxygen-16	Vienna-Standard Mean Ocean Water (Fritz and Fontes, 1980)
boron	boron-11/boron-10	National Bureau of Standards Boric Acid Sample No. 951 (Catanzaro and others, 1970)

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Quality of Groundwater at and near an Aquifer Storage and Recovery Site, Bexar, Atascosa, and Wilson Counties, Texas, June 2004–August 2008

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Abstract

The U.S. Geological Survey, in cooperation with the San Antonio Water System, did a study during 2004–08 to characterize the quality of native groundwater from the Edwards aquifer and pre- and post-injection water from the Carrizo aquifer at and near an aquifer storage and recovery (ASR) site in Bexar, Atascosa, and Wilson Counties, Texas. Groundwater samples were collected and analyzed for selected physical properties and constituents to characterize the quality of native groundwater from the Edwards aquifer and pre- and post-injection water from the Carrizo aquifer at and near the ASR site. Geochemical and isotope data indicated no substantial changes in major-ion, trace-element, and isotope chemistry occurred as the water from the Edwards aquifer was transferred through a 38-mile pipeline to the aquifer storage and recovery site. The samples collected from the four ASR recovery wells were similar in major-ion and stable isotope chemistry compared to the samples collected from the Edwards aquifer source wells and the ASR injection well. The similarity could indicate that as Edwards aquifer water was injected, it displaced native Carrizo aquifer water, or, alternatively, if mixing of Edwards and Carrizo aquifer waters was occurring, the major-ion and stable isotope signatures for the Carrizo aquifer water might have been obscured by the signatures of the injected Edwards aquifer water. Differences in the dissolved iron and dissolved manganese concentrations indicate that either minor amounts of mixing occurred between the waters from the two aquifers, or as Edwards aquifer water displaced Carrizo aquifer water it dissolved the iron and manganese directly from the Carrizo Sand. Concentrations of radium-226 in the samples collected at the ASR recovery wells were smaller than the concentrations in samples collected from the Edwards aquifer source wells and from the ASR injection well. The smaller radium-226 concentrations in the samples collected from the ASR recovery wells likely indicate some degree of mixing of the two waters occurred rather than continued decay of radium-226 in the injected water. Geochemical and isotope data measured in samples collected in May 2005 from two Carrizo aquifer monitoring wells and in July 2008 from the three ASR production-only wells in the northern section of the ASR site indicate that injected Edwards aquifer water had not migrated to these five sites. Geochemical and isotope data measured in samples collected from Carrizo aquifer wells in 2004, 2005, and 2008 were graphically analyzed to determine if changes in chemistry could be detected. Major-ion, trace element, and isotope chemistry varied spatially in the samples collected from the Carrizo aquifer. With the exception of a few samples, major-ion concentrations measured in samples collected in Carrizo aquifer wells in 2004, 2005, and 2008 were similar. A slightly larger sulfate concentration and a slightly smaller bicarbonate concentration were measured in samples collected in 2005 and 2008 from well NC1 compared to samples collected at well NC1 in 2004. Larger sodium concentrations and smaller calcium, magnesium, bicarbonate, and sulfate concentrations were measured in samples collected in 2008 from well WC1 than in samples collected at this well in 2004 and 2005. Larger calcium and magnesium concentrations and a smaller sodium concentration were measured in the samples collected in 2008 at well EC2 compared to samples collected at this well in 2004 and 2005. While in some cases the computed percent differences (compared to concentrations from June 2004) in dissolved iron and dissolved manganese concentrations in 11 wells sampled in the Carrizo aquifer in 2005 and 2008 were quite large, no trends that might have been caused by migration of injected Edwards aquifer water were observed. Because of the natural variation in geochemical data in the Carrizo aquifer and the small data set collected for this study, differences in major-ion and trace element data among the samples collected in 2004, 2005 and 2008 cannot be directly attributed to the ASR site operations. When the data were analyzed graphically, no appreciable differences in isotope concentrations were observed between samples collected in 2004 and 2008 from Carrizo aquifer wells, indicating that the Edwards aquifer source water might not have affected the isotope chemistry of the native Carrizo aquifer water near the sampled Carrizo wells by July 2008.

Introduction

The Edwards aquifer is the main source of public water supply for the city of San Antonio in Bexar County, Texas, and adjacent counties and provides nearly all of the water for industrial, military, and irrigation use in the region. Withdrawals from the aquifer are regulated by the Edwards Aquifer Authority (EAA) to protect federally listed endangered species that rely on the discharge at large springs emerging from the aquifer (Edwards Aquifer Authority, 2009). The San Antonio Water System (SAWS) is the primary water provider for the city.

In August 2002, SAWS began construction of an aquifer storage and recovery (ASR) plant in southern Bexar County on an approximately 3,200-acre site that extends into northern Atascosa and western Wilson Counties (fig. 1). Currently (2009) 29 wells at the site are designed to inject water into and withdraw water from the Carrizo aquifer (informal name commonly applied to the upper unit of the Carrizo-Wilcox aquifer in the area). In June 2004 phase one of the ASR plant became operational, enabling SAWS to pump water from the Edwards aquifer when water levels are sufficiently high and withdrawals from the Edwards aquifer are less than the EAA-enforced limit, transfer the water through a 38-mile pipeline (actual length) (Adam E. Conner, San Antonio Water System Planner II, Water Resources, written commun., 2010) to the ASR plant, and inject the water into the Carrizo aquifer through 16 wells. Injected water could then be recovered from the Carrizo aquifer, treated, and distributed during times of drought to alleviate stress on the Edwards aquifer.

The U.S. Geological Survey (USGS), in cooperation with SAWS, did a study during 2004–08 to characterize the quality of groundwater (native water from the Edwards aquifer and pre- and post-injection water from the Carrizo aquifer) at and near the ASR site. Findings of the study are intended to provide a better understanding of possible changes in the quality of groundwater near an active ASR site that might result from the mixing of water from different aquifers. Mobilization of trace elements in groundwater as a result of changes in oxidation and pH conditions has been observed at other ASR sites (Heilweil and others, 2009). Reduction-oxidation (redox) reaction conditions in an aquifer can change when non-native water is introduced to the aquifer, and redox conditions exercise important controls on water chemistry including several redox-influenced trace elements (Smedley and Edmunds, 2002; Basu and others, 2007). In particular, iron and manganese mobilization was a concern at the SAWS ASR site. The results of this study also are applicable to other ASR investigations in similar hydrogeologic environments and to investigations of the Carrizo-Wilcox aquifer. This study advances the knowledge of how ASR operations affect native groundwater in sandstone aquifers and the hydrologic processes that occur in carbonate/sand aquifer systems. Results of this investigation can be used by local and State water managers to address issues of increased demand for water resources in areas of increasing population.

Purpose and Scope

This report describes the results of chemical analyses of groundwater samples collected in 2004, 2005, and 2008 from the Carrizo aquifer in parts of Bexar, Atascosa, and Wilson Counties near an ASR site. Water-chemistry and isotope data collected in June 2004 are used to characterize the water of the Carrizo aquifer before the ASR site became operational; data collected in September 2005 and July–August 2008 are used to characterize groundwater near the ASR site after the site became operational. Native water from the Edwards aquifer is analyzed, and a preliminary assessment of the effects on groundwater quality from injecting Edwards aquifer water into the Carrizo aquifer is made using the water-quality data collected during the study. Stormwater samples also were collected from two surface-water quality stations near the ASR site to identify surface-water contaminants, if any, that potentially could enter the Carrizo aquifer through recharge. The ability to collect stormwater samples was dependent on large storms, which were infrequent during the study. Because only eight stormwater samples (representing five storms) could be collected, the stormwater analytical data are included in the appendix but not assessed in the report.

Geology and Hydrogeology

The Wilcox Group and the overlying Carrizo Sand of the Claiborne Group are important water-yielding formations near the ASR site (fig. 2). The Wilcox Group and Carrizo Sand consist mostly of sand, locally interbedded with gravel, silt, clay, and lignite, that dips into the subsurface toward the Gulf Coast. Most of the sand beds that compose the Wilcox Group are less permeable than those that compose the Carrizo Sand (Klemt and others, 1976).

The Wilcox Group and the hydraulically connected Carrizo Sand together form the Carrizo-Wilcox aquifer, a major aquifer in Texas (Ashworth and Hopkins, 1995). The recharge zone (outcrop) of the Carrizo-Wilcox aquifer forms a relatively narrow band roughly parallel to the Gulf Coast. Recharge to the Carrizo-Wilcox aquifer occurs through direct infiltration of rainfall on the land surface in the recharge zone, through the beds of streams that flow across the recharge zone, and as leakage from overlying formations that compose the Carrizo-Wilcox aquifer in subcrop areas. Water in the aquifer typically is fresh (dissolved-solids concentration less than 1,000 milligrams per liter) in and near the recharge zone and becomes progressively more saline with distance downdip. The limit of fresh to slightly saline water in the Carrizo-Wilcox aquifer is defined by the southern boundary of the Carrizo-Wilcox subcrop that extends southwest to northeast through south-central Texas. The ASR site is located at the southern margin of the recharge zone (fig. 2).

Part of the ASR site overlies the Carrizo-Wilcox aquifer (Klemt and others, 1976) (fig. 2). The upper unit of

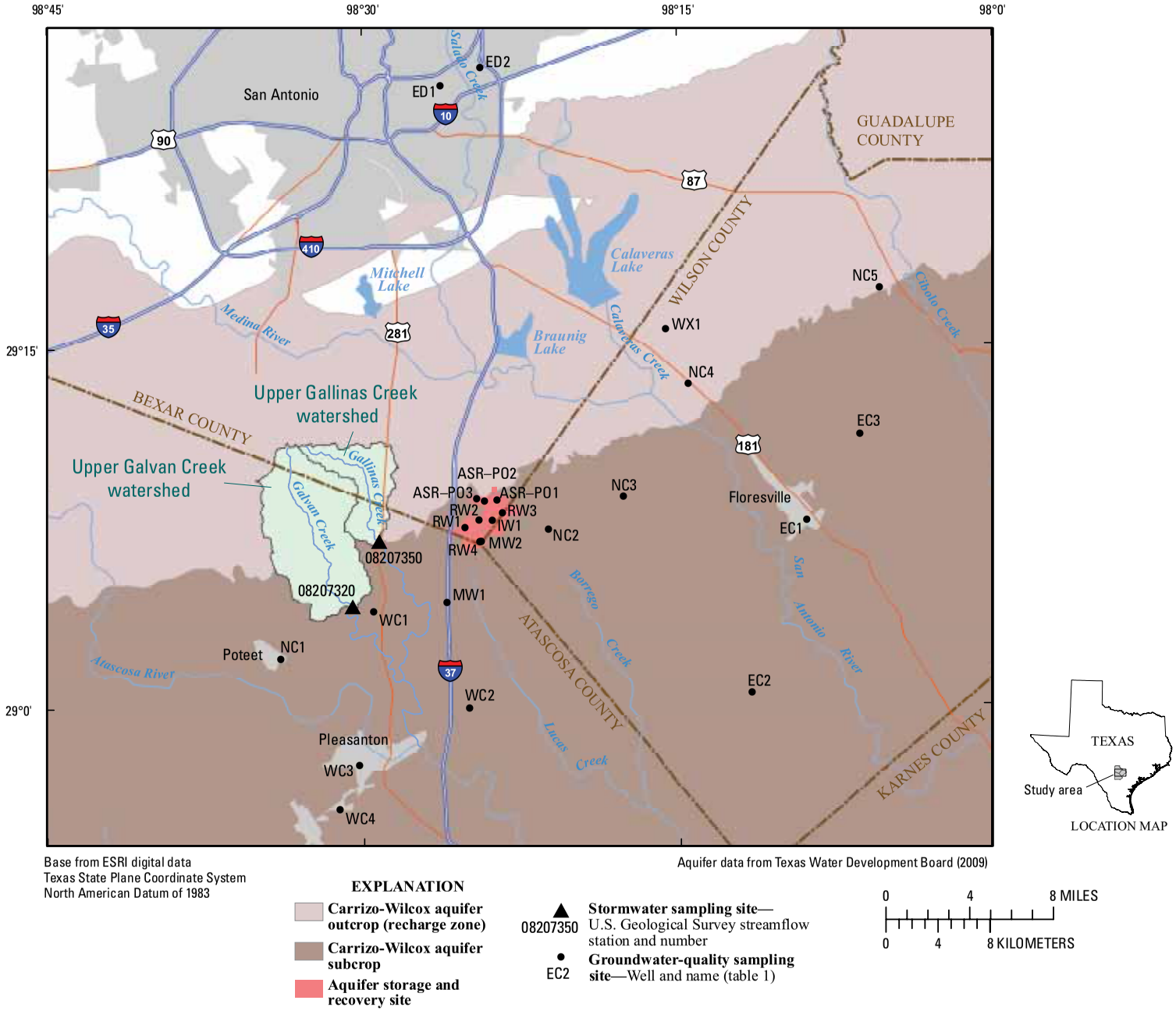

Figure 1. Location of an aquifer storage and recovery site and data-collection sites, Bexar, Atascosa, and Wilson Counties, Texas.

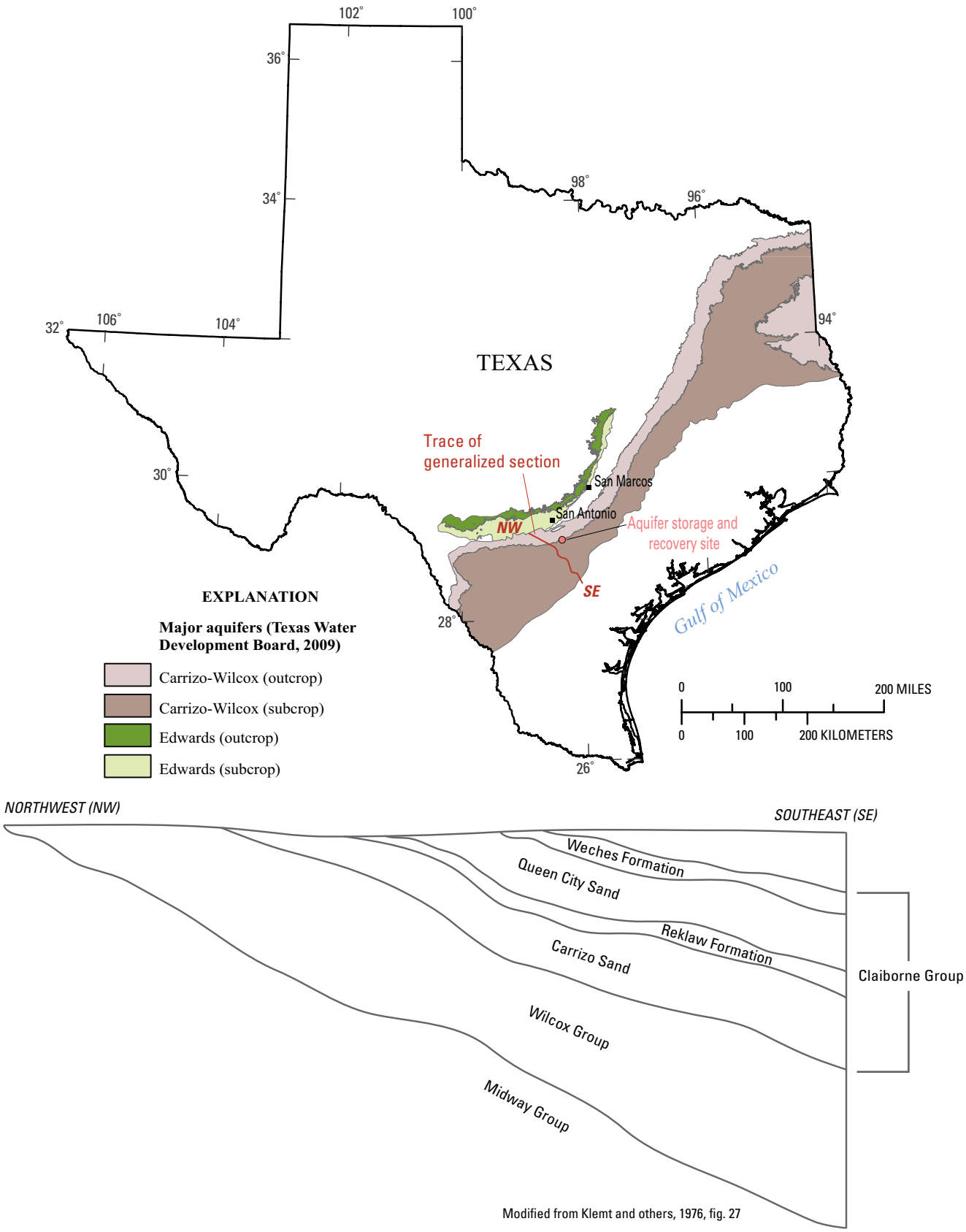

Figure 2. Outcrops and subcrops of the Carrizo-Wilcox aquifer and Edwards aquifer in Texas, and generalized hydrogeologic section of the water-yielding Carrizo Sand and Wilcox Group and other near-surface formations at an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties.

the Carrizo-Wilcox aquifer, the Carrizo Sand, ranges in thickness from 150 to 1,200 feet in south Texas (Klemt and others, 1976, p. 4) and commonly is referred to as the Carrizo aquifer. Some wells screened in the Carrizo aquifer yield more than 1,000 gallons per minute of water (Ashworth and Hopkins, 1995, p. 17), and the Carrizo aquifer is an important source of water for agriculture and public supply.

