Texas Water Development Board
Report 374

Aquifers of the Upper Coastal Plains of Texas

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Chapter 1

Aquifers of the Upper Coastal Plains

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The Upper Coastal Plains region of Texas is located directly to the north and west of the Gulf Coast region of the state (Figure 1-1). The region stretches northeast from Texas' border with Mexico, extending into Arkansas and Louisiana. The Carrizo-Wilcox Aquifer, one of the state's major aquifers, is the principal aquifer and the primary source of groundwater throughout the region. In addition, the Queen City, Sparta, Yegua-Jackson, and Brazos River Alluvium aquifers are important sources of groundwater for this region. Uses of groundwater vary throughout the region, with irrigation in the fertile Winter Garden area being the primary use in the southern portion. Municipal use dominates in the high-growth central portion, which includes parts of the San Antonio, Austin, and College Station metropolitan areas. The northeast portion of the area has plentiful surface water, and the major concern for groundwater is water marketing. This range of water uses and availability within the Upper Coastal Plains led the Texas Water Development Board (TWDB) to split the region into separate groundwater management areas to facilitate joint planning in areas with common concerns.

1.1
STUDY AREA DESCRIPTION

For our purposes, the Upper Coastal Plains region consists of the 79 counties that overlie the Carrizo-Wilcox, Yegua-Jackson, Sparta, Queen City, and Brazos River Alluvium aquifers. These counties are Anderson, Angelina, Atascosa, Austin, Bastrop, Bee, Bexar, Bosque, Bowie, Brazos, Burleson, Caldwell, Camp, Cass, Cherokee, DeWitt, Dimmit, Duval, Falls, Fayette, Fort Bend, Franklin, Freestone, Frio, Gonzales, Gregg, Grimes, Guadalupe, Harrison, Henderson, Hill, Hopkins, Houston, Jasper, Jim Hogg, Karnes, La Salle, Lavaca, Lee, Leon, Limestone, Live Oak, Madison, Marion, Maverick, McLennan, McMullen, Medina, Milam, Morris, Nacogdoches, Navarro, Newton, Panola, Polk, Rains, Red River, Robertson, Rusk, Sabine, San Augustine, Shelby, Smith, Starr, Titus, Trinity, Tyler, Upshur, Uvalde, Van Zandt, Walker, Waller, Washington, Webb, Williamson, Wilson, Wood, Zapata, and Zavala.

The population in this area more than doubled between 1950 and 2000, increasing from 2.3 million residents to 4.9 million (U.S. Census Bureau, 1952, 2003). During this time, 14 of these counties decreased in population, with Falls County showing the greatest loss, a decrease of 8,148 residents. Bexar County experienced the greatest population increase, with the addition of 892,471 people, and Fort Bend County in the Houston area increased over 11 times its 1950 population, from 31,056 to 323,396. Between 1980 and 2004, groundwater use in the area was relatively stable, at approximately 1.2 million acre-feet per year (TWDB, 2009). In 2004, groundwater made up just over half of all water used in the region (Table 1-1). Total water used in 2004 was primarily for municipal supplies (41 percent), irrigation (26 percent), and manufacturing (16 percent). Between 2000 and 2060, the population of this area is expected to more than double again, reaching more than 10.5 million. Projections of water demand indicate that demand for water in the area will rise from 2.7 million acre-

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[1] Texas Water Development Board

Figure 1-1. Location of the Upper Gulf Coast region, showing counties and areas of significant water use.

Table 1-1. Population and groundwater use for counties in the Upper Gulf Coast region for selected years.

County	Population				Groundwater use				Percent groundwater in 2004*
	1950	1980	1990	2000	1980	1990	2000	2004	
Anderson	31,875	38,381	48,024	55,109	6,066	6,557	7,879	6,427	50
Angelina	36,032	64,172	69,884	80,130	33,152	26,886	26,457	18,860	79
Atascosa	20,046	25,055	30,533	38,628	79,089	59,738	47,909	37,694	96
Austin	14,663	17,726	19,832	23,590	12,948	12,999	13,004	11,156	88
Bastrop	19,622	24,726	38,263	57,733	5,399	7,178	10,343	9,854	70
Bee	18,174	26,030	25,135	32,359	6,190	5,065	5,257	6,201	60
Bexar	500,460	988,971	1,185,395	1,392,931	252,748	269,505	269,433	261,420	91
Bosque	11,836	13,401	15,125	17,204	3,100	3,813	4,290	5,400	70
Bowie	61,966	75,301	81,665	89,306	4,434	5,029	2,231	5,533	24
Brazos	38,390	93,588	121,862	152,415	24,751	36,239	37,020	42,590	97
Burleson	13,000	12,313	13,625	16,470	8,099	8,975	17,918	23,358	77
Caldwell	19,350	23,637	26,392	32,194	2,982	4,371	3,994	3,632	60
Camp	8,740	9,275	9,904	11,549	1,928	1,853	1,500	1,718	60
Cass	26,732	29,430	29,982	30,438	4,987	4,593	3,206	2,440	2
Cherokee	38,694	38,127	41,049	46,659	6,369	6,526	7,333	5,380	68
DeWitt	22,973	18,903	18,840	20,013	3,511	4,170	3,527	3,019	56
Dimmit	10,654	11,367	10,433	10,248	23,263	9,592	8,286	5,627	78
Duval	15,643	12,517	12,918	13,120	5,812	7,842	11,476	10,184	93
Falls	26,724	17,946	17,712	18,576	4,216	5,889	2,732	3,386	37
Fayette	24,176	18,832	20,095	21,804	4,061	3,719	4,519	3,356	16
Fort Bend	31,056	130,962	225,421	354,452	74,113	91,373	102,899	76,107	50
Franklin	6,257	6,893	7,802	9,458	1,216	1,583	1,838	833	20
Freestone	15,696	14,830	15,818	17,867	2,409	2,500	3,289	2,645	30
Frio	10,357	13,785	13,472	16,252	78,959	85,073	120,128	86,950	99
Gonzales	21,164	16,949	17,205	18,628	4,226	4,660	5,932	5,111	42
Gregg	61,258	99,495	104,948	111,379	4,294	2,475	3,435	2,933	13
Grimes	15,135	13,580	18,828	23,552	2,662	3,750	4,675	4,749	49
Guadalupe	25,392	46,708	64,873	89,023	4,626	6,566	6,562	12,115	43
Harrison	47,745	52,265	57,483	62,110	3,924	3,202	3,438	3,133	8
Henderson	23,405	42,606	58,543	73,277	4,246	5,042	5,980	5,870	42
Hill	31,282	25,024	27,146	32,321	3,767	2,519	2,121	3,077	44
Hopkins	23,490	25,247	28,833	31,960	2,639	3,835	4,126	3,191	28
Houston	22,825	22,299	21,375	23,185	2,393	2,784	3,804	2,378	31
Jasper	20,049	30,781	31,102	35,604	51,471	49,486	52,250	38,187	72
Jim Hogg	5,389	5,168	5,109	5,281	1,065	828	1,749	1,364	73
Karnes	17,139	13,593	12,455	15,446	3,233	4,610	3,900	2,460	65
La Salle	7,485	5,514	5,254	5,866	11,938	7,529	5,698	5,489	91
Lavaca	22,159	19,004	18,690	19,210	30,749	19,337	9,154	9,060	77
Lee	10,144	10,952	12,854	15,657	2,856	3,719	4,477	4,622	80
Leon	12,024	9,594	12,665	15,335	2,437	3,571	4,849	4,385	64
Limestone	25,251	20,224	20,946	22,051	1,556	3,768	3,856	4,352	14