At the ASR site, the Carrizo aquifer is about 800 feet thick, with a net sand thickness of about 700 feet (Klemt and others, 1976, fig. 9). Haque and Johannesson (2006, p. 59) noted other investigators' findings that "precipitation recharges the Carrizo Sand aquifer in the outcrop area in northwest Atascosa County, and the resulting groundwaters subsequently flow down-gradient towards the southeast (Pearson and White, 1967; Castro et al. [and others], 2000). High fluid pressure causes groundwater to discharge from the aquifer by crossformational upward leakage (Castro and Goblet, 2003)." The prevailing regional flow pattern from northwest to southeast might affect the movement of injected groundwater. The hydrogeologic units above and below the aquifer are moderately confining, on the basis of permeability, relative to that of the Carrizo aquifer. Confining units adjacent to the aquifer at the site tend to keep injected water from migrating vertically into overlying and underlying units, allowing more of the injected water to be withdrawn later.

The water injected at the ASR site is sourced from the San Antonio segment of the Edwards aquifer (hereinafter, Edwards aquifer) (fig. 2). The Edwards aquifer comprises Lower Cretaceous-age rocks of the Edwards Group (Rose, 1972) and the Georgetown Formation. The Edwards Group in the study area comprises two stratigraphic units, the basal Kainer Formation and the upper Person Formation. Each of those units comprises several informal members.

Most recharge to the Edwards aquifer occurs in the recharge zone (aquifer outcrop) west of San Antonio, Tex. (fig. 2), where streams originating north of the aquifer flow across and lose most of all of their flows into highly faulted and fractured limestone. After water enters the aquifer, it moves generally in an easterly direction to discharge points in and near San Antonio, mainly municipal water-supply wells. Water not discharged to wells then continues generally toward the northeast along and parallel to northeast-trending faults in the study area to discharge at major spring complexes.

The thickness of the Edwards aquifer in the study area is about 450 feet (Small and Hanson, 1994, p. 5; Stein and Ozuna, 1994, p. 5). The rocks of the Edwards Group are characterized by a network of en-echelon, high-angle, mostly down-to-the-coast normal faults along the northwestern margin of the Gulf Coast Plain (Maclay and Small, 1984; Maclay, 1995). The faults, and their subsequent erosion and dissolution, are major factors affecting flow in the aquifer. Maclay and Small (1984, p. 50) estimated transmissivities for the Edwards aquifer to range from 200,000 to 2,000,000 feet squared per day.

Methods of Investigation

Methods described in this report for the water-quality investigation in and near the ASR site in Bexar, Atascosa, and Wilson Counties included components of sample collection, sample analysis, water-chemistry and isotope analysis, and quality control and quality assurance of water-quality samples. At all wells that were sampled, physical properties (dissolved oxygen, pH, specific conductance, water temperature, and alkalinity) and water-quality constituents (major ions, nutrients, and trace elements) were measured. Isotope concentrations (oxygen-16, oxygen-18, hydrogen-1, deuterium, strontium-86, strontium-87, boron-10, boron-11, radium-226, and radium-228) also were measured.

Sample Collection

Sample collection from Edwards aquifer wells and Carrizo aquifer wells was done following standard USGS methods documented in the "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated). Of the 25 wells sampled for this study, 23 had permanently installed pumps from which samples were collected at raw-water spigots at the well heads. The two remaining wells were monitoring wells (wells used only for monitoring water levels and collecting water-quality samples) into which a submersible pump equipped with 3/8-inch Teflon®-lined tubing was lowered to collect a raw-water sample. All wells were pumped until field properties stabilized before samples were collected and processed. Field properties were considered stable when the variation between five or more sequential field-measurement readings were within 0.05 unit for pH, 0.2 degree Celsius for temperature, 5 percent for specific conductivity, 0.3 milligram per liter for dissolved oxygen, and 10 percent for turbidity.

Edwards Aquifer Wells

Water-quality constituent concentrations and physical properties were measured in May 2005 at wells ED1 and ED2 (Edwards aquifer source wells), which are open in the Edwards aquifer at depths of 982 to 1,318 feet; these wells are the source of water that was injected at the ASR site for possible storage and future recovery (fig. 1; tables 1 and 2; appendix 1). Hardrock wells (such as those completed in the Edwards aquifer) typically do not need to be screened or cased because the borehole of a hardrock well will stand open (Harter, 2003). Groundwater-chemistry and isotope data also were collected in May 2005 at the wellhead of injection well 1 (IW1) (ASR injection well), which is screened between depths of 445 and 685 feet in the Carrizo aquifer at the ASR site and used for injecting water from the Edwards aquifer source wells into the Carrizo aquifer. Samples were collected at the ASR injection well before water from the Edwards aquifer was injected into the Carrizo aquifer to indicate whether changes in

Table 1. Wells from which water samples were collected at and near an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08.

[Datum for open interval and depth to pump intake is land surface; X, open hole; ASR, aquifer storage and recovery; S, screen; N/A, not applicable; --, unknown; G, gravel pack with screen; P, perforated or slotted; F, gravel pack with perforations]

Well name (fig. 1)	U.S. Geological Survey site number	State well number	Total depth (feet)	Open interval(s) (feet)	Completion type	Depth to pump intake (feet)
Edwards aquifer source wells						
ED1	292557098261401	AY–68–37–508	1,318	982–1,318	X	569
ED2	292643098242101	AY–68–37–610	1,145	995–1,145	X	542
ASR injection well						
IW1	290750098235301	AY–68–53–912	685	445–685	S	400
Carrizo aquifer monitoring wells						
MW1	290425098260301	AL–68–61–505	725	685–715	S	N/A
MW2	290657098242401	AY–68–61–321	810	--	--	N/A
ASR recovery wells						
RW1	290732098251101	AY–68–53–811	665	605–660	S	--
RW2	290751098243101	AY–68–53–911	685	510–685	S	400
RW3	290809098232301	AY–68–53–913	685	450–685	S	400
RW4	290657098242801	AY–68–61–319	775	610–775	G	400
ASR production-only wells						
ASR–PO1	290841098234001	AY–68–53–915	630	400–410 465–475 495–545 605–615	G	360
ASR–PO2	290838098241401	AY–68–53–916	565	380–390 480–550	G	355
ASR–PO3	290844098243601	AY–68–53–917	605	460–470 490–590	G	375
Northern Carrizo wells						
NC1	290205098335601	AL–68–60–851	1,064	858–1,058	S	210
NC2	290727098211301	ZL–68–62–108	938	838–938	P	--
NC3	290849098174001	ZL–68–54–807	838	738–828	S	231
NC4	291330098143301	ZL–68–55–111	422	--	G	275
NC5	291728098052401	ZL–68–48–708	519	292–374 379–396	G	260
Western Carrizo wells						
WC1	290403098293201	AL–68–61–413	1,220	1,124–1,200	S	320
WC2	290001098250101	AL–68–61–810	1,000	--	F	--
WC3	285738098301401	AL–78–04–312	1,751	1,524–1,744	F	260
WC4	285548098310901	AL–78–04–612	2,125	1,706–1,938	F	300
Eastern Carrizo wells						
EC1	290748098085601	ZL–68–55–907	1,260	1,020–1,250	G	--
EC2	290037098113701	ZL–68–63–803	2,215	2,084–2,184	P	240
EC3	291122098062301	ZL–68–56–408	1,058	--	P	350
Carrizo-Wilcox aquifer well						
WX1	291547098153501	ZL–68–46–902	692	612–692	S	300

Table 2. Well-sampling schedule by aquifer for samples collected at and near an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08.

Well name (fig. 1)	June 2004	May 2005	September 2005	July–August 2008
Edwards aquifer				
ED1		X		
ED2		X		
Carrizo aquifer				
	Pre-injection	Post-injection		
IW1		X		
MW1		X		
MW2		X		
RW1				X
RW2				X
RW3				X
RW4				X
ASR–PO1				X
ASR–PO2				X
ASR–PO3				X
NC1	X		X	X
NC2	X			X
NC3	X		X	X
NC4	X		X	X
NC5	X			
WC1	X		X	X
WC2	X		X	
WC3	X		X	X
WC4	X		X	X
EC1	X		X	X
EC2	X		X	X
EC3	X			
Carrizo-Wilcox aquifer				
WX1	X		X	X

water chemistry occurred when transferring the water through a 38-mile pipeline from the source wells to the ASR site.

Carrizo Aquifer Wells

Pre-injection Carrizo aquifer water was characterized by samples collected from 12 wells (NC1, NC2, NC3, NC4, NC5—northern Carrizo wells; WC1, WC2, WC3, WC4—western Carrizo wells; EC1, EC2, EC3—eastern Carrizo wells) in the Carrizo aquifer screened at depths of 292 to 2,184 feet (fig. 1; table 1). Wells completed in alluvial aquifers (such as the Carrizo aquifer) are screened at specific depth intervals to ensure that screened zones match the aquifer zones from which water will be drawn (Harter, 2003). The analytical results from one additional well, WX1 (Wilcox-Carrizo well), intended to characterize the Carrizo aquifer were different from the analytical results of the 12 Carrizo wells. Prior to sampling, well WX1, screened between depths of 612 and 692 feet, was believed to be screened in the Carrizo aquifer; additional investigation after the analytical results were obtained, including a careful review of well logs, indicated well WX1 was partially screened in the Wilcox Group of the Carrizo-Wilcox aquifer. Analytical results from well WX1 thus were not used to characterize the Carrizo aquifer. The locations of wells from which water samples were collected at and near the ASR site, including the Carrizo aquifer well locations, are shown in figure 1. Samples from the 12 Carrizo wells and the Carrizo-Wilcox well were collected in June 2004 (table 2) before injection of Edwards aquifer water into the Carrizo aquifer. Hereinafter, samples collected during June 2004 in the 12 Carrizo wells are referred to as the 2004 Carrizo samples.

Post-injection Carrizo aquifer water near the ASR site was characterized after injection of Edwards aquifer water began at the ASR site. Water-quality samples were collected at selected subsets of the 12 Carrizo wells during September 2005 (hereinafter 2005 Carrizo samples) and during July–August 2008 (hereinafter, 2008 Carrizo samples). Most of the Carrizo wells sampled in 2004 were resampled in 2005 and 2008. Two wells (EC3 and NC5) sampled in 2004 were not sampled in either 2005 or 2008 because they were beyond a 15-mile radius (centered on the ASR site), which was a criterion for well selection implemented after the 2004 sampling. The 15-mile radius was decided upon because that is the distance from the ASR site to the San Antonio River, which is a gaining stream that might prevent groundwater from flowing past the stream from either direction. One well (NC2) could not be sampled in 2005 because of pump problems but was sampled in 2008; another well (WC2) was sampled in 2005 but was unavailable for sampling during July–August 2008. Two additional wells (MW1 and MW2; hereinafter, Carrizo aquifer monitoring wells) at and near the ASR site and screened at depths of 685 to 715 feet and completed in an unknown manner to about 810 feet, respectively, in the Carrizo aquifer were sampled in May 2005. Samples also were collected in July 2008 at four Carrizo aquifer wells (RW1, RW2, RW3, and RW4; hereinafter, ASR recovery wells) to characterize post-injection water from the Carrizo aquifer; these wells, screened at depths of 450 to 775 feet, were used for recovery of injected water. To indicate the extent to which injected Edwards aquifer water might migrate north, three wells (ASR–PO1, ASR–PO2, and ASR–PO3; hereinafter, ASR production-only wells) on the north side of the ASR site were sampled in July 2008; these wells were designed to pump water from, but not inject water into, the Carrizo aquifer.

Sample Analysis

Physical property (dissolved oxygen, pH, specific conductance, and water temperature), major-ion, alkalinity, and trace-element data were obtained for all groundwater samples that were collected (appendix 1). The 2004 Carrizo samples also were analyzed for nutrients. Trace-element concentrations were measured for the dissolved phase. Prior to analysis, water samples analyzed for dissolved-phase constituents were filtered through a 0.45-micrometer membrane filter and acidified with ultrapure nitric acid to pH less than 2 standard units (Garbarino and Taylor, 1996). In addition to analyzing for dissolved iron and manganese, total-phase (whole water) iron and manganese concentrations in groundwater were measured by analyzing unfiltered samples that had undergone an in-bottle acid digestion process (Garbarino and Struzeski, 1998).

Stable isotope data were analyzed for all samples except the 2005 Carrizo samples. Water samples were collected, processed, and preserved using standard USGS protocols as described in the "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated). The concentrations of major ions, nutrients, and trace elements in the water samples were analyzed by the USGS National Water Quality Laboratory (NWQL) in Denver, Colo., using approved methods (Fishman and Friedman, 1989; Patton and Truitt, 1992, 2000; Fishman, 1993; Garbarino and Struzeski, 1998; Garbarino, 1999; Garbarino and others, 2006).

Stable environmental isotopes are measured as the ratio of the two most abundant isotopes of a given element. The most abundant isotopes of oxygen are oxygen-18 (^{18}O) and oxygen-16 (^{16}O), whereas the most abundant isotopes of hydrogen are hydrogen-2 (^{2}H) and hydrogen-1 (^{1}H) (Clark and Fritz, 1997). Water molecules with a greater amount of the lightest oxygen and hydrogen isotopes (^{16}O and ^{1}H, respectively) evaporate preferentially compared to water molecules with a greater amount of the heaviest oxygen and hydrogen isotopes (^{18}O and ^{2}H, respectively) (Bruckner, 2009). The USGS Isotope Tracers Project (U.S. Geological Survey, 2004) provides a description of stable isotope compositions:

> "The stable isotopic compositions of low-mass (light) elements such as oxygen and hydrogen are normally reported as "delta" values ($\delta^{18}O$ for oxygen and δD for hydrogen) in parts per thousand enrichments or depletions relative to a standard of known composition. For the element oxygen, the average terrestrial abundance ratio of ^{18}O to ^{16}O is 1:500; the average ratio of ^{2}H to ^{1}H is 1:6,410 (Kendall and Caldwell, 1998). A positive δD or $\delta^{18}O$ value means that the sample contains more of the heavy isotope than the standard; a negative δD or $\delta^{18}O$ value means that the sample contains less of the heavy isotope than the standard."

The ratios of naturally occurring, stable isotopes of hydrogen ($^{2/1}H$) and oxygen ($^{18/16}O$) of water were measured by the USGS Stable Isotope Laboratory in Reston, Va., using approved methods (Epstein and Mayeda, 1953; Coplen and others, 1991). The ratios of naturally occurring, stable isotopes of strontium (strontium-87/strontium-86 [$^{87/86}Sr$]) and boron (boron-11/boron-10 [$^{11/10}B$]) were measured by the USGS National Research Program Laboratory in Menlo Park, Calif., using approved methods (Bayless and others, 2004). Natural radium is composed of four isotopes (Focazio and others, 2001), two of which were analyzed for this study: radium-226 (^{226}Ra) and radium-228 (^{228}Ra). ^{226}Ra and ^{228}Ra isotopes were analyzed by Eberline Services in Richmond, Calif., using U.S. Environmental Protection Agency methods 903.1 and 904.0 (U.S. Environmental Protection Agency, 1980), respectively. Results for stable isotope analysis of $^{2/1}H$ and $^{18/16}O$ are reported as delta deuterium (δD) and delta 18-oxygen ($\delta^{18}O$), respectively, which represent the relative difference in parts per thousand (per mil) between the sample isotope ratio and the isotope ratio of a known standard (Kendall and McDonnell, 1998). The molar ratio $^{87/86}Sr$ is computed by dividing the concentration of ^{87}Sr, in moles per liter, by the concentration of ^{86}Sr, in moles per liter. A molar ratio is dimensionless. Results for stable isotope analysis of $^{11/10}B$ are reported as delta 11-boron ($\delta^{11}B$) (Davidson and Bassett, 1993) and as the molar ratio of ^{11}B to ^{10}B ($^{11/10}B$). The values for all ^{226}Ra and ^{228}Ra concentrations are reported in picocuries per liter. Focazio and others (2001, p. v) explain "picocuries per liter is a unit expressing the concentration (or activity) of radionuclides in solution as particles emitted per unit volume (liter) of water. By definition, 1 gram of radium has 1 curie of activity. A picocurie is a millionth of a millionth of a curie. In practical terms, 1 picocurie per liter equals 2.2 radioactive disintegrations per minute per unit volume (liter) of water."

The precision estimate (PE), a common term for radium isotope measurement uncertainty or measurement error (for example, see Inoue and Komura, 2007), was computed at 2 standard deviations (2-sigma) about the count value and the sample-specific critical level (ssL_C) for ^{226}Ra and ^{228}Ra. The ssL_C is the smallest measured concentration calculated from measurements obtained using the same analytical parameter values that were used during the analysis of a sample that is statistically different from the instrument background or analytical blank, and it serves as the detection threshold for deciding whether the radionuclide is present in a sample (McCurdy and others, 2008).

Two stormwater-sample collection sites were established in the study area on small basins in Atascosa County near the ASR site (fig. 1). The drainage area for the western site, USGS streamflow station 08207320 Galvan Creek near Leming, Tex., is 28.4 square miles. The Carrizo Sand and Reklaw Formation are exposed in the upper Galvan Creek watershed. The drainage area for the eastern site, USGS streamflow station 08207350 Gallinas Creek near Leming, Tex., is 11.9 square miles. The Carrizo Sand is exposed in the upper Gallinas Creek watershed. Water-quality data were collected from these sites to help determine what contaminants, if any, might be

entering the Carrizo aquifer through the recharge of runoff following storms.