Sources: U.S. Census Bureau, 1952, 2003; TWDB, 2009
*Percent of total water use in 2004 that was groundwater.

Table 1-1 (continued).

County	Population				Groundwater use				Percent groundwater in 2004*
	1950	1980	1990	2000	1980	1990	2000	2004	
Live Oak	9,054	9,606	9,556	12,309	4,526	5,997	8,519	7,161	79
Madison	7,996	10,649	10,931	12,940	2,199	2,672	3,180	2,611	79
Marion	10,172	10,360	9,984	10,941	963	903	1,508	939	32
Maverick	12,292	31,398	36,378	47,297	3,296	6,074	341	478	1
McLennan	130,194	170,755	189,123	213,517	13,017	12,588	15,677	17,744	28
McMullen	1,187	789	817	851	624	396	1,340	706	62
Medina	17,013	23,164	27,312	39,304	79,266	83,509	50,906	40,763	70
Milam	23,585	22,732	22,946	24,238	4,376	18,382	36,228	33,033	65
Morris	9,433	14,629	13,200	13,048	1,406	7,490	1,139	863	1
Nacogdoches	30,326	46,786	54,753	59,203	7,411	8,370	7,769	8,528	72
Navarro	39,916	35,323	39,926	45,124	327	391	438	396	3
Newton	10,832	13,254	13,569	15,072	2,850	3,486	2,494	2,366	82
Panola	19,250	20,724	22,035	22,756	2,817	4,046	4,597	3,992	46
Polk	16,194	24,407	30,687	41,133	4,306	4,434	4,626	4,969	68
Rains	4,266	4,839	6,715	9,139	419	547	602	558	27
Red River	21,851	16,101	14,317	14,314	2,324	1,763	2,011	1,825	22
Robertson	19,908	14,653	15,511	16,000	20,613	21,364	22,452	27,074	72
Rusk	42,348	41,382	43,735	47,372	7,584	8,419	7,988	6,622	39
Sabine	8,568	8,702	9,586	10,469	1,061	1,030	1,019	1,075	36
San Augustine	8,837	8,785	7,999	8,946	864	651	914	830	30
Shelby	23,479	23,084	22,034	25,224	2,780	2,447	3,400	2,428	28
Smith	74,701	128,366	151,309	174,706	13,273	14,235	19,675	18,149	42
Starr	13,948	27,266	40,518	53,597	677	1,515	1,481	949	6
Titus	17,302	21,442	24,009	28,118	1,335	1,570	3,071	2,546	8
Trinity	10,040	9,450	11,445	13,779	1,461	1,201	1,370	1,000	43
Tyler	11,292	16,223	16,646	20,871	2,383	2,193	2,918	3,473	96
Upshur	20,822	28,595	31,370	35,291	3,924	4,679	4,955	4,083	79
Uvalde	16,015	22,441	23,340	25,926	81,196	144,522	66,083	71,246	99
Van Zandt	22,593	31,426	37,944	48,140	6,322	5,303	5,014	5,141	50
Walker	20,163	41,789	50,917	61,758	9,867	5,499	5,386	4,157	28
Waller	11,961	19,798	23,389	32,663	30,692	32,645	27,526	29,551	97
Washington	20,542	21,998	26,154	30,373	1,848	2,469	3,760	3,083	41
Webb	56,141	99,258	133,239	193,117	857	1,158	1,460	1,770	4
Williamson	38,853	76,521	139,551	249,967	13,214	16,842	17,820	20,108	34
Wilson	14,672	16,756	22,650	32,408	9,663	15,898	21,611	18,608	90
Wood	21,308	24,697	29,380	36,752	7,087	7,644	4,982	6,357	64
Zapata	4,405	6,628	9,279	12,182	242	80	47	48	1
Zavala	11,201	11,666	12,162	11,600	85,386	80,138	39,172	54,153	92
Total	2,269,062	3,343,593	4,003,896	4,910,835	1,222,320	1,333,289	1,247,953	1,157,633	56

Sources: U.S. Census Bureau, 1952, 2003; TWDB, 2009
*Percent of total water use in 2004 that was groundwater.