Stormwater samples were collected from the Galvan Creek and Gallinas Creek sites between April 2004 and February 2005. Selected field properties (pH and specific conductance) were measured and selected water-quality constituents (nutrients, trace elements, oil and grease, and pesticides) were analyzed in the stormwater samples (appendix 3). The Galvan Creek and Gallinas Creek sites were equipped with automatic water samplers programmed to take discrete samples every 30 minutes from a single point in the channel over the duration of a period of runoff. These discrete samples were combined into one flow-weighted composite storm sample per site. In addition to the composite samples, discrete grab samples were collected and analyzed for bacteria (appendix 4) at the USGS Texas Water Science Center in San Antonio, Tex. Four composite and four grab samples were collected at each stormwater-sample collection site. The eight samples represented five discrete storms. Stormwater samples were collected, processed, and preserved using standard USGS protocols as described in the "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated). The concentrations of nutrients, trace elements, oil and grease, and pesticides in the water samples were measured by the USGS NWQL in Denver, Colo., using approved methods (Wershaw and others, 1987; Fishman and Friedman, 1989; Patton and Truitt, 1992, 2000; Fishman, 1993; Garbarino and others, 2006).

Water-Chemistry and Isotope Analysis

Water-chemistry and isotope data were analyzed to evaluate the quality of water in the Carrizo aquifer before and after water from the Edwards aquifer was injected at the ASR site. Water-chemistry and isotope data also were used to evaluate whether any change in water-chemistry or isotope composition occurred in the Edwards aquifer source water as it was transferred through a 38-mile pipeline to the ASR site.

Major-ion, trace element, and isotope data were graphically evaluated to indicate differences between samples of the Edwards aquifer source water before it was injected at the ASR site and samples of native (pre-injection of Edwards aquifer water) Carrizo aquifer water collected from wells near the ASR site, and to assess changes in pre- and post-injection quality of water in the Carrizo aquifer in the study area. For wells sampled more than once, a trilinear diagram (Hem, 1992) and Stiff diagrams (Stiff, 1951) were constructed using major-ion chemistry data to depict changes in water composition. Water composition is depicted as percentage milliequivalents in a trilinear diagram and concentrations of milliequivalents per liter in a stiff diagram. Iron and manganese concentrations, which were observed to be generally much larger in water from the Carrizo aquifer than in water from the Edwards aquifer, were used as indicators of whether the injected Edwards aquifer water might be causing any changes in water chemistry at wells screened in the Carrizo aquifer at or near the ASR site. The major concern was that the injected chlorinated, oxygen-rich Edwards aquifer water might cause an increase in iron or manganese precipitation in parts of the Carrizo aquifer where reducing conditions might be present. Scatter plots of stable isotope data measured in samples collected from the Carrizo aquifer were constructed to help discern whether any changes in isotope chemistry occurred before and after the injection of water from the Edwards aquifer into the Carrizo aquifer.

Quality Control and Quality Assurance of Water-Quality Samples

Quality-assurance procedures outlined in the "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated) were followed for collecting and processing water-quality samples. Three duplicate samples were collected to evaluate potential bias, variability, or contamination introduced during sample collection, processing, or laboratory analysis (appendix 2). Duplicate samples for major ions, nutrients, and trace elements were collected at well WX1 in June 2004. Duplicate samples for major ions and trace elements were collected at well WC2 in September 2005. Duplicate samples were collected for major ions, trace elements, and isotopes at well EC1 in August 2008.

Duplicate samples were compared to the associated environmental samples by calculating the relative percent difference (RPD) for each pair of detected constituents (appendix 2). The RPD was not computed for a constituent pair if one or both of the concentrations either were less than the long-term method detection level (LT–MDL) (nondetection) or were reported as estimated. An estimated concentration is measured between the LT–MDL and the laboratory reporting level, or LRL (two times the LT–MDL) and concentrations less than the LT–MDL are reported as less than the LRL (Childress and others, 1999). Of the total 112 constituent pairs, RPD was computed for 71 pairs. RPD was computed using the equation

$$RPD = |C_1 - C_2|/((C_1 + C_2)/2) \times 100, \qquad (1)$$

where

C_1 = concentration from environmental sample; and
C_2 = concentration from duplicate sample.

RPDs of 15 percent or less indicate good agreement between analytical results if the concentrations are sufficiently large compared to the LRL. For sample pairs for which RPD was computed, the RPD was within 15 percent for all 27 sample pairs of major ions, both sample pairs for nutrients, 30 of 35 sample pairs for trace elements, and all seven sample pairs for isotopes. RPDs of zero were computed for nine sample pairs for major ions, one sample pair for nutrients, and 11 sample pairs for trace elements. The non-zero RPDs between environmental and duplicate samples collected for major ions, nutrients, and trace elements for this study ranged from 0.14

percent for magnesium in well WC2 to 97.7 percent for dissolved iron in well WC2 with a median value of 1.28 percent. The non-zero RPDs between environmental and duplicate samples collected for isotopes for this study ranged from 0.003 percent for $^{87/86}$Sr to 14.0 percent for δ^{11}B in well EC1 with a median of 1.74 percent. Four of the five sample pairs with RPDs exceeding 15 percent for trace elements (dissolved iron being the exception; LRL 6 micrograms per liter [µg/L]) had concentrations that were not sufficiently large compared to the LRL, resulting in a large RPD from a small difference between concentrations.

Quality of Groundwater

Groundwater quality was assessed by aquifer. Water from wells providing Edwards aquifer water for injection into the ASR site was analyzed. Water from wells in the Carrizo aquifer near the ASR site was analyzed before injection of Edwards aquifer water. Water from wells in the Carrizo aquifer both at and near the ASR site was analyzed after injection of Edwards aquifer water to determine how much, if any, mixing of the injected Edwards aquifer water with the native Carrizo aquifer water was evident.

Edwards Aquifer

Major-Ion Chemistry

The major-ion chemistry of groundwater samples collected in May 2005 from the Edward aquifer source wells is indicative of calcium-bicarbonate type water, the dominant groundwater type in the freshwater section of the Edwards aquifer (Lambert and others, 2000; Fahlquist and Ardis, 2004; Otero, 2007). No substantial differences were measured in major-ion chemistry of water samples collected from the ASR injection well compared to major-ion chemistry of water samples collected from the Edwards aquifer source wells (appendix 1). This similarity in the major-ion chemistry indicates no substantial changes in major-ion chemistry occurred as the water was transferred through a 38-mile pipeline from the Edwards aquifer source wells to the ASR injection well.

Trace-Element Chemistry

In the water samples collected from the two Edwards aquifer source wells and the ASR injection well, the dissolved iron concentrations were less than 6 µg/L (LRL) and dissolved manganese concentrations ranged from less than 0.2 µg/L (LRL) to 0.3 µg/L (appendix 1). No substantial differences were measured in trace-element chemistry of water samples collected from the ASR injection well compared to the trace-element chemistry of water samples collected from the Edwards aquifer source wells (appendix 1). The similarity in the trace-element chemistry indicates no substantial changes in trace-element water chemistry occurred as the water was transferred through a 38-mile pipeline from the Edwards aquifer source wells to the ASR injection well.

Isotopes

The relation between δD and δ^{18}O in water samples collected from 25 wells is shown in figure 3. Two meteoric water lines are shown in figure 3. Craig (1961) constructed the global meteoric water line using isotopic signatures from precipitation all over the world, whereas Otero (2007) constructed the local meteoric water line (LMWL) using isotopic signatures from precipitation in south-central Texas. Samples from the Edwards aquifer source wells plotted below the LMWL of $\delta D = 8.8032\ \delta^{18}O + 17.825$ calculated by Otero (2007), indicating that the lighter water molecules were preferentially removed by evaporation before any precipitation could enter the Edwards aquifer as recharge. Similarity of δD and δ^{18}O values in samples collected from Edwards aquifer source wells (represented by triangles in fig. 3) and the ASR injection well (represented by a rectangle in fig. 3) (appendix 1) indicates that little, if any, evaporation of water piped from the Edwards aquifer occurred within the pipeline connecting the Edwards aquifer source wells to the ASR injection well.

The relation between $^{87/86}$Sr and $^{11/10}$B ratios in water samples collected from 24 wells ($^{11/10}$B not measured in NC5) is shown in figure 4. Similar $^{87/86}$Sr and $^{11/10}$B ratios were measured in the samples from the Edwards aquifer source wells and the ASR injection well (a 38-mile pipeline between source wells and injection well), consistent with the similar isotopic ratios of δD and δ^{18}O (fig. 3) measured in samples from these same wells. In samples collected from the Edwards aquifer source wells, $^{87/86}$Sr ratios ranged from 0.70785 in well ED1 to 0.70790 in well ED2 and $^{11/10}$B ratios ranged from 4.157 in well ED2 to 4.161 in well ED1. In the sample from the ASR injection well, $^{87/86}$Sr and $^{11/10}$B ratios were 0.70790 and 4.154, respectively.

The relation between ^{226}Ra and ^{228}Ra in water samples collected from 25 wells is shown in figure 5. The concentrations of ^{226}Ra in the samples collected from the Edwards aquifer source wells (represented by the triangle symbol in fig. 5) were 0.639 and 0.644 picocurie per liter (pCi/L); the concentration of ^{228}Ra was 0.230 pCi/L in well ED1 and a nondetection in well ED2. In the ASR injection well (represented by the rectangle symbol in fig. 5) ^{226}Ra and ^{228}Ra concentrations (0.624 pCi/L and 0.285 pCi/L, respectively) were similar to concentrations in the Edwards aquifer source wells. The similarity in radium isotope concentrations in samples collected from the Edwards aquifer source wells and ASR injection well provides additional evidence of no substantial change in the water quality as the water was piped from the Edwards aquifer source wells to the ASR site.

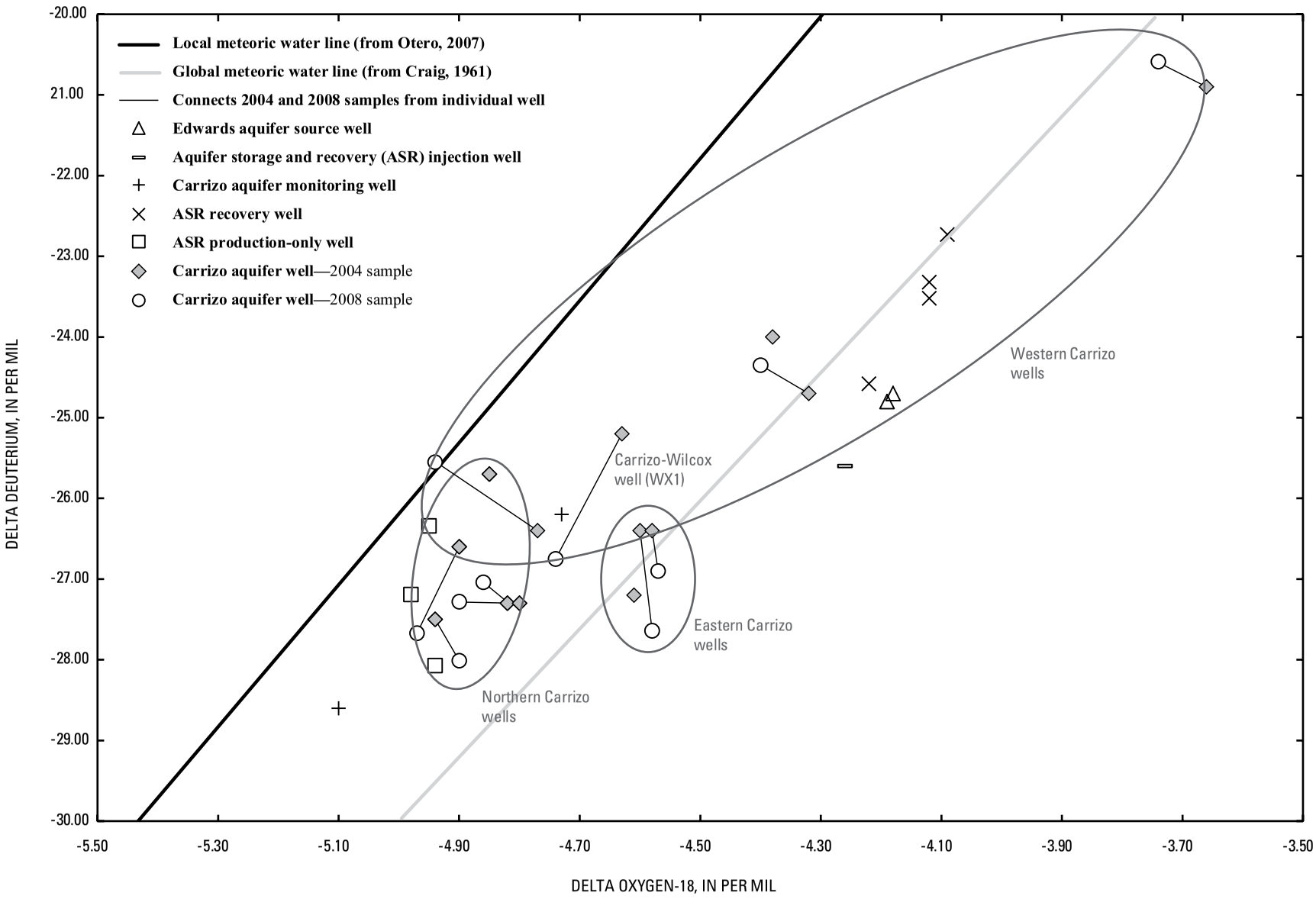

Figure 3. Relation between delta oxygen-18 and delta deuterium for 25 wells screened or open in the Carrizo and Edwards aquifers, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08.

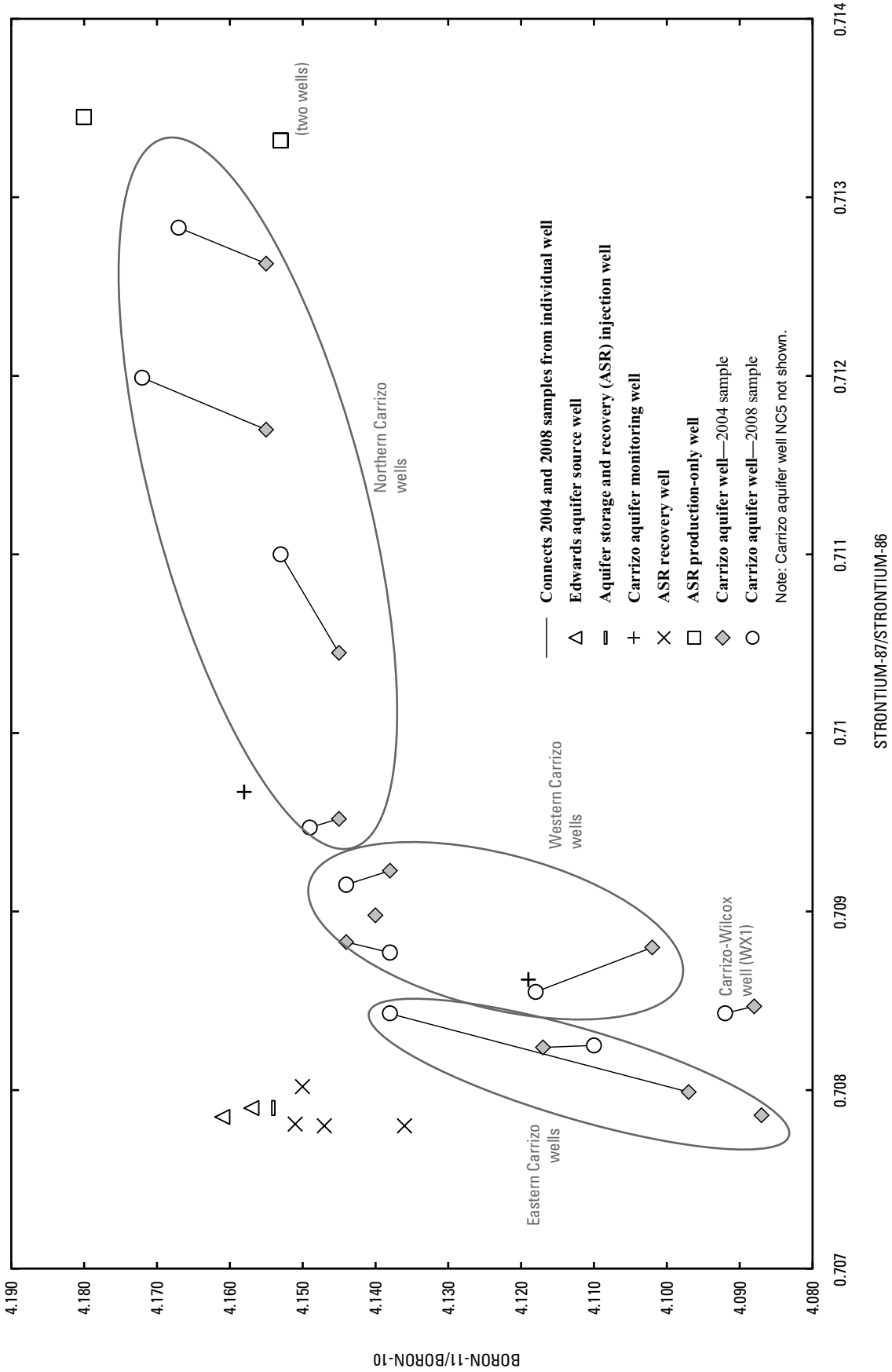

Figure 4. Relation between strontium-87/strontium-86 and boron-11/boron-10 for 24 wells screened or open in the Carrizo and Edwards aquifers, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08.

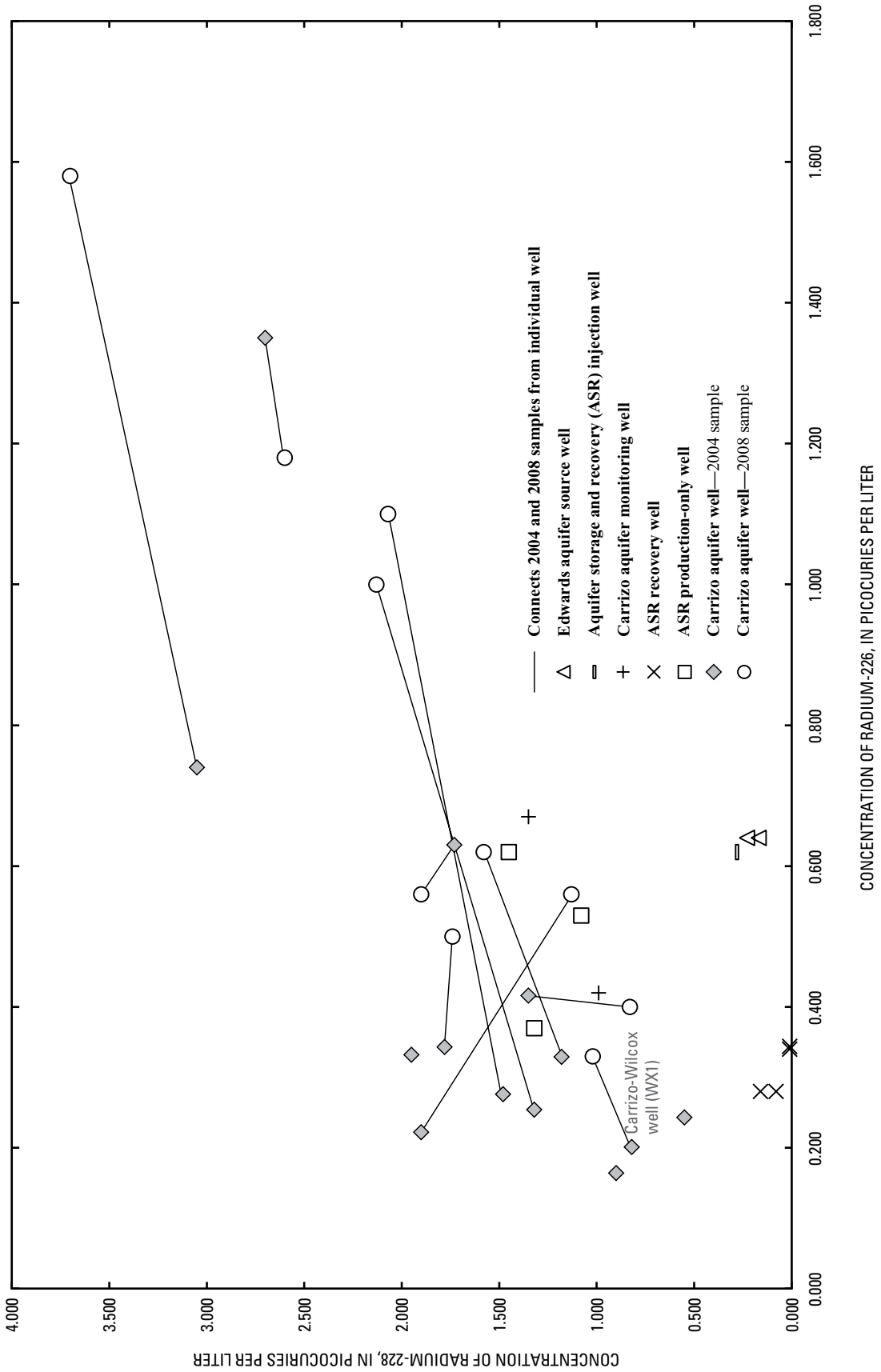

Figure 5. Relation between radium-226 and radium-228 for 25 wells screened or open in the Carrizo and Edwards aquifers, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08.

Pre-Injection Carrizo Aquifer

Before any water from the Edwards aquifer was injected at the ASR site, the quality of groundwater in the Carrizo aquifer was assessed. Samples were collected from the 12 Carrizo wells (2004 Carrizo samples) and the Carrizo-Wilcox well within a 20-mile radius of the ASR site.

Major-Ion Chemistry

Calcium, sodium, bicarbonate, and chloride concentrations in the samples collected from the Carrizo wells varied greatly in the study area, resulting in a wide range of water types. Stiff diagrams (Stiff, 1951) were constructed using the major-ion chemistry from the 2004, 2005, and 2008 Carrizo samples (fig. 6). Because well WX1 is screened in the Wilcox Group, it is not shown in figure 6. Wells NC1, NC2, NC3, NC4, and NC5 (northern Carrizo wells), screened at depths of 292 to 1,058 feet below land surface in the recharge zone and shallow sections of the confined Carrizo aquifer, produced water with small concentrations of major ions, as indicated by the narrow shape of the stiff diagram (fig. 6). Wells WC1, WC2, WC3, and WC4 (western Carrizo wells), screened at depths ranging from 1,124 to 1,938 feet below land surface, produced water with relatively large calcium concentrations compared to water sampled from the other wells in the study area, as indicated by the diamond-shaped stiff diagram (fig. 6). Wells EC1, EC2, and EC3 (eastern Carrizo wells), completed at depths ranging from 1,020 to 2,184 feet below land surface, produced water with relatively large sodium and bicarbonate concentrations compared to the other wells in the study area, as indicated by stiff diagrams that roughly resemble a right-pointing arrow (fig. 6).

Trace-Element Chemistry

In the 2004 Carrizo samples, dissolved iron concentrations ranged from less than 6 µg/L (LRL) in well WC2 to 2,550 µg/L in well NC2, whereas dissolved manganese concentrations ranged from 8.2 µg/L in well EC3 to 132 µg/L in well WC3 (table 3; appendix 1). The largest dissolved iron concentrations in the study area were generally measured in samples collected from the Northern Carrizo wells (1,130 to 2,550 µg/L). The dissolved iron concentration measured in the sample collected from well WX1 was 109 µg/L, which was smaller than the dissolved iron concentrations measured in samples from any northern Carrizo wells. Although well WX1 is in the same area as the northern Carrizo wells, it penetrates the Wilcox Group. 2004 Carrizo samples from all western Carrizo wells, except WC3, had the smallest dissolved iron concentrations in the study area, ranging from less than 6 µg/L (LRL) to 10 µg/L. Well WC3, with major-ion chemistry similar to that of the other western Carrizo wells, had the largest dissolved iron concentration (124 µg/L) compared to samples from the remaining western Carrizo wells; however, the dissolved iron concentration from WC3 was smaller compared to samples from northern Carrizo wells. Dissolved iron concentrations ranged from 16 to 363 µg/L in samples from the eastern Carrizo wells. Dissolved manganese concentrations in 2004 Carrizo samples varied greatly throughout the study area and generally were smaller in eastern Carrizo wells compared to all other Carrizo wells.

Isotopes

In the graph showing the relation between δD and $\delta^{18}O$ (fig. 3), all 2004 Carrizo samples plot below the LMWL line calculated by Otero (2007), indicating that the lighter water molecules were preferentially removed, by various amounts of evaporation, from the precipitation before any of it entered the Carrizo aquifer as recharge. Similar to the highly variable major-ion and trace-element concentrations in the 2004 Carrizo samples, isotope concentrations and ratios in the 2004 Carrizo samples also were highly variable. δD ranged from -27.50 per mil in well NC1 to -20.90 per mil in well WC4, whereas $\delta^{18}O$ ranged from -4.94 per mil in well NC1 to -3.66 per mil in well WC4 (fig. 3; appendix 1). The relation between the isotopic ratios $^{87/86}Sr$ and $^{11/10}B$ in the 2004 Carrizo samples is shown in figure 4. Well NC5 is excluded from this plot because no value for $^{11/10}B$ was measured for the sample collected at this well. The $^{87/86}Sr$ ratios ranged from 0.70786 in well EC3 to 0.71263 in well NC2 and the $^{11/10}B$ ratios ranged from 4.087 in well EC3 to 4.155 in wells NC2 and NC3. The relation of ^{226}Ra and ^{228}Ra in the 2004 Carrizo samples is shown in figure 5. The concentration of ^{226}Ra ranged from 0.164 pCi/L in well EC3 to 1.354 pCi/L in well WC3. The concentration of ^{228}Ra ranged from 0.553 pCi/L in well NC5 to 3.047 pCi/L in well WC4.

Post-Injection Carrizo Aquifer

After water from the Edwards aquifer was injected at the ASR site, the quality of groundwater in the Carrizo aquifer was assessed. Samples from all but two Carrizo wells were collected during either 2005 (2005 Carrizo samples) or 2008 (2008 Carrizo samples), or both, and from the Carrizo-Wilcox well during 2005 and 2008. Samples also were collected in July 2008 at four wells at the ASR site (ASR recovery wells) used for recovery of injected water to characterize post-injection water from the Carrizo aquifer. To indicate the extent to which injected Edwards aquifer water might migrate north, three wells on the north side of the ASR site (ASR production-only wells) designed to pump water from, but not inject water into, the Carrizo aquifer were sampled in July 2008.

Major-Ion Chemistry

With only a few exceptions, major-ion concentrations in post-injection groundwater (2005 and 2008 Carrizo samples) were similar to concentrations in pre-injection groundwater (2004 Carrizo samples) (fig. 6). Slightly larger sulfate

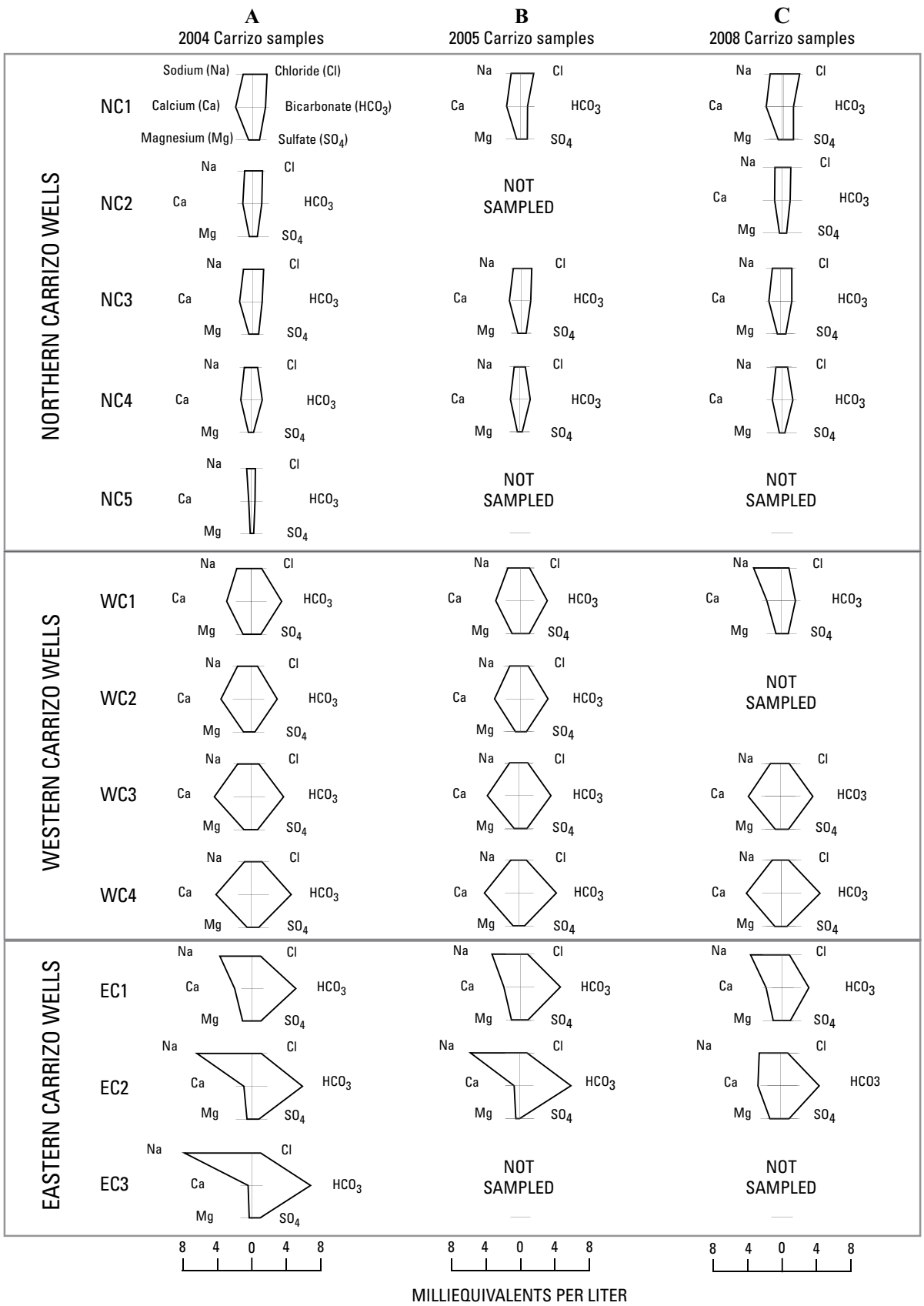

Figure 6. Concentrations of selected cations and anions for wells screened in the Carrizo aquifer in northeastern Atascosa and western Wilson Counties, Texas (A) 2004 Carrizo samples, (B) 2005 Carrizo samples, and (C) 2008 Carrizo samples.

Table 3. Dissolved iron and dissolved manganese concentrations from 11 wells sampled in northeastern Atascosa and western Wilson Counties, Texas, 2004–08, with percent difference between 2005 or 2008 concentrations and 2004 concentration.

[USGS, U.S. Geological Survey; µg/L, micrograms per liter; --, not applicable]

Well name (fig. 1)	USGS site number	State well number	Date	Dissolved iron[1] (µg/L)	Percent difference between 2005 or 2008 dissolved iron concentration and 2004 concentration	Dissolved manganese (µg/L)	Percent difference between 2005 or 2008 dissolved manganese concentration and 2004 concentration
Northern Carrizo wells							
NC1	290205098335601	AL–68–60–851	6/16/2004	1,440	--	77.4	--
			9/21/2005	1,440	0	66.4	-14.2
			8/27/2008	1,240	-13.9	64.6	-16.5
NC2	290727098211301	ZL–68–62–108	6/17/2004	2,550	--	46.6	--
			7/15/2008	4,690	83.9	76.1	63.3
NC3	290849098174001	ZL–68–54–807	6/14/2004	1,400	--	51.7	--
			9/19/2005	2,530	80.7	136	163
			7/21/2008	3,270	134	162	213
NC4	291330098143301	ZL–68–55–111	6/15/2004	2,310	--	125	--
			9/20/2005	2,150	-6.9	136	8.8
			7/14/2008	1,920	-16.9	118	-5.6
Western Carrizo wells							
WC1	290403098293201	AL–68–61–413	6/14/2004	10	--	26.7	--
			9/19/2005	597	5,870	24	-10.1
			8/14/2008	0	-100	34.3	28.5
WC2	290001098250101	AL–68–61–810	6/18/2004	0	--	77	--
			9/19/2005	32	3,200	68.3	-11.3
WC3	285738098301401	AL–78–04–312	6/15/2004	124	--	132	--
			9/21/2005	55	-55.6	161	22.0
			7/11/2008	146	17.7	134	1.5
WC4	285548098310901	AL–78–04–612	6/18/2004	10	--	59.3	--
			9/21/2005	20	100	45.6	-23.1
			7/10/2008	118	1,080	52.2	-12.0
Eastern Carrizo wells							
EC1	290748098085601	ZL–68–55–907	6/15/2004	363	--	19.7	--
			9/20/2005	161	-55.6	14.5	-26.4
			8/13/2008	41	-88.7	12.7	-35.5
EC2	290037098113701	ZL–68–63–803	6/14/2004	16	--	17	--
			9/20/2005	136	750	18.3	7.6
			8/27/2008	30	87.5	22.4	31.8
Carrizo-Wilcox aquifer well							
WX1	291547098153501	ZL–68–46–902	6/17/2004	109	--	24.7	--
			9/20/2005	1,300	1,093	24	-2.8
			7/14/2008	28	-74.3	34.2	38.5

[1] Nondetections considered zero for percent difference computation.

concentrations and slightly smaller bicarbonate concentrations were measured in samples collected from well NC1 in 2005 and 2008 compared to the sulfate and bicarbonate concentrations measured in the sample collected from this well in 2004. Well WC1 had a larger sodium concentration and smaller calcium, magnesium, bicarbonate, and sulfate concentrations in the 2008 sample compared to those concentrations in the 2004 or 2005 samples collected from this well. Larger calcium and magnesium concentrations and a smaller sodium concentration were measured in samples collected in 2008 from well EC2 compared to the concentrations measured in samples collected from this well in 2004 and 2005. Additional temporal samples would be necessary to determine whether these fluctuations in major-ion chemistry indicate an influence from the ASR operations on groundwater quality because the chemistry of the Carrizo aquifer naturally might vary spatially in the study area.