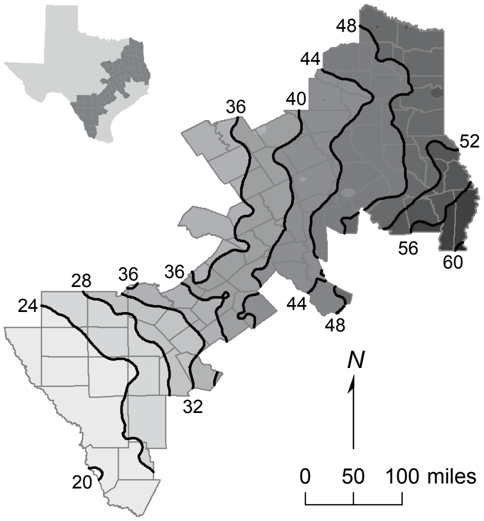

Figure 1-2. Average precipitation (in inches) in the Upper Gulf Coast region from 1971 to 2000 (data from SCAS, 2004).

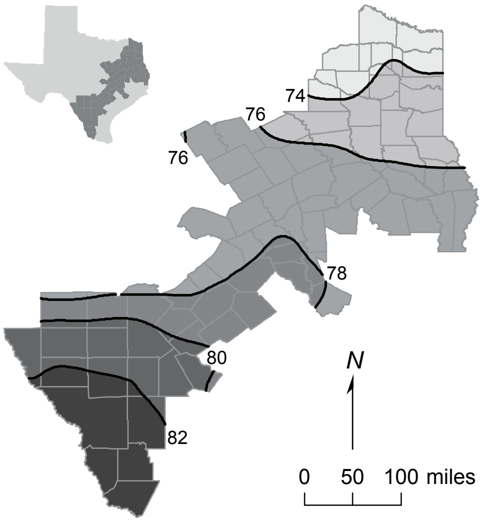

Figure 1-3. Average maximum daily temperature (in degrees Fahrenheit) in the Upper Gulf Coast region from 1971 to 2000 (data from SCAS, 2004).

feet in 2010 to 3.9 million acre-feet in 2060, an increase of about 45 percent (TWDB, 2007).

The Upper Coastal Plains is bounded to the west by the Balcones Escarpment and the Edwards and Trinity formations and to the east by the coastal plains and the Gulf Coast Aquifer. The climate in the region ranges from subtropical and humid in the northeast to more arid subtropical steppe in the southwest (Larkin and Bomar, 1983). Average annual rainfall ranges from less than 20 inches in the southwest to over 60 inches in the northeast, and the average maximum daily temperature ranges from about 73°F in the northeast to over 82°F in the southwest (Figures 1-2 and 1-3; SCAS, 2004). Of the 16 major rivers of the state recognized by the TWDB, 14 flow over at least part of the Carrizo-Wilcox Aquifer (Figure 1-4). These rivers flow generally to the southeast, toward the Gulf of Mexico and perpendicular to the geologic formations that make up most of the aquifers in the region.

1.2
AQUIFERS OF THE UPPER COASTAL PLAINS

The Upper Coastal Plains region includes the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Brazos River Alluvium aquifers (Figure 1-5). In addition to defining the boundaries of these aquifers, TWDB has designated them as major or minor aquifers based on overall area covered or amount of water held. The Carrizo-Wilcox is the only major aquifer in the area; the others are classified as minor aquifers. In addition to these aquifers, there are other water-bearing geologic formations that produce water on the local level.

With the exception of the Brazos River Alluvium Aquifer, these aquifers run subparallel to the Gulf of Mexico about 100–200 miles inland from the coast and are composed of aquifer formations that tend to thicken and dip to the south and southeast, forming a layered wedge of sediments. All of the aquifers are composed mostly of sediments originally deposited in and along rivers and deltas. The Brazos River Alluvium Aquifer and the outcrop areas of the other aquifers are generally unconfined, and downdip parts of aquifers that