The major-ion chemistry for samples collected in May 2005 from the Edwards aquifer source wells, ASR injection well, and Carrizo aquifer monitoring wells and for samples collected in July 2008 from the ASR recovery wells and ASR production-only wells is represented by a trilinear diagram (fig. 7). Larger chloride and sodium concentrations and smaller bicarbonate concentrations were measured in samples collected from the Carrizo aquifer monitoring wells compared to samples collected from the Edwards-aquifer source wells and ASR injection well. The samples collected from the four ASR recovery wells were similar in major-ion chemistry compared to samples collected from the Edwards aquifer source wells and ASR injection well. The similarity could indicate that as Edwards aquifer water was injected, it displaced native Carrizo aquifer water, or alternatively, if mixing of Edwards and Carrizo aquifer waters was occurring, the major-ion signature for the Carrizo aquifer water might have been obscured by the signature of the injected Edwards aquifer water. The ASR production-only wells were 0.75 to 1.25 miles from the nearest ASR recovery well. Larger concentrations of sodium and chloride and smaller concentrations of bicarbonate were measured in samples collected from the ASR production-only wells compared to those concentrations in samples collected from the ASR recovery wells. Because the open intervals and pump depths for all seven wells (four ASR recovery

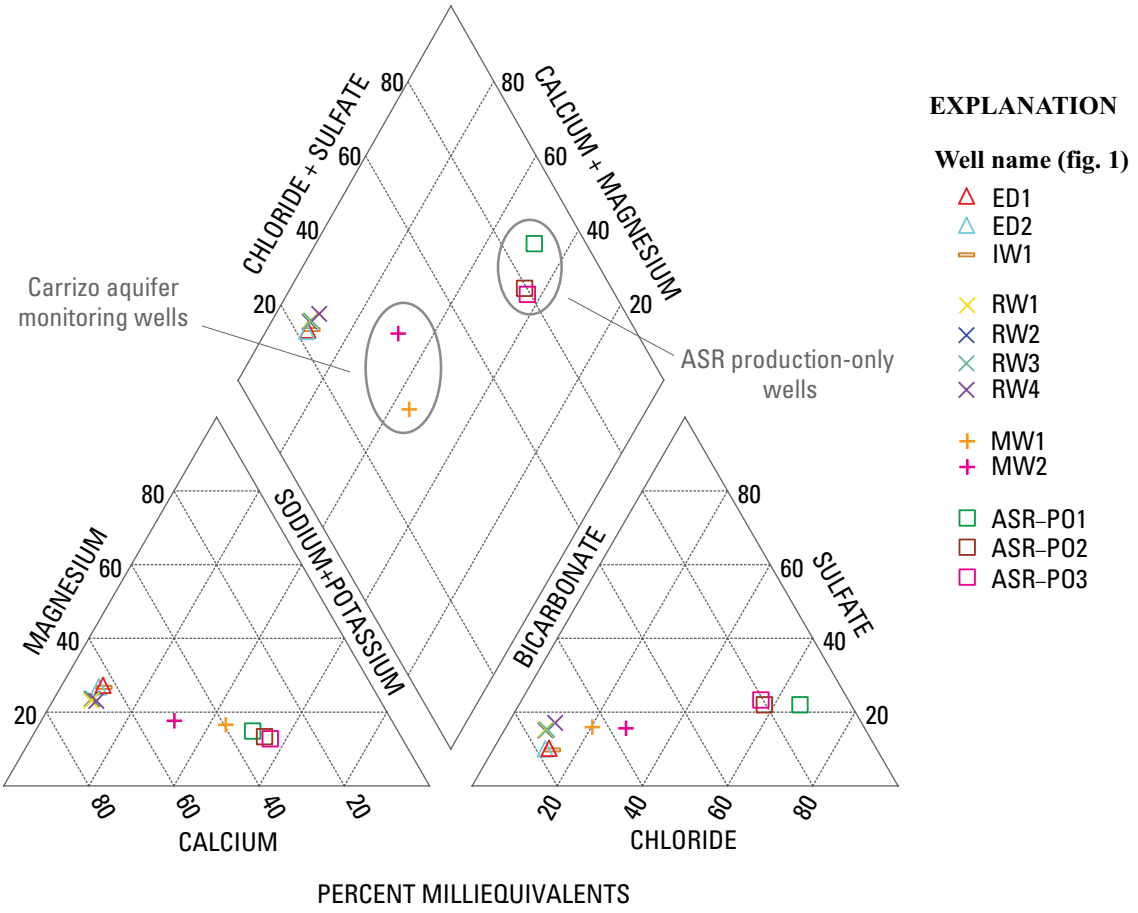

Figure 7. Trilinear diagram showing composition of Edwards aquifer water injected at an aquifer storage and recovery (ASR) site, May 2005, and composition of water recovered from ASR site, July 2008, southern Bexar County, Texas.

wells and three ASR production-only wells) that samples were collected from in July 2008 are within approximately the same interval (table 1), the differences in major-ion chemistry might indicate that Edwards aquifer water being injected at the ASR site did not migrate north after entering the Carrizo aquifer by July 2008.

Trace-Element Chemistry

Dissolved iron concentrations in the 2005 Carrizo samples ranged from 20 µg/L in well WC4 to 2,530 µg/L in well NC3; dissolved manganese concentrations ranged from 14.5 µg/L in well EC1 to 161 µg/L in well WC3. Dissolved iron concentrations in the 2008 Carrizo samples ranged from less than 8 µg/L (LRL) in well WC1 to 4,690 µg/L in well NC2; dissolved manganese concentrations ranged from 12.7 µg/L in well EC1 to 162 µg/L in well NC3. The percent difference (PD) between the post-injection concentration (2005 or 2008 Carrizo sample) and the pre-injection concentration (2004 sample) was computed using the equation

$$PD = ((C_1 - C_3)/C_3) \times 100, \qquad (2)$$

where

C_1 = 2005 or 2008 concentration from environmental sample; and

C_3 = 2004 concentration from environmental sample.

The dissolved iron PDs for the 2005 Carrizo samples ranged from a 55.6-percent decrease in wells WC3 and EC1 to a 5,870-percent increase in well WC1. The dissolved manganese PDs for the 2005 Carrizo samples ranged from a 26.4-percent decrease in well EC1 to a 163-percent increase in well NC3. No spatial patterns were observed in PDs for either dissolved iron or dissolved manganese concentrations for the study area in 2005.

The dissolved iron PDs for the 2008 Carrizo samples ranged from a 100-percent decrease in well WC1 to a 1,080-percent increase in well WC4. Dissolved iron PDs were positive for both 2005 and 2008 Carrizo samples in wells NC3, WC4, and EC2 and negative for both 2005 and 2008 Carrizo samples in wells NC4 and EC1. The dissolved manganese PDs for the 2008 Carrizo samples ranged from a 35.5-percent decrease in well EC1 to a 213-percent increase in well NC3. Dissolved manganese PDs were positive for both 2005 and 2008 Carrizo samples in wells NC3, WC3, and EC2 and negative for both 2005 and 2008 Carrizo samples in wells NC1, WC4, and EC1. The changes in dissolved iron and dissolved manganese concentrations cannot be attributed to ASR operations with the small amount of data collected for this study.

Larger dissolved iron and dissolved manganese concentrations, in general, were measured in the samples collected from the Carrizo aquifer compared to those concentrations in samples collected from the Edwards aquifer. The Carrizo aquifer monitoring wells (MW1 and MW2) produced water with dissolved iron concentrations of 95 and 6,020 µg/L, respectively, and dissolved manganese concentrations of 15.1 and 124 µg/L, respectively (appendix 1). In the ASR recovery wells dissolved iron concentrations ranged from 5 µg/L (estimated) in well RW1 to 279 µg/L in well RW4 and dissolved manganese concentrations ranged from 5.8 µg/L in well RW2 to 15.8 µg/L in well RW4, consistently larger than those concentrations in the samples collected from the Edwards aquifer source wells. These data indicate that after the Edwards aquifer source water was injected at the ASR site, it might have mixed with the native Carrizo aquifer; a mix of water from both aquifers would explain the dissolved iron and dissolved manganese concentrations that are different from those concentrations in either the native Carrizo aquifer water or the Edwards aquifer water. Another possibility is that Edwards aquifer water displaced Carrizo aquifer water as it was injected, and water from the Edwards aquifer dissolved the iron and manganese directly from the Carrizo Sand, which has naturally large iron and manganese concentrations (Pearson and White, 1967). Dissolved iron concentrations in the ASR production-only wells ranged from 373 µg/L in well ASR–PO2 to 683 µg/L in well ASR–PO1 and dissolved manganese concentrations ranged from 9.2 µg/L in well ASR–PO3 to 25.4 µg/L in well ASR–PO1. Similar to the observation for major-ion chemistry, the trace-element chemistry also appears to indicate that the injected Edwards aquifer source water did not migrate north by July 2008.

Isotopes

For the 2008 Carrizo samples, δD ranged from -28.01 per mil in well NC1 to -20.59 per mil in well WC4 and $\delta^{18}O$ ranged from -4.97 per mil in well NC4 to -3.74 per mil in well WC4 (fig. 3; appendix 1). No substantial differences in either δD or $\delta^{18}O$ were observed between the 2004 and 2008 Carrizo samples, indicating that the Edwards aquifer source water did not affect the isotope chemistry of the native Carrizo aquifer water in the 2008 Carrizo samples.

In the graph showing the relation between δD and $\delta^{18}O$ (fig. 3), all but one 2008 Carrizo sample plotted below the LMWL calculated by Otero (2007), indicating that the lighter water molecules were preferentially removed, by various amounts of evaporation, from the precipitation before any of it entered the Carrizo aquifer as recharge. Similarities in δD and $\delta^{18}O$ in samples collected from the Edwards aquifer source wells, ASR injection well, and ASR recovery wells indicate little change in isotopic composition between the time of injection and the time of recovery, supporting the premise that the injected Edwards aquifer source water displaced native water in the Carrizo aquifer as it was injected. The differences in the isotopic ratios of the Edwards aquifer source wells, ASR injection well, and ASR recovery wells compared to those in the ASR production-only wells again indicate that the source water, once injected, did not migrate north in the subsurface by July 2008. The isotopic ratios from the Carrizo aquifer monitoring well samples were more similar to those from the ASR production-only well samples than from the Edwards

aquifer source water samples. However, the isotopic ratios from Carrizo aquifer monitoring well MW2, closest to the zone of injection, are heavier than the isotopic ratios from Carrizo aquifer monitoring well MW1 or from the ASR production-only wells (fig. 3). The pattern observed in the isotopic ratios indicates there might be some mixing of native Carrizo aquifer water with Edwards aquifer source water.

For the 2008 Carrizo samples, $^{87/86}$Sr ratios ranged from 0.70825 in well EC1 to 0.71283 in well NC2 and $^{11/10}$B ratios ranged from 4.110 in well EC1 to 4.172 in well NC3 (fig. 4; appendix 1). The smallest $^{11/10}$B ratio (4.092) of all wells sampled in the study area during 2008 was in the sample from well WX1, the well later determined to be partially screened in the Carrizo-Wilcox aquifer. Compared to the 2004 Carrizo samples and the Edwards aquifer source well samples, no substantial change in $^{87/86}$Sr and $^{11/10}$B ratios were observed in the 2008 Carrizo samples, again indicating that the Edwards aquifer source water has not affected the isotope chemistry of the native Carrizo aquifer water post-injection by July 2008.

Samples collected from the ASR recovery wells produced $^{87/86}$Sr ratios that ranged from 0.70780 in wells RW1 and RW3 to 0.70802 in well RW4 and $^{11/10}$B ratios that ranged from 4.136 in well RW1 to 4.151 in well RW2. These ratios are comparable to the ratios for the Edwards aquifer source wells and the ASR injection well, indicating no substantial change occurred in these isotopic ratios as the water was stored in the subsurface. In contrast, $^{87/86}$Sr and $^{11/10}$B ratios for samples collected from ASR production-only wells were substantially different from $^{87/86}$Sr and $^{11/10}$B ratios for samples collected from ASR recovery wells, providing additional evidence that the injected Edwards aquifer source water did not migrate north by July 2008 (fig. 4).

The smallest ^{226}Ra concentration of all wells sampled in the study area during 2008 was 0.327 pCi/L in well WX1, which is partially screened in the Carrizo-Wilcox aquifer. ^{226}Ra concentrations in the 2008 Carrizo samples ranged from 0.402 pCi/L in well NC3 to 1.580 pCi/L in well WC4, whereas ^{228}Ra concentrations ranged from 0.829 pCi/L in well NC3 to 3.690 pCi/L in well WC4 (fig. 5; appendix 1). Although ^{226}Ra concentrations are mostly larger in 2008 Carrizo samples compared to ^{226}Ra concentrations in 2004 Carrizo samples, there does not appear to be a consistent shift in the plotted positions of ^{226}Ra and ^{228}Ra concentrations in the 2008 Carrizo samples toward the plotted positions of ^{226}Ra and ^{228}Ra concentrations measured in samples from either Edwards aquifer source wells or ASR recovery wells. The distinction between ^{226}Ra and ^{228}Ra concentrations in Carrizo aquifer samples from those in Edwards aquifer source water samples provides additional evidence that Edwards aquifer source water has not affected the concentration of radium isotopes in the Carrizo aquifer near the ASR site.

^{226}Ra concentrations in samples collected from the ASR recovery wells ranged from 0.277 pCi/L in well RW2 to 0.344 pCi/L in well RW3 (appendix 1); ^{228}Ra concentrations were not detected in the ASR recovery wells. Ranges in concentrations of ^{226}Ra and ^{228}Ra in the Edwards aquifer source wells and in the ASR injection well were similar. The concentrations of ^{226}Ra and ^{228}Ra in the samples collected at all four ASR recovery wells were noticeably smaller than the concentrations in samples collected from the Edwards aquifer source wells and the ASR injection well. The half-life of ^{226}Ra is approximately 1,600 years (Wieser, 2005); therefore, the smaller ^{226}Ra concentrations indicate that some mixing of the Edwards aquifer water and the Carrizo aquifer water might have occurred in the subsurface after the source water had been injected. Carrizo aquifer monitoring wells MW1 and MW2 produced water with ^{226}Ra concentrations of 0.419 and 0.672 pCi/L, respectively, and ^{228}Ra concentrations of 0.987 and 1.352 pCi/L, respectively. The ASR production-only wells produced water with ^{226}Ra concentrations that ranged from 0.374 pCi/L in well ASR–PO3 to 0.619 pCi/L in well ASR–PO1 and ^{228}Ra concentrations that ranged from 1.080 pCi/L in well ASR–PO2 to 1.450 pCi/L in well ASR–PO1. Concentrations of ^{226}Ra and ^{228}Ra in samples from the Carrizo aquifer monitoring wells and the ASR production-only wells were within a similar range indicating that the wells might have been producing from a single water source that differed from the water source for the Edwards aquifer source wells and ASR recovery wells.

Summary

The U.S. Geological Survey (USGS), in cooperation with the San Antonio Water System (SAWS), did a study during 2004–08 to characterize the quality of native groundwater from the Edwards aquifer and pre- and post-injection water from the Carrizo aquifer (informal name commonly applied to the upper part of the Carrizo-Wilcox aquifer in the area) at and near an aquifer storage and recovery (ASR) site in Bexar, Atascosa, and Wilson Counties, Tex. Findings of the study are intended to provide a better understanding of possible changes in the quality of groundwater near an active ASR site that might result from the mixing of water from different aquifers. Possible iron and manganese mobilization, caused by changes in reduction-oxidation (redox) reaction conditions in an aquifer that might occur when non-native water is introduced to the aquifer, was a concern at the ASR site.

Groundwater samples were collected and analyzed for selected physical properties and constituents to characterize the quality of native groundwater from the Edwards aquifer and pre- and post-injection water from the Carrizo aquifer near the ASR site. Water-chemistry and isotope data were analyzed to evaluate the quality of water in the Carrizo aquifer prior to and after water from the Edwards aquifer was injected at the ASR site. Water-chemistry and isotope data also were used to evaluate whether any change in water-chemistry or isotope composition occurred in the Edwards aquifer source water as it was transferred through a 38-mile pipeline to the ASR site. Groundwater sampling was done four times during the study. Water-quality constituent concentrations and physical properties were measured in May 2005 in samples collected from

the Edwards aquifer source wells. Groundwater-chemistry and isotope data also were measured in samples collected in May 2005 at the wellhead of an ASR injection well, which is screened in the Carrizo aquifer at the ASR site and used for injecting water from the Edwards aquifer source wells into the Carrizo aquifer. Pre-injection Carrizo aquifer water was characterized by analyzing samples collected from 12 wells (2004 Carrizo wells) screened in the Carrizo aquifer near the ASR site. Samples from these wells were collected in June 2004 before injection of Edwards aquifer water into the Carrizo aquifer. Post-injection Carrizo aquifer water near the ASR site was characterized after injection of Edwards aquifer water began at the ASR site. Water-quality samples were collected in September 2005 (2005 Carrizo wells) and during July–August 2008 (2008 Carrizo wells) at selected subsets of the 2004 Carrizo wells. Two Carrizo aquifer monitoring wells at and near the ASR site completed in the Carrizo aquifer were sampled in May 2005. To characterize post-injection water from the Carrizo aquifer, samples also were collected in July 2008 at four wells (ASR recovery wells) at the ASR site used to recover injected water. To indicate the extent to which injected Edwards aquifer water might migrate north, three wells (ASR production-only wells) on the north side of the ASR site, designed to pump water from but not inject water into the Carrizo aquifer, were sampled in July 2008. Water-quality data also were collected from two stormwater sampling sites near the ASR site to identify surface-water contaminants, if any, that potentially could enter the Carrizo aquifer through recharge. Because only eight stormwater samples (representing five storms) could be collected, the stormwater analytical data were included in the appendix but not assessed in the report.

Geochemical and isotope data from the samples collected from the Edwards aquifer source wells and the ASR injection well indicate no substantial changes in major-ion, trace-element, and isotope chemistry occurred as the water was transferred through a 38-mile pipeline from the Edwards aquifer source wells to the ASR injection well. Geochemical and isotope data from the Edwards aquifer source wells, ASR injection well, and ASR recovery wells were graphically analyzed to help evaluate in a preliminary way if water in the Carrizo aquifer had undergone any chemical changes after Edwards aquifer source water was injected at the ASR site. Only minor differences in major-ion and stable isotope chemistry measured in samples collected from the Edwards aquifer source wells, ASR injection well, and the four ASR recovery wells were observed. The samples collected from the four ASR recovery wells were similar in major-ion and stable isotope chemistry compared to the samples collected from the Edwards aquifer source wells and the ASR injection well. The similarity could indicate that as Edwards aquifer water was injected, it displaced native Carrizo aquifer water or, alternatively, if mixing of Edwards and Carrizo aquifer waters was occurring, the major-ion and stable isotope signatures for the Carrizo aquifer water might have been obscured by the signatures of the injected Edwards aquifer water. Dissolved iron and dissolved manganese concentrations in samples collected from the ASR recovery wells were consistently larger than those in the samples collected from the Edwards aquifer source wells. These data indicate that after the Edwards aquifer source water was injected at the ASR site, it might have mixed with the native Carrizo aquifer; a mix of water from both aquifers would explain the dissolved iron and dissolved manganese concentrations that are different from those in either the native Carrizo aquifer water or the Edwards aquifer water. Another possibility is that Edwards aquifer water displaced Carrizo aquifer water as it was injected, and water from the Edwards aquifer dissolved the iron and manganese directly from the Carrizo Sand, which has naturally large iron and manganese concentrations. Concentrations of Ra-226 and Ra-228 in the Edwards aquifer source wells and ASR injection well were within a similar range. The concentrations of Ra-226 and Ra-228 in the samples collected at all four ASR recovery wells were noticeably smaller than the concentrations in samples collected from the Edwards aquifer source wells and from the ASR injection well. The half-life of Ra-226 is approximately 1,600 years; therefore the smaller Ra-226 concentrations indicate that some mixing of the Edwards aquifer water and the Carrizo aquifer water might have occurred in the subsurface after the source water had been injected.

Geochemical and isotope data measured in samples collected from the Carrizo aquifer monitoring wells and the ASR production-only wells were graphically analyzed with the Edwards aquifer source wells, ASR injection well, and ASR recovery wells to determine the extent injected Edwards aquifer water might have migrated to the south by May 2005 and to the north by July 2008. The distinctness of the major-ion, trace-element, and isotope data collected from the Carrizo aquifer monitoring wells and ASR production-only wells in relation to the data collected from the Edwards aquifer source wells, ASR injection well, and ASR recovery wells indicates that injected Edwards aquifer water had not migrated either to the monitoring wells located in the southern section of the ASR site and south of the ASR site by May 2005 or to the ASR production-only wells located in the northern section of the ASR site by July 2008.

Geochemical and isotope data measured from samples collected from the 2004 Carrizo wells, 2005 Carrizo wells, and 2008 Carrizo wells were graphically analyzed to determine if any changes in chemistry could be discerned. Major-ion, trace-element, and isotope chemistry varied spatially in the samples collected from the Carrizo aquifer. The northern Carrizo wells (wells NC1, NC2, NC3, NC4, and NC5, in the northern part of the study area) produced water with small major-ion concentrations. The western Carrizo wells (wells WC1, WC2, WC3, and WC4, in the western part of the study area) produced water with relatively large calcium concentrations compared to water sampled from the other wells in the study area. The eastern Carrizo wells (wells EC1, EC2 and EC3 in the southeastern part of the study area) contained water with relatively large sodium and bicarbonate concentrations. With the exception of a few samples, major-ion concentrations measured in samples

collected from Carrizo aquifer wells in 2004, 2005, and 2008 were similar. A slightly larger sulfate concentration and a slightly smaller bicarbonate concentration were measured in samples collected in 2005 and 2008 from well NC1 compared to samples collected at well NC1 in 2004. Larger sodium concentrations and smaller calcium, magnesium, bicarbonate, and sulfate concentrations were measured in samples collected in 2008 from well WC1 than in samples collected at this well in 2004 and 2005. Larger calcium and magnesium concentrations and a smaller sodium concentration were measured in the samples collected in 2008 at well EC2 compared to samples collected at this well in 2004 and 2005. While in some cases the computed percent difference (compared to concentrations from June 2004) in dissolved iron and dissolved manganese concentrations in 11 wells sampled in the Carrizo aquifer in 2005 and 2008 were quite large, no trends that might have been caused by migration of injected Edwards aquifer water were observed. Because of the variation in geochemical data in the Carrizo aquifer, differences in major-ion and trace-element data between the three sampling periods cannot be directly attributed to the ASR site operations using the small data set collected for this study. No appreciable difference in isotope data from 2004 and 2008 Carrizo wells were discerned, indicating that the Edwards aquifer source water might not have affected the isotope chemistry of the native Carrizo aquifer water near the sampled Carrizo wells by July 2008.

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Appendixes 1–4

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Appendix 1. Chemical and isotope data from wells sampled at and near an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08.

[NTRU, nephelometric turbidity ratio units; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; $CaCO_3$, calcium carbonate; <, less than; ASR, aquifer storage and recovery; --, not analyzed for or not detected; E, estimated; dup, duplicate; µg/L, micrograms per liter; M, presence verified but not quantified; ^{226}Ra, radium-226; pCi/L, picocuries per liter; PE, precision estimate; ssL_C, sample-specific critical level; ^{228}Ra, radium-228; $^{87/86}$Sr, strontium-87/strontium-86; $^{11/10}$B, boron-11/boron-10; δ^{11}B, delta boron-11; δ^{18}O, delta oxygen-18; δD, delta deuterium; R, nondetection; blue shading, 2004 Carrizo samples; pink shading, 2005 Carrizo samples; green shading, 2008 Carrizo samples]

Well name (fig. 1)	U.S. Geological Survey site number	State well number	Date	Time	Turbidity (NTRU)	Dissolved oxygen (mg/L)	pH (standard units)	Specific conductance (µS/cm)	Temperature, water (°C)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L)	Carbonate (mg/L)
Edwards aquifer source wells																
ED1	292557098261401	AY–68–37–508	5/9/2005	1345	<2.0	4.9	7.3	510	27.0	70.9	18.30	1.25	11.6	200	243	<1
ED2	292643098242101	AY–68–37–610	5/9/2005	1425	<2.0	4.7	7.3	505	27.0	71.0	18.00	1.23	11.4	199	242	<1
ASR injection well																
IW1	290750098235301	AY–68–53–912	5/9/2005	1600	<2.0	5.9	7.5	510	26.5	72.5	18.20	1.27	11.7	199	241	<1
Carrizo aquifer monitoring wells																
MW1	290425098260301	AL–68–61–505	5/31/2005	1730	10	<1.0	8.3	367	27.0	28.7	7.24	13.5	28.7	113	137	<1
MW2	290657098242401	AY–68–61–321	5/12/2005	1820	--	<1.0	6.8	323	26.5	28.6	6.00	6.09	16.6	78	95	<1
ASR recovery wells																
RW1	290732098251101	AY–68–53–811	7/18/2008	0800	<2.0	3.1	7.1	520	25.0	73.1	15.20	1.39	11.1	200	243	<1
RW2	290751098243101	AY–68–53–911	7/18/2008	0900	<2.0	4.2	7.2	516	24.5	70.9	15.10	1.38	10.3	200	243	<1
RW3	290809098232301	AY–68–53–913	7/18/2008	1100	<2.0	3.0	7.1	515	24.5	71.8	15.40	1.42	10.6	197	240	<1
RW4	290657098242801	AY–68–61–319	7/18/2008	1000	2.4	3.1	7.0	E474	25.0	62.4	13.50	2.07	11.8	169	206	<1
ASR production-only wells																
ASR–PO1	290841098234001	AY–68–53–915	7/28/2008	1400	<2.0	3.8	5.8	E336	25.5	19.3	4.98	7.04	28.2	18	21	<1
ASR–PO2	290838098241401	AY–68–53–916	7/28/2008	1430	<2.0	3.7	5.8	E208	25.0	11.0	2.77	5.8	18.3	17	21	<1
ASR–PO3	290844098243601	AY–68–53–917	7/28/2008	1500	<2.0	3.9	5.9	E212	25.0	10.6	2.72	5.67	19.4	18	21	<1
Northern Carrizo wells																
NC1	290205098335601	AL–68–60–851	6/16/2004	1400	13	<1.0	6.4	421	28.5	38.2	5.88	7.21	25.2	68	E83	E<1
			9/21/2005	1130	<2.0	1.7	5.9	416	28.0	32.5	5.23	7.37	25.0	44	54	<1
			8/27/2008	0900	E1.9	3.3	6.5	462	28.0	39.3	7.07	8.59	35.1	56	69	<1
NC2	290727098211301	ZL–68–62–108	6/17/2004	1100	22	E5.5	E6.8	E304	E27.5	22.1	4.72	6.37	20.7	48	E59	E<1
			7/15/2008	1800	12	1.7	6.3	E270	28.0	18.1	4.04	6.54	19.6	45	54	<1
NC3	290849098174001	ZL–68–54–807	6/14/2004	1130	5.3	<1.0	6.1	346	29.0	28.3	4.77	7.37	22.9	55	E67	E<1
			9/19/2005	1310	13	3.9	6.6	349	29.0	28.9	4.97	7.35	22.0	58	70	<1
			7/21/2008	0900	9.6	E4.2	E7.7	E312	E27.0	27.2	4.95	7.62	22.5	63	76	<1
NC4	291330098143301	ZL–68–55–111	6/15/2004	0930	21	<1.0	6.4	255	24.0	22.8	3.45	5.18	17.2	63	E77	E<1
			9/20/2005	1030	16	2.9	6.5	253	24.5	22.7	3.46	5.1	15.5	64	78	<1
			7/14/2008	1100	13	4.1	6.7	E247	24.5	21.7	3.43	5.41	15.8	63	77	<1
NC5	291728098052401	ZL–68–48–708	6/16/2004	1020	<2.0	1.0	5.9	142	23.5	6.2	1.72	6.55	12.2	20	E24	E<1
Western Carrizo wells																
WC1	290403098293201	AL–68–61–413	6/14/2004	1330	2.5	5.9	7.2	561	29.0	54.1	11.20	6.92	36.4	167	E204	E<1
			9/19/2005	1010	5.7	4.5	7.2	531	29.5	58.8	11.70	7.16	34.0	162	198	<1
			8/14/2008	1200	E1.9	4.1	7.8	549	29.5	32.4	7.07	6.14	72.1	E82	100	<1
WC2	290001098250101	AL–68–61–810	6/18/2004	0950	3.4	5.2	7.6	503	33.0	60.7	6.61	5.68	27.3	158	E193	E<1
			9/19/2005	1030	2.6	5.9	7.6	507	33.5	61.4	7.01	6.21	28.6	167	204	<1
			9/19/2005 dup	1035	2.8	5.9	7.6	507	33.5	61.4	7.00	6.14	28.6	165	201	<1
WC3	285738098301401	AL–78–04–312	6/15/2004	1330	4.4	<1.0	7.0	589	34.0	77.3	7.40	5.61	29.2	188	E229	E<1
			9/21/2005	1000	3.1	4.8	7.0	588	34.0	76.6	7.37	5.53	26.4	191	233	<1
			7/11/2008	1000	E1.7	5.2	7.5	565	33.0	74.2	7.60	5.74	27.1	184	224	<1
WC4	285548098310901	AL–78–04–612	6/18/2004	1230	10	<1.0	7.1	584	34.5	82.5	8.77	6.35	23.1	206	E251	E<1
			9/21/2005	1050	<2.0	4.7	7.1	584	35.5	84.2	9.00	6.46	23.6	223	272	<1
			7/10/2008	0900	2.4	5.5	7.5	589	35.5	79.4	9.09	6.51	23.5	220	267	<1
Eastern Carrizo wells																
EC1	290748098085601	ZL–68–55–907	6/15/2004	1030	3.9	<1.0	7.2	668	35.5	39.3	13.00	10.4	82.8	243	E296	E<1
			9/20/2005	1140	<2.0	3.0	7.4	651	35.5	39.2	12.80	10.4	78.0	242	294	<1
			8/13/2008	1400	<2.0	E4.0	E7.6	E662	E35.5	36.1	12.20	10.7	82.2	E155	E188	E<1
			8/13/2008 dup	1405	<2.0	E4.0	E7.6	E662	E35.5	36.0	12.20	10.6	82.7	E139	E169	E<1
EC2	290037098113701	ZL–68–63–803	6/14/2004	0950	<2.0	<1.0	7.5	682	42.5	17.4	6.34	7.74	138	279	E340	E<1
			9/20/2005	1318	5.9	2.2	7.7	697	42.5	12.8	5.05	6.94	135	312	378	1
			8/27/2008	1100	4.7	3.4	7.6	652	45.0	51.2	14.20	11.0	55.7	223	271	<1
EC3	291122098062301	ZL–68–56–408	6/18/2004	1030	<2.0	<1.0	7.7	816	30.5	8.1	3.40	5.88	172	327	E399	E<1
Carrizo-Wilcox well																
WX1	291547098153501	ZL–68–46–902	6/17/2004	1000	9.8	<1.0	7.3	1,710	26.0	57.7	18.40	5.51	304	267	E326	E<1
			6/17/2004 dup	1010	10	--	7.3	1,710	26.0	57.0	18.60	5.45	308	267	E326	E<1
			9/20/2005	1108	9.8	4.4	7.5	1,720	26.5	57.2	18.90	5.39	288	262	318	<1
			7/14/2008	0900	19	3.4	7.6	1,720	25.0	55.6	17.70	5.59	288	264	319	1

Appendix 1. Chemical and isotope data from wells sampled at and near an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08—Continued.