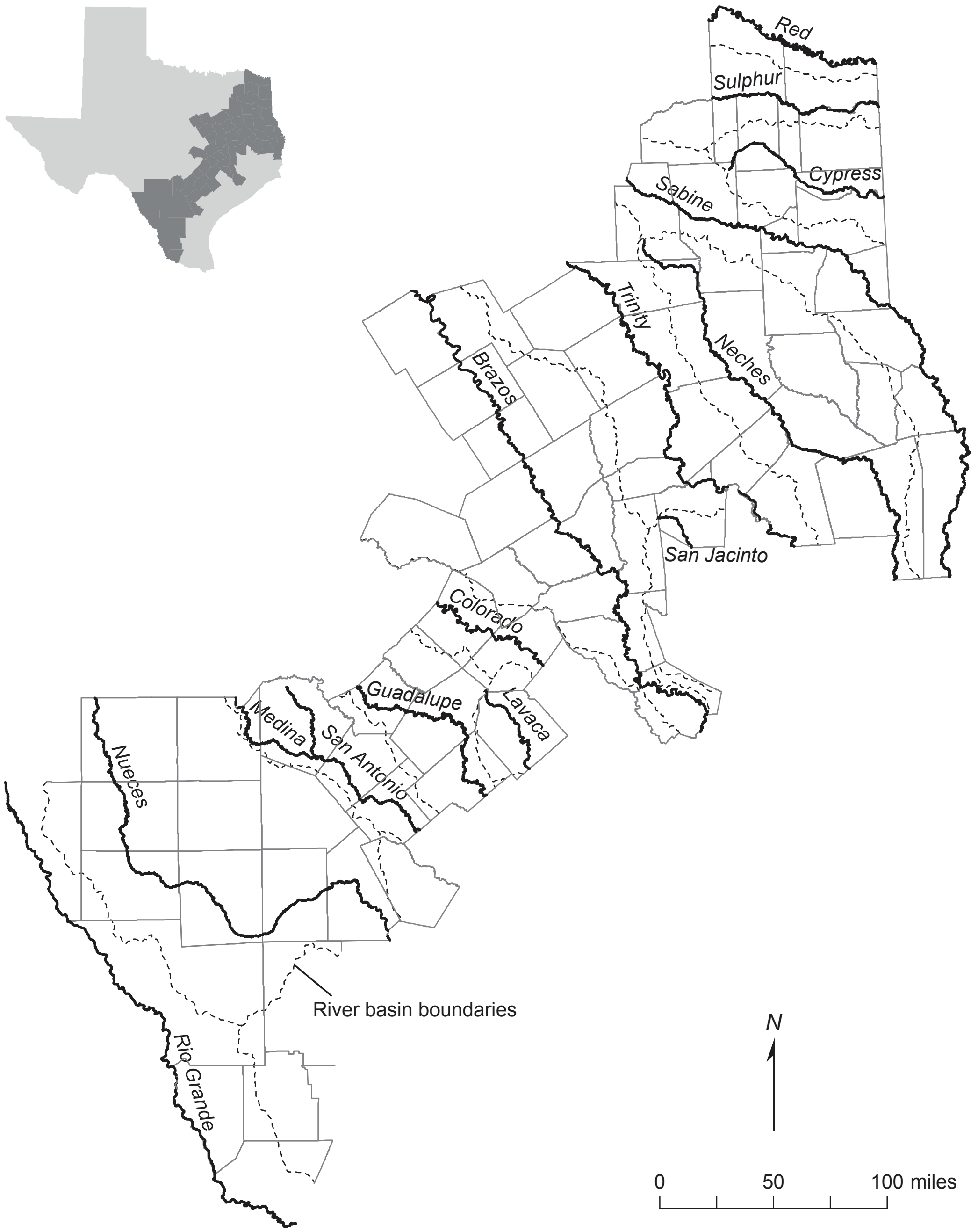

Figure 1-4. Location of major rivers and river basin boundaries in the Upper Gulf Coast region.

underlie younger formations are generally confined. Regional water flow in the aquifers is to the south and southeast.

The amount of water withdrawn from these aquifers annually since 1980 has varied, ranging from 390,000 acre-feet in 1987 to 607,000 acre-feet in 2002 (Figure 1-6; TWDB, 2009). The Carrizo-Wilcox is by far the largest source of groundwater in the region, accounting for about 90 percent of these withdrawals. The water is used primarily for irrigation and municipal supplies.

Groundwater studies have focused primarily on the Carrizo-Wilcox Aquifer, but each of the minor aquifers has been

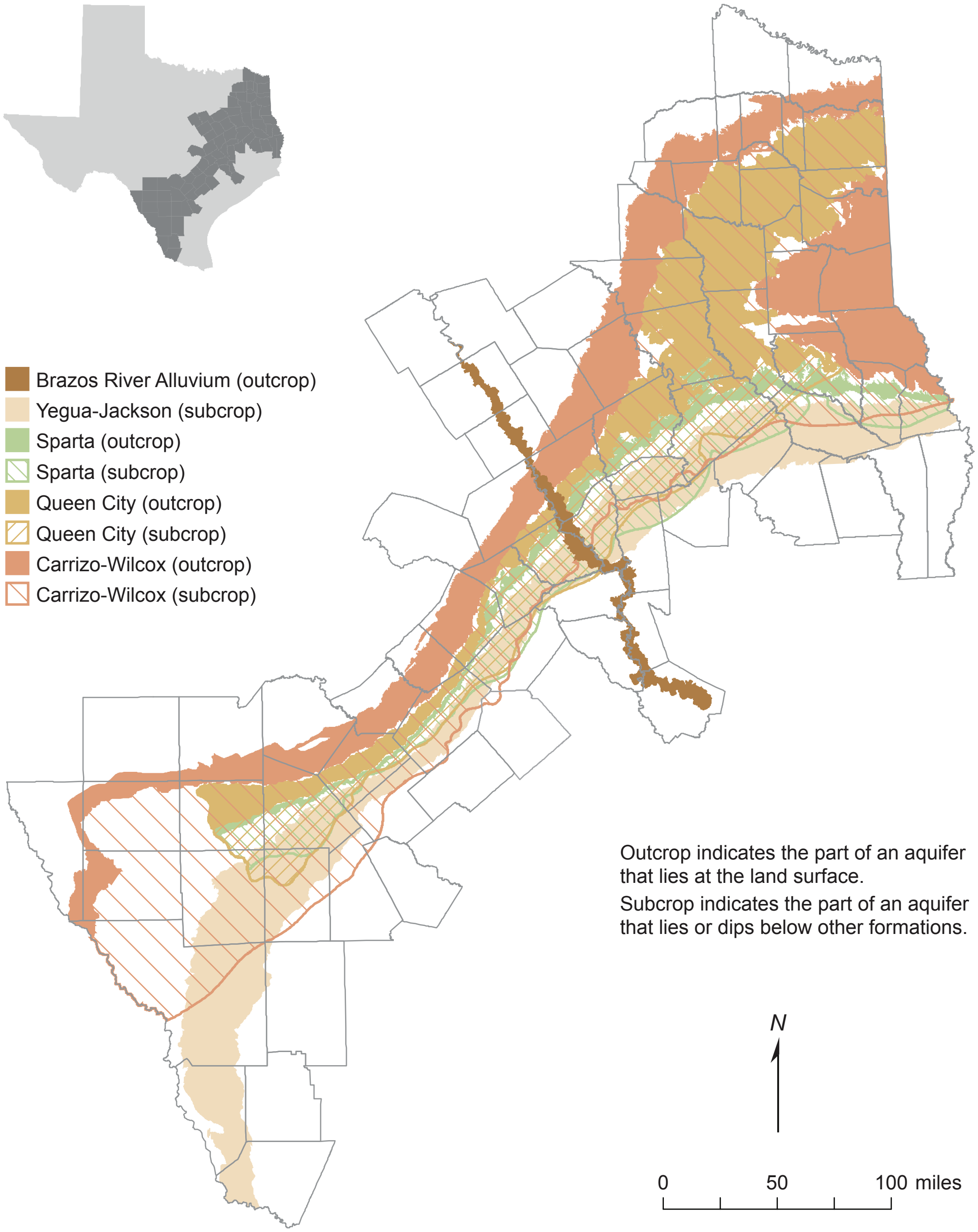

Figure 1-5. Location of major and minor aquifers recognized by TWDB and discussed in this report.

studied as well. Below are brief descriptions of the aquifers of the Upper Coastal Plains; more thorough information will be found throughout this report.

1.3
CARRIZO-WILCOX AQUIFER

The Carrizo-Wilcox Aquifer extends across Texas, stretching from Mexico across the Rio Grande and northeast into Arkansas and Louisiana. This aquifer lies beneath all or parts of Anderson, Angelina, Atascosa, Bastrop, Bee, Bexar, Bowie, Brazos, Burleson, Caldwell, Camp, Cass, Cherokee, DeWitt, Dimmit, Duval, Falls, Fayette, Franklin, Freestone, Frio, Gonzales, Gregg, Grimes, Guadalupe, Harrison, Henderson, Hopkins, Houston, Jim Hogg, Karnes, La Salle, Lavaca, Lee, Leon, Limestone,

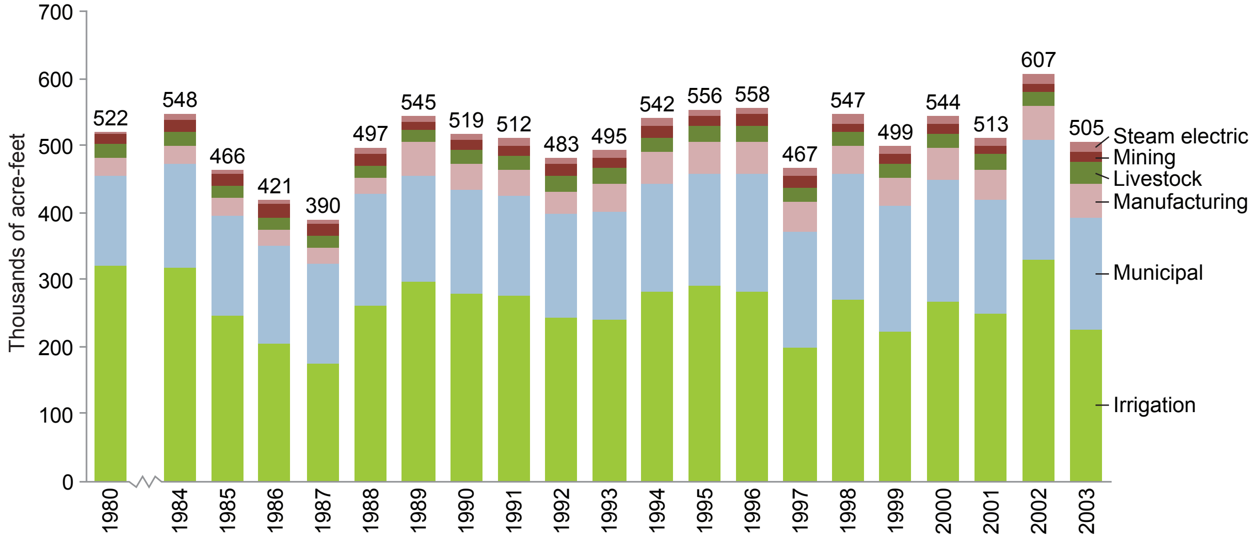

Figure 1-6. Estimated annual groundwater withdrawals from the Brazos River Alluvium, Carrizo-Wilcox, Queen City, and Sparta aquifers by type of use. Estimates are not available for the years 1981–1983 or for the Yegua-Jackson Aquifer.

Live Oak, Madison, Marion, Maverick, McClennan, McMullen, Medina, Milam, Morris, Nacogdoches, Navarro, Panola, Rains, Red River, Robertson, Rusk, Sabine, San Augustine, Shelby, Smith, Starr, Titus, Trinity, Upshur, Uvalde, Van Zandt, Walker, Webb, Williamson, Wilson, Wood, Zapata, and Zavala counties.