Well name (fig. 1)	Date	Hydroxide (mg/L)	Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L)	Sulfate (mg/L)	Residue (sum of constituents) (mg/L)	Dissolved ammonia plus organic nitrogen (mg/L)	Dissolved ammonia nitrogen (mg/L)	Dissolved nitrate plus nitrite nitrogen (mg/L)	Dissolved nitrite nitrogen (mg/L)	Dissolved orthophosphate phosphorus (mg/L)	Dissolved phosphorus (mg/L)	Aluminum (µg/L)	Antimony (µg/L)	Arsenic (µg/L)
Edwards aquifer source wells																
ED1	5/9/2005	<1	23.6	0.28	13.2	24.8	289	--	--	--	--	--	--	4.3	<0.20	0.60
ED2	5/9/2005	<1	23.1	.29	13.2	23.9	295	--	--	--	--	--	--	2.8	<.20	.50
ASR injection well																
IW1	5/9/2005	<1	24.4	.54	13.5	23.8	290	--	--	--	--	--	--	16.3	<.20	.70
Carrizo aquifer monitoring wells																
MW1	5/31/2005	<1	25.4	.28	11.5	26.7	221	--	--	--	--	--	--	6.0	<.20	.30
MW2	5/12/2005	<1	28.1	.18	17.8	20.7	193	--	--	--	--	--	--	E.9	<.20	.60
ASR recovery wells																
RW1	7/18/2008	<1	19.2	.35	11.8	39.3	264	--	--	--	--	--	--	1.8	<.14	.79
RW2	7/18/2008	<1	18.6	.47	11.3	38.9	299	--	--	--	--	--	--	E1.5	<.14	.90
RW3	7/18/2008	<1	18.8	.47	11.5	39.3	313	--	--	--	--	--	--	E1.2	<.14	.82
RW4	7/18/2008	<1	21.5	.40	13.4	39.4	255	--	--	--	--	--	--	E1.1	<.14	1.10
ASR production-only wells																
ASR–PO1	7/28/2008	<1	64.1	E.08	24.6	29.2	213	--	--	--	--	--	--	<1.6	<.14	.20
ASR–PO2	7/28/2008	<1	35.0	<.12	24.4	18.0	147	--	--	--	--	--	--	<1.6	<.14	.14
ASR–PO3	7/28/2008	<1	34.8	E.06	24.9	19.3	142	--	--	--	--	--	--	<1.6	<.14	.28
Northern Carrizo wells																
NC1	6/16/2004	E<1	54.6	<.17	16.4	34.3	238	<0.10	E0.03	<0.06	<0.008	<0.02	<0.04	<1.6	<.20	E.2
	9/21/2005	<1	57.3	.11	17.2	41.1	225	--	--	--	--	--	--	<1.6	<.20	.17
	8/27/2008	<1	65.2	E.11	15.5	55.3	284	--	--	--	--	--	--	<1.6	<.14	.24
NC2	6/17/2004	E<1	37.8	<.17	18.5	22.7	165	<.10	<.04	<.06	<.008	<.02	<.04	<1.6	<.20	E.2
	7/15/2008	<1	34.6	.12	18.2	22.7	165	--	--	--	--	--	--	<1.6	<.14	.11
NC3	6/14/2004	E<1	44.7	<.17	16.6	33.1	207	E.08	E.03	<.06	<.008	<.02	<.04	<1.6	<.20	E.1
	9/19/2005	<1	45.2	.14	15.1	28.9	197	--	--	--	--	--	--	<1.6	<.20	.18
	7/21/2008	<1	44.2	.13	15.2	28.0	204	--	--	--	--	--	--	<1.6	<.14	.27
NC4	6/15/2004	E<1	26.0	.17	24.4	14.3	156	.24	.25	<.06	<.008	<.02	<.04	<1.6	<.20	<.2
	9/20/2005	<1	24.2	.19	23.6	14.8	153	--	--	--	--	--	--	<1.6	<.20	<.12
	7/14/2008	<1	23.0	.21	23.8	16.7	151	--	--	--	--	--	--	<1.6	<.14	<.06
NC5	6/16/2004	E<1	15.6	<.17	33.3	11.8	109	<.10	E.03	<.06	<.008	.46	.86	<1.6	<.20	<.2
Western Carrizo wells																
WC1	6/14/2004	E<1	40.5	<.17	13.3	50.2	312	.14	.11	<.06	<.008	<.02	<.04	<1.6	<.20	E.1
	9/19/2005	<1	39.2	.18	13.4	52.2	325	--	--	--	--	--	--	<1.6	<.20	<.12
	8/14/2008	<1	31.0	.26	12.7	39.8	322	--	--	--	--	--	--	<1.6	<.14	.07
WC2	6/18/2004	E<1	35.5	.38	15.4	33.7	263	E.07	E.03	<.06	<.008	<.02	<.04	<1.6	<.20	<.2
	9/19/2005	<1	34.6	.39	15.1	35.1	296	--	--	--	--	--	--	<1.6	<.20	<.12
	9/19/2005 dup	<1	34.5	.39	15.1	35.0	284	--	--	--	--	--	--	2.4	<.20	<.12
WC3	6/15/2004	E<1	37.3	.31	15.4	43.5	296	<.10	E.03	<.06	<.008	<.02	<.04	<1.6	<.20	<.2
	9/21/2005	<1	36.5	.33	14.9	44.8	346	--	--	--	--	--	--	<1.6	<.20	<.12
	7/11/2008	<1	34.4	.32	14	42.7	343	--	--	--	--	--	--	<1.6	<.14	<.06
WC4	6/18/2004	E<1	31.9	.4	15.3	27.9	276	E.07	E.03	<.06	<.008	<.02	<.04	<1.6	<.20	<.2
	9/21/2005	<1	30.1	.42	15.8	30.7	340	--	--	--	--	--	--	<1.6	<.20	<.12
	7/10/2008	<1	29.0	.39	14.5	30.2	344	--	--	--	--	--	--	E1.0	<.14	<.06
Eastern Carrizo wells																
EC1	6/15/2004	E<1	32.8	.42	18.9	46.6	368	<.10	E.04	<.06	<.008	E.01	.21	E.8	<.20	<.2
	9/20/2005	<1	30.9	.42	18.6	44.6	387	--	--	--	--	--	--	<1.6	<.20	<.12
	8/13/2008	<1	29.9	.41	17.4	45.5	394	--	--	--	--	--	--	<1.6	<.14	<.06
	8/13/2008 dup	<1	30.0	.41	17.1	45.5	392	--	--	--	--	--	--	<1.6	<.14	<.06
EC2	6/14/2004	E<1	36.9	.45	19.3	38.2	427	.32	.32	<.06	<.008	E.01	<.04	7.5	<.20	<.2
	9/20/2005	<1	32.7	.47	19.4	1.31	426	--	--	--	--	--	--	2.2	<.20	<.12
	8/27/2008	<1	29.9	.42	18.2	47.8	370	--	--	--	--	--	--	<1.6	<.14	<.06
EC3	6/18/2004	E<1	35.3	.52	16.2	44.9	478	.55	.45	<.06	<.008	<.02	<.04	E.9	<.20	<.2
Carrizo-Wilcox well																
WX1	6/17/2004	E<1	170	.73	22.2	328	1,040	.51	.47	<.06	<.008	<.02	<.04	<1.6	<.20	E.2
	6/17/2004 dup	E<1	170	.73	21.8	326	1,080	.51	.48	<.06	<.008	<.02	<.04	<1.6	<.20	E.2
	9/20/2005	<1	170	.74	23.4	344	1,100	--	--	--	--	--	--	<1.6	<.20	<.12
	7/14/2008	<1	163	.73	18.1	347	1,070	--	--	--	--	--	--	<1.6	<.14	E.05

Appendix 1. Chemical and isotope data from wells sampled at and near an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08—Continued.

Well name (fig. 1)	Date	Barium (µg/L)	Beryl-lium (µg/L)	Boron (µg/L)	Cad-mium (µg/L)	Chro-mium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Dis-solved iron (µg/L)	Total iron (µg/L)	Lead (µg/L)	Lithium (µg/L)	Dissolved manga-nese (µg/L)	Total manga-nese (µg/L)	Molyb-denum (µg/L)	Nickel (µg/L)	Sele-nium (µg/L)
Edwards aquifer source wells																	
ED1	5/9/2005	115	<0.06	63	<0.04	<.8	0.13	1.6	<6	<6	0.09	10.2	<0.2	<0.2	3.1	0.90	0.90
ED2	5/9/2005	114	<.06	61	<.04	<.8	.12	1.0	<6	E3	.18	9.7	.3	.2	2.4	.91	1.0
ASR injection well																	
IW1	5/9/2005	107	E.05	63	<.04	<.8	.12	.9	<6	<6	.11	10.0	<.2	<.2	3.1	.77	1.0
Carrizo aquifer monitoring wells																	
MW1	5/31/2005	136	<.06	105	<.04	<.8	.07	E.3	95	7,010	<.08	36.3	15.1	131	2.2	1.18	<.4
MW2	5/12/2005	139	E.04	58	<.04	<.8	.12	E.3	6,020	5,710	<.08	13.5	124	106	5.1	1.10	E.3
ASR recovery wells																	
RW1	7/18/2008	70	<.01	49	<.04	<.12	.55	3.5	E5	6	2.63	3.9	11.6	13.4	1.8	.63	E.02
RW2	7/18/2008	57	<.01	46	E.02	<.12	1.60	1.1	11	14	3.60	4.1	5.8	6.3	6.0	1.20	<.04
RW3	7/18/2008	62	E.01	46	E.03	<.12	2.40	1.3	87	105	1.45	4.3	8.6	9.4	4.1	1.70	<.04
RW4	7/18/2008	78	.01	48	E.03	<.12	4.20	1.2	279	311	1.72	4.9	15.8	18.3	7.7	3.00	<.04
ASR production-only wells																	
ASR–PO1	7/28/2008	110	.17	46	<.04	<.12	2.70	<1.0	683	651	.25	9.3	25.4	26.1	.2	5.70	<.04
ASR–PO2	7/28/2008	90	.10	44	<.04	<.12	.92	<1.0	373	368	.16	7.7	10.8	11.8	<.2	3.10	<.04
ASR–PO3	7/28/2008	84	.10	37	<.04	<.12	.81	<1.0	455	438	.24	7.3	9.2	10.0	.6	3.30	<.04
Northern Carrizo wells																	
NC1	6/16/2004	130	E.03	71	<.04	<.8	.42	E.3	1,440	1,710	<.08	16.2	77.4	83.9	E.3	1.23	<.4
	9/21/2005	137	E.04	53	<.04	<.04	.31	.61	1,440	1,360	<.08	15.2	66.4	57.4	E.3	.45	<.08
	8/27/2008	153	.07	65	<.04	<.12	.34	1.6	1,240	1,170	<.08	15.1	64.6	71.3	.4	.85	<.04
NC2	6/17/2004	100	.07	58	<.04	<.8	.72	E.2	2,550	2,580	<.08	9.7	46.6	48.5	E.3	1.24	<.4
	7/15/2008	89	.06	43	<.04	<.12	.73	<1.0	4,690	6,080	<.08	8.0	76.1	88.8	.3	2.00	<.04
NC3	6/14/2004	91	<.06	62	<.04	<.8	.07	E.3	1,400	1,430	<.08	13.6	51.7	50.3	E.4	.17	E.2
	9/19/2005	98	<.06	50	<.04	<.04	.07	E.4	2,530	2,550	<.08	12.4	136	127	.7	1.01	<.08
	7/21/2008	89	.02	59	<.04	<.12	<.02	<1.0	3,270	2,250	.17	12.8	162	247	.8	.25	<.04
NC4	6/15/2004	104	<.06	51	<.04	<.8	.05	E.3	2,310	2,300	<.08	13.6	125	124	<.4	.11	<.4
	9/20/2005	99	<.06	53	<.04	<.04	<.04	<.40	2,150	1,980	E.04	16.3	136	141	<.4	<.06	<.08
	7/14/2008	99	.01	43	<.04	<.12	<.02	<1.0	1,920	1,980	<.08	12.8	118	132	E.1	<.20	<.04
NC5	6/16/2004	77	.10	34	<.04	<.8	.79	E.4	1,130	1,130	.13	11.0	31.8	33.2	<.4	3.35	<.4
Western Carrizo wells																	
WC1	6/14/2004	75	<.06	96	<.04	<.8	.13	.40	10	622	<.08	34.1	26.7	25.8	<.4	.39	E.3
	9/19/2005	73	<.06	93	<.04	<.04	<.04	<.40	597	575	<.08	37.6	24.0	26.7	E.2	<.06	<.08
	8/14/2008	66	M	148	<.04	<.12	E.02	<1.0	<8	397	<.08	34.0	34.3	38.2	.4	E.15	<.04
WC2	6/18/2004	127	<.06	145	<.04	<.8	.14	.50	<6	739	<.08	16.1	77.0	81.6	1.2	.29	<.4
	9/19/2005	116	<.06	134	<.04	<.04	<.04	.67	32	688	<.08	16.9	68.3	74.8	1.2	<.06	<.08
	9/19/2005 dup	117	<.06	133	<.04	<.04	.14	.40	11	681	<.08	17.1	78.8	77.1	1.2	2.10	<.08
WC3	6/15/2004	129	<.06	120	<.04	<.8	.18	.40	124	608	<.08	15.7	132	131	.8	.43	<.4
	9/21/2005	123	<.06	97	<.04	<.04	<.04	.67	55	619	<.08	14.7	161	134	.9	E.04	<.08
	7/11/2008	127	.01	122	<.04	<.12	.03	<1.0	146	361	<.08	14.7	134	138	.8	.28	<.04
WC4	6/18/2004	190	<.06	144	<.04	<.8	.19	E.4	10	1,130	<.08	16.5	59.3	62.8	1.0	.45	E.2
	9/21/2005	175	<.06	134	<.04	<.04	<.04	.62	20	386	<.08	15.2	45.6	49.3	1.1	<.06	<.08
	7/10/2008	184	.01	146	<.04	<.12	<.02	<1.0	118	518	<.08	15.5	52.2	55.7	1.0	E.12	<.04
Eastern Carrizo wells																	
EC1	6/15/2004	109	<.06	142	<.04	<.8	.09	.40	363	227	<.08	38.2	19.7	18.9	<.4	.27	<.4
	9/20/2005	110	<.06	157	<.04	<.04	<.04	<.40	161	155	<.08	41.9	14.5	16.4	<.4	<.06	<.08
	8/13/2008	119	.01	130	<.04	<.12	E.02	<1.0	41	48	.31	36.6	12.7	14.2	<.2	.28	<.04
	8/13/2008 dup	119	.01	128	<.04	<.12	.04	<1.0	41	53	<.08	36.7	12.4	14.1	<.2	.23	<.04
EC2	6/14/2004	163	<.06	192	<.04	<.8	.04	.50	16	23	<.08	44.4	17.0	16.4	<.4	.50	.90
	9/20/2005	156	<.06	220	<.04	.05	<.04	<.40	136	292	<.08	47.4	18.3	20.7	<.4	<.06	.11
	8/27/2008	144	E.01	111	<.04	<.12	.02	<1.0	30	643	<.08	30.6	22.4	24.4	<.2	.35	<.04
EC3	6/18/2004	171	<.06	230	<.04	<.8	.02	.60	29	42	<.08	47.6	8.2	9.0	<.4	E.04	E.2
Carrizo-Wilcox well																	
WX1	6/17/2004	17	<.06	405	<.04	<.8	.15	1.6	109	1,190	<.08	124	24.7	29.3	1.7	.37	.60
	6/17/2004 dup	17	<.06	410	<.04	<.8	.15	1.6	120	1,130	<.08	124	24.7	28.6	1.7	.36	.70
	9/20/2005	17	<.06	447	<.04	<.04	<.04	<.40	1,300	1,360	<.08	153	24.0	28.9	1.9	<.06	<.08
	7/14/2008	18	<.01	451	<.04	<.12	.04	<1.0	28	1,760	<.08	127	34.2	41.8	1.8	.45	E.03

Appendix 1. Chemical and isotope data from wells sampled at and near an aquifer storage and recovery site, Bexar, Atascosa, and Wilson Counties, Texas, 2004–08—Continued.

Well name (fig. 1)	Date	Silver (µg/L)	Strontium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)	Uranium (µg/L)	^{226}Ra (pCi/L)	^{226}Ra PE (pCi/L)	^{226}Ra ssL$_c$ (pCi/L)	^{228}Ra (pCi/L)	^{228}Ra PE (pCi/L)	^{228}Ra ssL$_c$ (pCi/L)	$^{87/86}$Sr	$^{11/10}$B	δ^{11}B (per mil)	δ^{18}O (per mil)	δD (per mil)
Edwards aquifer source wells																	
ED1	5/9/2005	<0.2	1,660	4.7	1.3	0.87	0.644	--	0.028	0.230	--	0.450	0.70785	4.161	38.1	-4.19	-24.80
ED2	5/9/2005	<.2	1,570	4.8	6.5	.83	.639	--	.036	R.17	--	.400	.70790	4.157	39.1	-4.18	-24.70
ASR injection well																	
IW1	5/9/2005	<.2	1,600	4.6	9.5	.84	.624	--	.037	.285	--	.420	.70790	4.154	37.6	-4.26	-25.60
Carrizo aquifer monitoring wells																	
MW1	5/31/2005	<.2	455	<.1	E.6	E.03	.419	--	.035	.987	--	.440	.70862	4.119	28.6	-5.10	-28.60
MW2	5/12/2005	<.2	233	E.1	.80	<.04	.672	--	.033	1.352	--	.410	.70967	4.158	38.4	-4.73	-26.20
ASR recovery wells																	
RW1	7/18/2008	<.1	612	2.0	2.5	.47	.279	0.030	.026	R.08	0.130	.620	.70780	4.136	33.0	-4.12	-23.32
RW2	7/18/2008	<.1	613	1.7	5.7	.67	.277	.032	.030	R.16	.130	.540	.70781	4.151	36.7	-4.09	-22.73
RW3	7/18/2008	<.1	654	1.1	8.4	.55	.344	.037	.032	R.01	.160	.750	.70780	4.147	35.6	-4.12	-23.52
RW4	7/18/2008	<.1	572	.81	29.3	.27	.340	.026	.033	R.01	.150	.580	.70802	4.150	36.5	-4.22	-24.58
ASR production-only wells																	
ASR–PO1	7/28/2008	<.1	95.1	.10	30.3	<.02	.619	.058	.030	1.450	.150	.540	.71345	4.180	43.8	-4.94	-28.07
ASR–PO2	7/28/2008	<.1	58.3	.06	18.9	<.02	.527	.051	.030	1.080	.140	.600	.71332	4.153	37.1	-4.95	-26.34
ASR–PO3	7/28/2008	<.1	58.8	.07	82.1	<.02	.374	.037	.030	1.320	.150	.590	.71332	4.153	37.1	-4.98	-27.19
Northern Carrizo wells																	
NC1	6/16/2004	<.2	195	<.1	2.7	<.04	.276	--	.012	1.476	--	.540	.71045	4.145	35.2	-4.94	-27.50
	9/21/2005	<.2	169	<.10	1.1	<.04	--	--	--	--	--	--	--	--	--	--	--
	8/27/2008	<.1	205	E.04	3.3	<.02	1.100	.100	.037	2.070	.160	.480	.71100	4.153	37.1	-4.90	-28.01
NC2	6/17/2004	<.2	108	<.1	3.5	<.04	.222	--	.010	1.872	--	.700	.71263	4.155	37.6	-4.82	-27.30
	7/15/2008	<.1	92.8	<.04	<1.8	<.02	.564	.054	.029	1.130	.150	.560	.71283	4.167	40.7	-4.86	-27.04
NC3	6/14/2004	<.2	154	<.1	2.4	<.04	.416	--	.011	1.352	--	.530	.71170	4.155	37.6	-4.80	-27.30
	9/19/2005	<.2	161	<.10	1.0	<.04	--	--	--	--	--	--	--	--	--	--	--
	7/21/2008	<.1	145	.05	E1.5	<.02	.402	.040	.024	.829	.130	.590	.71199	4.172	41.8	-4.90	-27.28
NC4	6/15/2004	<.2	123	<.1	2.0	<.04	.329	--	.009	1.180	--	.530	.70952	4.145	35.1	-4.90	-26.60
	9/20/2005	<.2	130	<.10	3.3	<.04	--	--	--	--	--	--	--	--	--	--	--
	7/14/2008	<.1	124	<.04	4.5	<.02	.618	.057	.030	1.580	.150	.510	.70947	4.149	36.2	-4.97	-27.67
NC5	6/16/2004	<.2	61.1	<.1	9.5	<.04	.243	--	.011	.553	--	.560	.71107	--	--	-4.85	-25.70
Western Carrizo wells																	
WC1	6/14/2004	<.2	479	.20	1.3	<.04	.343	--	.008	1.782	--	.530	.70880	4.102	24.5	-4.77	-26.40
	9/19/2005	<.2	461	<.10	1.9	<.04	--	--	--	--	--	--	--	--	--	--	--
	8/14/2008	<.1	378	E.04	<1.8	<.02	.501	.049	.034	1.740	.180	.500	.70855	4.118	28.5	-4.94	-25.55
WC2	6/18/2004	<.2	308	.50	1.2	<.04	.332	--	.015	1.946	--	.570	.70898	4.140	32.8	-4.38	-24.00
	9/19/2005	<.2	369	<.10	.74	<.04	--	--	--	--	--	--	--	--	--	--	--
	9/19/2005 dup	<.2	372	<.10	.60	<.04	--	--	--	--	--	--	--	--	--	--	--
WC3	6/15/2004	<.2	302	.20	.70	<.04	1.354	--	.008	2.700	--	.510	.70923	4.138	33.6	-4.32	-24.70
	9/21/2005	<.2	319	<.10	1.4	<.04	--	--	--	--	--	--	--	--	--	--	--
	7/11/2008	<.1	306	<.04	5.6	<.02	1.180	.100	.031	2.580	.200	.520	.70915	4.144	35.0	-4.40	-24.35
WC4	6/18/2004	<.2	368	.60	1.2	<.04	.740	--	.012	3.047	--	.530	.70883	4.144	35.1	-3.66	-20.90
	9/21/2005	<.2	404	<.10	<.60	<.04	--	--	--	--	--	--	--	--	--	--	--
	7/10/2008	<.1	392	<.04	<1.8	<.02	1.580	.140	.031	3.690	.250	.520	.70877	4.138	33.3	-3.74	-20.59
Eastern Carrizo wells																	
EC1	6/15/2004	--	925	.30	E.6	<.04	.628	--	.011	1.731	--	.550	.70824	4.117	28.1	-4.58	-26.40
	9/20/2005	<.2	901	<.10	<.60	<.04	--	--	--	--	--	--	--	--	--	--	--
	8/13/2008	<.1	941	E.04	<1.8	<.02	.557	.053	.031	1.920	.240	.600	.70825	4.110	26.5	-4.57	-26.90
	8/13/2008 dup	<.1	929	E.04	<1.8	<.02	.566	.053	.025	1.690	.200	.560	.70823	4.126	30.5	-4.65	-25.68
EC2	6/14/2004	--	584	.40	E.5	<.04	.254	--	.009	1.325	--	.540	.70799	4.097	23.2	-4.60	-26.40
	9/20/2005	<.2	488	<.10	1.6	<.04	--	--	--	--	--	--	--	--	--	--	--
	8/27/2008	<.1	917	E.02	E.98	<.02	.998	.094	.037	2.130	.170	.480	.70843	4.138	33.3	-4.58	-27.64
EC3	6/18/2004	--	402	1.0	.80	<.04	.164	--	.014	.900	--	.550	.70786	4.087	20.6	-4.61	-27.20
Carrizo-Wilcox well																	
WX1	6/17/2004	<.2	1,660	.10	2.4	<.04	.201	--	.009	.817	--	.610	.70847	4.088	21.0	-4.63	-25.20
	6/17/2004 dup	<.2	1,660	E.1	2.4	<.04	--	--	--	--	--	--	--	--	--	--	--
	9/20/2005	<.2	1,650	<.10	.79	<.04	--	--	--	--	--	--	--	--	--	--	--
	7/14/2008	<.1	1,680	.15	<1.8	E.01	.327	.036	.030	1.020	.130	.510	.70843	4.092	21.9	-4.74	-26.75