The aquifer is made up of the Wilcox Group and Carrizo Formation, which are sedimentary deposits primarily of sand, along with interbedded layers of gravel, silt, clay, shale, and lignite that were deposited during the upper Paleocene-lower Eocene. It is separated from the overlying Queen City Aquifer by the relatively impermeable Reklaw Formation. The aquifer has a maximum thickness of more than 3,000 feet, and the thickness of sands saturated with fresh water averages about 700 feet. Water from the aquifer is commonly hard but fresh in and near outcrop areas, containing less than 500 milligrams per liter of total dissolved solids. Higher concentrations of total dissolved solids, rarely exceeding 3,000 milligrams per liter, are more common at depth and in the central and southwestern parts of the aquifer. Localized areas of high iron content are found throughout the aquifer, particularly in the northeast (Rogers, 1967; William F. Guyton and Associates, 1972; Klemt and others, 1976; Preston and Moore, 1991; Thorkildsen and Price, 1991; Beynon, 1992; Ashworth and Hopkins, 1995; TWDB, 2007; Boghici, 2009).

The Carrizo-Wilcox Aquifer is one of the most productive aquifers in Texas. Groundwater production from the Carrizo-Wilcox is predominately for irrigation and municipal water supplies. Irrigation pumping from the aquifer is greatest in the Winter Garden region in South Texas, and the largest areas of municipal use are in the Bryan-College Station, Lufkin-Nacogdoches, and Tyler areas. In addition, a significant volume of groundwater in the central part of the aquifer has been extracted as part of lignite mining operations. Withdrawals from the aquifer totaled 450,000 acre-feet per year in 2003, of which 43 percent was used for irrigation and 35 percent was used for municipal supplies (TWDB, 2009). Since groundwater withdrawals from the aquifer began, water levels have declined at least 50 feet in much of the aquifer and hundreds of feet near major municipal users and in the Winter Garden area. Groundwater pumpage from the aquifer is expected to increase between 2010 and 2060, largely to meet municipal demand for San Antonio, other cities along the Interstate 35 corridor, and Bryan-College Station (TWDB, 2007). The Carrizo-Wilcox Aquifer is discussed in more detail throughout this report.

1.4
QUEEN CITY AND SPARTA AQUIFERS

The Queen City and Sparta aquifers are widespread minor aquifers stretching across the Texas Upper Coastal Plain from Louisiana into South Texas, including all or parts of Anderson, Angelina, Atascosa, Bastrop, Brazos, Burleson, Caldwell, Camp, Cass, Cherokee, Fayette, Freestone, Frio, Gonzales, Gregg, Grimes, Harrison, Henderson, Houston, Karnes, La Salle, Lee, Leon, Madison, Marion, McMullen, Milam, Morris, Nacogdoches, Robertson, Rusk, Sabine, San Augustine, Smith, Trinity, Upshur, Van Zandt, Walker, Wilson, and Wood counties.

The Queen City and Sparta aquifers consist of water held in formations of the same names, both part of the Eocene-aged Claiborne Group. Although the Queen City overlies a large portion of the Sparta, they are separated by the low-permeability Weches Formation, which restricts flow between the aquifers (Preston and Moore, 1991). Chapter 5 of this report provides more information about these aquifers.

The Queen City Formation is composed of sand, sandstone, shale, and clay, with lignite found locally. The aquifer thickness is less than 500 feet in most places but reaches almost 700 feet in parts of northeast Texas. Water in the aquifer is fresh to slightly saline, with quality decreasing to the southwest and in deeper parts of the aquifer. The average concentration of total dissolved solids increases from about 300 milligrams per liter in outcrop areas to about 750 milligrams per liter in downdip parts of the aquifer (Rogers, 1967; William F. Guyton and Associates, 1972; Klemt and others, 1976; Preston and Moore, 1991; Ashworth and Hopkins, 1995; TWDB, 2007).

In 2003, an estimated 16,000 acre-feet of water was withdrawn from the Queen City Aquifer, mostly for municipal and livestock use (TWDB, 2009). Between 1990 and 2000, water levels in monitored wells showed a median decline of 1.5 feet (Boghici, 2008). Use of the aquifer is expected to remain fairly constant from 2010 through 2060 (TWDB, 2007).

The Sparta Formation consists of sand and interbedded clays, with small amounts of lignite in some locations. The sediment thickness increases to the northeast, reaching more than 700 feet. The average saturated thickness of the aquifer is about 120 feet. Water is generally fresh in and near the outcrop area, containing about 300 milligrams per liter of total dissolved solids, and becomes increasingly saline with depth, containing an average of 800 milligrams per liter of total dissolved solids. High concentrations of iron occur throughout the aquifer (Rogers, 1967; William F. Guyton and Associates, 1972; Klemt and others, 1976; Ashworth and Hopkins, 1995; TWDB, 2007).

The approximately 10,000 acre-feet of water withdrawn from the Sparta Aquifer in 2003 was used primarily for municipal and manufacturing uses (TWDB, 2009). Water level measurements indicate a median decline of 1.4 feet in water levels in the aquifer from 1990 to 2000 (Boghici, 2008). Total withdrawals from the aquifer are likely to remain approximately the same from 2010 through 2060 (TWDB, 2007).

1.5
YEGUA-JACKSON AQUIFER

The Yegua-Jackson Aquifer is a minor aquifer that runs in a narrow band between the Gulf Coast Aquifer and the outcrop areas of the Carrizo-Wilcox

Aquifer. It is located in all or parts of Angelina, Atascosa, Bastrop, Brazos, Burleson, Duval, Fayette, Frio, Gonzales, Grimes, Houston, Jasper, Jim Hogg, Karnes, LaSalle, Lavaca, Lee, Leon, Live Oak, Madison, McMullen, Nacogdoches, Newton, Polk, Sabine, San Augustine, Starr, Trinity, Tyler, Walker, Washington, Webb, Wilson, and Zapata counties.