Appendix 2. Relative percent difference for duplicate chemical and isotope data from wells sampled at and near an aquifer storage and recovery site, Atascosa and Wilson Counties, Texas, 2004–08.

[dup, duplicate; RPD, relative percent difference; mg/L, milligrams per liter;--, not analyzed for or not detected; <, less than; nc, not computed; µg/L, micrograms per liter; E, estimated; ^{226}Ra, radium-226; pCi/L, picocuries per liter; ^{228}Ra, radium-228; $^{87/86}$Sr, strontium-87/strontium-86; $^{11/10}$B, boron-11/boron-10; δ^{11}B, delta boron-11; δ^{18}O, delta oxygen-18; δD, delta deuterium]

Well name (fig. 1):	WC2			EC1			WX1		
U.S. Geological Survey site number:	290001098250101			290748098085601			291547098153501		
State well number:	AL–68–61–810			ZL–68–55–907			ZL–68–46–902		
Date:	9/19/2005	9/19/2005 dup	RPD	8/13/2008	8/13/2008 dup	RPD	6/17/2004	6/17/2004 dup	RPD
Time:	1030	1035		1400	1405		1000	1010	
Calcium (mg/L)	61.4	61.4	0	36.1	36	0.28	57.7	57	1.22
Magnesium (mg/L)	7.01	7.00	.14	12.20	12.20	0	18.40	18.60	1.08
Potassium (mg/L)	6.21	6.14	1.13	10.7	10.6	.94	5.51	5.45	1.09
Sodium (mg/L)	28.6	28.6	0	82.2	82.7	.61	304	308	1.31
Chloride (mg/L)	34.6	34.5	.29	29.9	30	.33	170	170	0
Fluoride (mg/L)	.39	.39	0	.41	.41	0	.73	.73	0
Silica (mg/L)	15.1	15.1	0	17.4	17.1	1.74	22.2	21.8	1.82
Sulfate (mg/L)	35.1	35	.29	45.5	45.5	0	328	326	.61
Residue (sum of constituents) (mg/L)	296	284	4.14	394	392	.51	1,040	1,080	3.77
Dissolved ammonia plus organic nitrogen (mg/L)	--	--	--	--	--	--	.51	.51	0
Dissolved ammonia nitrogen (mg/L)	--	--	--	--	--	--	.47	.48	2.11
Dissolved nitrate plus nitrite nitrogen (mg/L)	--	--	--	--	--	--	<.06	<.06	nc
Dissolved nitrite nitrogen (mg/L)	--	--	--	--	--	--	<.008	<.008	nc
Dissolved orthophosphate phosphorus (mg/L)	--	--	--	--	--	--	<.02	<.02	nc
Dissolved phosphorus (mg/L)	--	--	--	--	--	--	<.04	<.04	nc
Aluminum (µg/L)	<1.6	2.4	nc	<1.6	<1.6	nc	<1.6	<1.6	nc
Antimony (µg/L)	<.20	<.20	nc	<.14	<.14	nc	<.20	<.20	nc
Arsenic (µg/L)	<.12	<.12	nc	<.06	<.06	nc	E.2	E.2	nc
Barium (µg/L)	116	117	.86	119	119	0	17	17	0
Beryllium (µg/L)	<.06	<.06	nc	.01	.01	0	<.06	<.06	nc
Boron (µg/L)	134	133	.75	130	128	1.55	405	410	1.23
Cadmium (µg/L)	<.04	<.04	nc	<.04	<.04	nc	<.04	<.04	nc
Chromium (µg/L)	<.04	<.04	nc	<.12	<.12	nc	<.8	<.8	nc
Cobalt (µg/L)	<.04	.138	nc	E.02	.04	nc	.149	.151	1.33
Copper (µg/L)	.67	.4	50.5	<1.0	<1.0	nc	1.6	1.6	0
Dissolved iron (µg/L)	32	11	97.7	41	41	0	109	120	9.61
Total iron (µg/L)	688	681	1.02	48	53	9.90	1,190	1,130	5.17
Lead (µg/L)	<.08	<.08	nc	.31	<.08	nc	<.08	<.08	nc
Lithium (µg/L)	16.9	17.1	1.18	36.6	36.7	.27	124	124	0
Dissolved manganese (µg/L)	68.3	78.8	14.3	12.7	12.4	2.39	24.7	24.7	0
Total manganese (µg/L)	74.8	77.1	3.03	14.2	14.1	.71	29.3	28.6	2.42
Molybdenum (µg/L)	1.2	1.2	0	<.2	<.2	nc	1.7	1.7	0
Nickel (µg/L)	<.06	2.1	nc	.28	.23	19.6	.37	.36	2.74
Selenium (µg/L)	<.08	<.08	nc	<.04	<.04	nc	.6	.7	15.4
Silver (µg/L)	<.2	<.2	nc	<.1	<.1	nc	<.2	<.2	nc
Strontium (µg/L)	369	372	.81	941	929	1.28	1,660	1,660	0
Vanadium (µg/L)	<.10	<.10	nc	E.04	E.04	nc	.1	E.1	nc
Zinc (µg/L)	.74	.6	20.9	<1.8	<1.8	nc	2.4	2.4	0
Uranium (µg/L)	<.04	<.04	nc	<.02	<.02	nc	<.04	<.04	nc
^{226}Ra (pCi/L)	--	--	--	.557	.566	1.60	.201	--	--
^{228}Ra (pCi/L)	--	--	--	1.920	1.690	12.7	.817	--	--
$^{87/86}$Sr	--	--	--	.708	.708	.003	.708	--	--
$^{11/10}$B	--	--	--	4.110	4.126	.39	4.088	--	--
δ^{11}B (per mil)	--	--	--	26.5	30.5	14.0	20.98	--	--
δ^{18}O (per mil)	--	--	--	-4.57	-4.65	1.74	-4.63	--	--
δD (per mil)	--	--	--	-26.90	-25.68	4.64	-25.20	--	--

Appendix 3. Chemical data in stormwater samples from two surface-water sites near an aquifer storage and recovery site, Atascosa County, Texas, 2004–05.

[min, minutes; hr, hours; in., inches; Mgal/d, millions gallons per day; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed for; <, less than; E, estimated; M, presence verified but not quantified]

U.S. Geological Survey station number (fig. 1)	Date	Time	Discharge duration (min)	Elapsed time of storm (hr)	Precipitation total, per storm (in.)	Precipitation, duration of storm event (min)	Stormwater flow (Mgal/d)	pH (standard units)	Specific conductance (µS/cm)	Temperature, water (°C)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L)	Carbonate (mg/L)	Residue (sum of constituents) (mg/L)	Dissolved ammonia plus organic nitrogen (mg/L)	Total ammonia plus organic nitrogen (mg/L)	Dissolved ammonia nitrogen (mg/L)	Dissolved nitrate plus nitrite nitrogen (mg/L)	Dissolved phosphorus (mg/L)	Total phosphorus (mg/L)
08207320	4/4/2004	2130	3,030	29.8	1.5	135	2.5	7.3	259	--	--	--	--	40	0.46	1.6	<0.040	0.18	0.23	0.69
	6/9/2004	1930	1,540	21.4	3.2	405	E311	6.9	76	--	--	--	--	232	.36	2.3	.049	.29	.17	.8
	6/22/2004	0851	2,010	26.5	2	225	38.6	7	102	--	--	--	--	126	.85	1.6	.061	.28	.34	.59
	11/16/2004	2045	1,280	21.2	2.3	1,220	89.6	6.7	71	18	--	--	--	282	.51	1.9	.041	.53	.72	1.07
08207350	4/4/2004	2000	1,100	12	2.6	150	21.8	8.1	123	--	--	--	--	80	.23	3.1	<.040	.19	E.03	1.04
	6/22/2004	0745	1,620	15.5	.32	300	10.5	7.3	93	--	--	--	--	84	.47	1.6	E.024	.06	E.03	.46
	11/16/2004	2215	1,770	29.5	2.9	900	8.2	6.7	88	18	--	--	--	456	.22	1.3	<.040	.05	E.03	.48
	2/24/2005	0815	1,820	30.2	2.6	330	29	7.3	137	--	40	49	<1	700	.36	1.4	<.040	.2	E.03	.45

U.S. Geological Survey station number (fig. 1)	Date	Total organic carbon (mg/L)	Biochemical oxygen demand (mg/L)	Chemical oxygen demand (mg/L)	Aluminum (µg/L)	Antimony (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Cyanide (mg/L)	Dissolved lead (µg/L)	Total lead (µg/L)	Manganese (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Silver (µg/L)	Uranium (µg/L)
08207320	4/4/2004	15.5	--	20	2.2	<0.20	68	<0.06	<0.04	<0.8	0.148	1.4	<0.01	<0.08	11.9	0.6	0.7	1.06	<0.2	0.17
	6/9/2004	13.9	--	30	5.2	<.20	24	<.06	<.04	<.8	.092	1.6	<.01	<.08	13.7	.4	E.3	.82	<.2	.07
	6/22/2004	20	--	30	10.4	<.20	31	<.06	<.04	<.8	.178	2.7	M	E.08	4.5	1.1	.4	1.34	<.2	.07
	11/16/2004	14.3	--	30	9.9	<.20	18	<.06	<.04	<.8	.13	2	<.01	E.06	6.9	.7	E.3	1.07	<.2	E.03
08207350	4/4/2004	17.7	--	40	5.2	<.20	34	<.06	<.04	<.8	.147	.8	<.01	<.08	48.2	1	1.6	.61	<.2	1.27
	6/22/2004	13.8	--	30	4.6	<.20	39	<.06	<.04	<.8	.113	2.1	<.01	E.04	12.7	.6	1	.8	<.2	.32
	11/16/2004	12.1	--	20	4.1	<.20	29	<.06	<.04	<.8	.073	1.3	<.01	<.08	14.7	.8	.7	.35	<.2	.15
	2/24/2005	16.1	E5.3	30	3.7	E.10	37	<.06	<.04	<.8	.139	1.1	<.01	E.05	14.9	1	1	.73	<.2	.99

Appendix 3. Chemical data in stormwater samples from two surface-water sites near an aquifer storage and recovery site, Atascosa County, Texas, 2004–05—Continued.

U.S. Geological Survey station number (fig. 1)	Date	Zinc (µg/L)	Total oil and grease (mg/L)	Aldrin (µg/L)	alpha-Endosulfan (µg/L)	Chlordane (technical) (µg/L)	Dieldrin (µg/L)	Endrin (µg/L)	Heptachlor epoxide (µg/L)	Heptachlor (µg/L)	Lindane (µg/L)	Mirex (µg/L)	*p,p′*-DDD (µg/L)	*p,p′*-DDE (µg/L)	*p,p′*-DDT (µg/L)	*p,p′*-Methoxychlor (µg/L)	PCBs (µg/L)	Petroleum hydrocarbons (mg/L)	Phenolic compounds (µg/L)	Toxaphene (µg/L)
08207320	4/4/2004	E0.6	<7	<0.001	<0.002	<0.1	<0.002	<0.002	<0.001	<0.001	<0.0020	<0.001	<0.002	<0.002	<0.002	<0.003	<0.1	2	<16	<1
	6/9/2004	E.6	<7	<.001	<.002	<.1	<.002	<.002	<.001	<.001	<.0020	<.001	<.002	<.002	<.002	<.003	<.1	<2	<16	<1
	6/22/2004	1.4	E5	<.001	<.002	<.1	<.002	<.002	<.001	<.001	<.0020	<.001	<.002	<.002	<.002	<.003	<.1	<2	<16	<1
	11/16/2004	.9	E3	<.001	<.001	<.1	<.001	<.002	<.001	<.001	<.0020	<.001	<.002	<.002	<.002	<.003	<.1	<2	<16	<1
08207350	4/4/2004	<.6	<7	<.001	<.002	<.1	<.002	<.002	<.001	<.001	<.0020	<.001	<.002	<.002	<.002	<.003	<.1	4	<16	<1
	6/22/2004	.6	E4	<.001	<.002	<.1	<.002	<.002	<.001	<.001	<.0020	<.001	<.002	<.002	<.002	<.003	<.1	<2	<16	<1
	11/16/2004	.6	<7	<.001	<.001	<.1	<.001	<.002	<.001	<.001	<.0020	<.001	<.002	<.002	<.002	<.003	<.1	--	<16	<1
	2/24/2005	.7	E4	<.001	<.001	<.1	<.001	<.002	<.001	<.001	<.0020	<.001	<.002	<.002	<.002	<.003	<.1	<2	<16	<1

Appendix 4. Bacteria data in stormwater samples from two surface-water sites near an aquifer storage and recovery site, Atascosa County, Texas, 2004–05.

[cols./100 mL, colonies per 100 milliliters; --, not analyzed; E, estimated from non-ideal colony count]

U.S. Geological Survey station number (fig. 1)	Date	Time	*Escherichia coli* (cols./100 mL)	Fecal streptococci (cols./100 mL)
08207320	4/4/2004	2100	480,000	--
	6/9/2004	2010	22,000	--
	6/22/2004	1220	E6,000	--
	11/16/2004	2145	78,000	110,000
08207350	4/4/2004	1930	24,000	--
	6/22/2004	1200	E23,000	--
	11/16/2004	2205	49,000	--
	2/24/2005	0820	31,000	--

Publishing support provided by
Lafayette Publishing Service Center

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ISBN 978-1-4113-2784-9

Printed on recycled paper