The Yegua-Jackson includes the Eocene-aged Yegua Formation of the Claiborne Group and the overlying Eocene-Oligocene-aged Jackson Group. These units are composed of interbedded sand, silt, and clay, with smaller amounts of lignite, limestone, tuff, shells, and gypsum. Although the combined thickness of these formations can reach thousands of feet, the average thickness of sediments saturated with fresh water, found only in shallower parts of the formations, is less than 200 feet in most places. Water quality in the aquifer is highly variable, becoming more saline with depth and changing as a result of differences in sediment composition (Rogers, 1967; Thorkildsen and Price, 1991; Preston, 2006; TWDB, 2007; Knox and others, 2009).

Because the Yegua-Jackson Aquifer was not recognized as a minor aquifer until 2002 (TWDB, 2002), historical pumping estimates have grouped use from the aquifer with “other” aquifers. However, draft analysis of historical pumping made for the development of the TWDB groundwater availability model for the aquifer estimate that approximately 15,000 acre-feet of water was withdrawn from the aquifer in 1997, more than half of which was for rural domestic use. Monitored water levels indicated a median water level rise in the aquifer of 0.6 foot from 1990 to 2000 (Boghici, 2008). Withdrawals from the aquifer are projected to increase between 2010 and 2060, mostly to provide supplies for municipal use and manufacturing (TWDB, 2007). See Chapter 6 for further description of this aquifer.

1.6

BRAZOS RIVER ALLUVIUM AQUIFER

The Brazos River Alluvium Aquifer, a minor aquifer, is located in parts of Austin, Bosque, Brazos, Burleson, Falls, Fort Bend, Grimes, Hill, McLennan, Milam, Robertson, Waller, and Washington counties.

The aquifer is composed of alluvial terrace and floodplain deposits along the Brazos River, which flows through east-central Texas into the Gulf of Mexico. The sediments include sand, gravel, silt, and clay that reach up to around 75 feet in thickness in terrace deposits and up to 100 feet in thickness in floodplain deposits. The average thickness of the floodplain deposits is about 45 feet, with the thickness increasing toward the coast. Water quality varies but typically is hard and contains less than 1,000 milligrams per liter of total dissolved solids (Cronin and Wilson, 1967), although total dissolved solids occasionally reach about 3,000 milligrams per liter (TWDB, 2007). The Brazos River Alluvium Aquifer is hydraulically connected to the Brazos River as well as to underlying bedrock aquifers, including the Yegua-Jackson.

The primary use of water pumped from the aquifer is for irrigation. Between 1980 and 2003, withdrawals from the aquifer typically ranged from 20,000 acre-feet to 40,000 acre-feet (TWDB, 2007). In 2003, over 99 percent of the estimated 33,000 acre-feet of water withdrawn from the aquifer was used for irrigation (TWDB, 2009). Water levels monitored between 1990 and 2000 showed a median water level increase of 0.4 foot (Boghici, 2008). Further development of the aquifer has not been planned, and use of the aquifer is expected to decrease between 2010 and 2060 (TWDB, 2007). More information about this aquifer is available in Chapter 7 of this report.

1.7

GROUNDWATER MANAGEMENT IN THE UPPER COASTAL PLAINS

The future use of these aquifers will be managed by local groundwater conservation districts, the preferred method of groundwater management in Texas. The specifics of groundwater management in the region are based primarily on state legislation that authorizes local groundwater conservation districts to establish policies for managing their groundwater resources and to coordinate these policies within regional groundwater management areas. Policies developed by groundwater conservation districts will be used in coming years by regional water planning groups in developing management strategies to meet future water demands.

1.8

REGIONAL WATER PLANNING

Comprehensive water legislation passed in 1997 called for regional water planning groups representing a wide range of interests to develop 50-year water plans within 16 defined regional water planning areas. Parts of 10 of these regional water planning areas are located within the study area (Figure 1-7). Each regional water planning group must create a water plan every five years that defines current and projected water supplies and demands, identifies specific water needs—demands that could not be met under drought conditions—and develops water management strategies to meet these needs. TWDB then uses these regional plans to develop a state water plan. The most recent state water plan was released in 2007 (TWDB, 2007). Future water projects and permits must be consistent with the state water plan to qualify for financial assistance from TWDB and water rights permits from the Texas Commission on Environmental Quality.

Using only existing permits, contracts, and infrastructure in the study area, unmet needs in a drought of record are expected to reach 1.2 million acre-feet by 2060 (TWDB, 2007). To meet these needs, regional water planners recommended implementing a wide range of management strategies, many of which include further development of the aquifers discussed in this report. Strategies that involve these aquifers include new wells and well fields, expanded use of existing wells, brackish water desalination, conjunctive management with surface water supplies, water transfers, and temporary overdrafting of aquifers (withdrawing more than the amount considered available by water managers, based on management philosophy and knowledge of the aquifer). Other types of strategies involve surface water resources, water reuse, and water conservation. Financing those strategies that involve significant costs will provide a challenge to implementing these strategies. Chapters 9 and 10 of this report address specific groundwater development projects that address future needs in the region.

1.9

GROUNDWATER CONSERVATION DISTRICTS

In 1949, Texas House Bill 162, authorizing the creation of underground water conservation districts, was passed by the Texas Legislature and signed into law. Over the past two decades, the legislature has passed further legislation empowering groundwater conservation districts to manage the groundwater within their borders and to coordinate management within regional groundwater management areas. Groundwater conservation districts develop management plans and rules to implement these management plans. They have the ability to modify and replace the “rule of capture” via the management plan and rules. Areas in the state that have no groundwater conservation district still exist under the “rule of capture.” However, over 90 percent of all groundwater used in the state is withdrawn from an

Figure 1-7. Location of regional water planning areas in the Upper Gulf Coast region.

area within a groundwater conservation district.

The Upper Coastal Plains region is currently home to 30 confirmed groundwater conservation districts and all or parts of 10 groundwater management areas (Figure 1-8). Over 60 percent of the area is within a groundwater conservation district, including many of the region's population and pumping centers. The groundwater conservation districts include the following:

- Anderson County Underground Water Conservation District
- Barton Springs/Edwards Aquifer Conservation District
- Bee Groundwater Conservation District

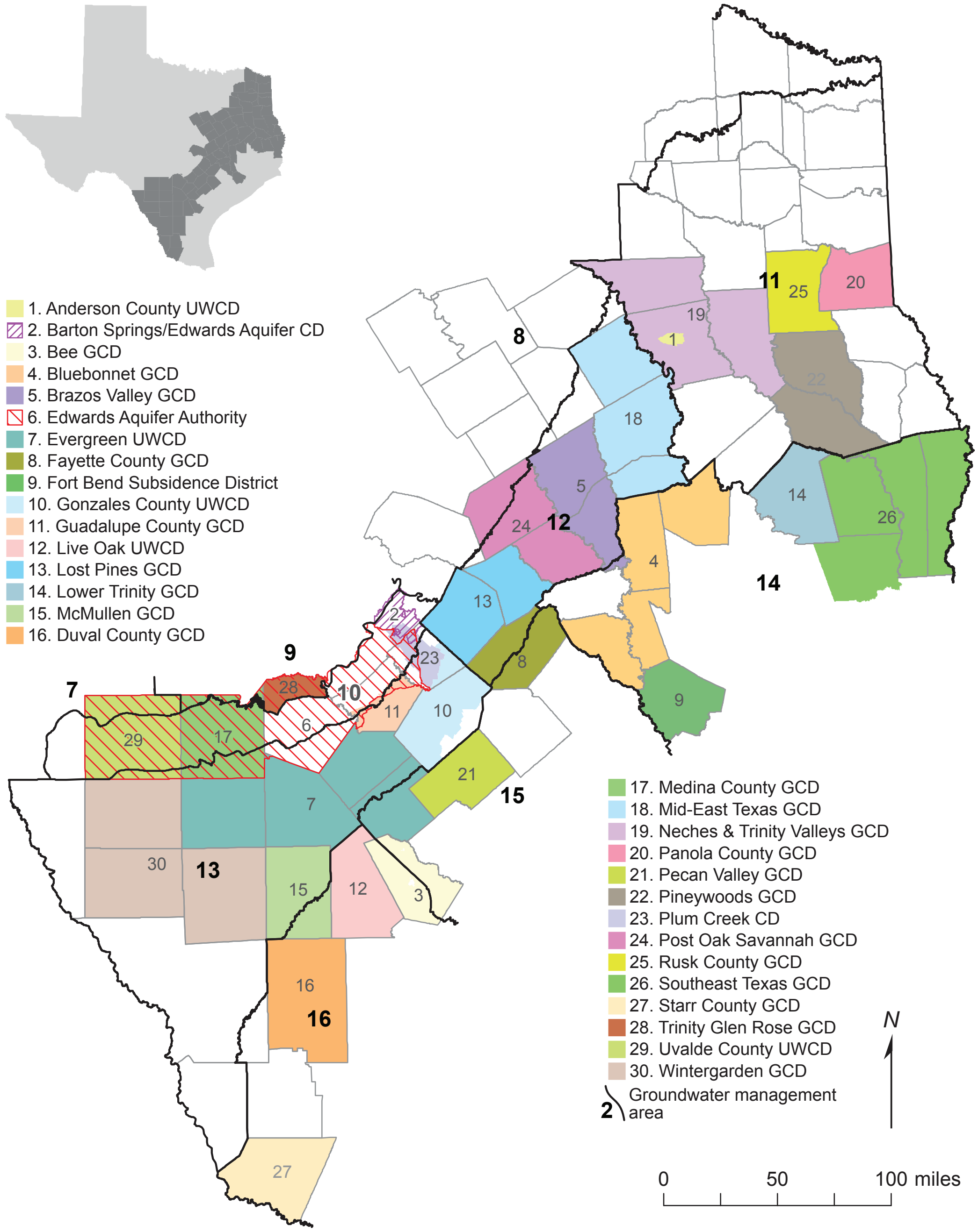

Figure 1-8. Location of groundwater conservation districts and groundwater management areas in the Upper Gulf Coast region. GCD = groundwater conservation district; UWCD = Underground water conservation district

- Bluebonnet Groundwater Conservation District
- Brazos Valley Groundwater Conservation District
- Duval County Groundwater Conservation District
- Edwards Aquifer Authority
- Evergreen Underground Water Conservation District
- Fayette County Groundwater Conservation District
- Fort Bend Subsidence District
- Gonzales County Underground Water Conservation District
- Guadalupe County Groundwater Conservation District
- Live Oak Underground Water Conservation District

- Lost Pines Groundwater Conservation District
- Lower Trinity Groundwater Conservation District
- McMullen Groundwater Conservation District
- Medina County Groundwater Conservation District
- Mid-East Texas Groundwater Conservation District
- Neches and Trinity Valleys Groundwater Conservation District
- Panola County Groundwater Conservation District
- Pecan Valley Groundwater Conservation District
- Pineywoods Groundwater Conservation District
- Plum Creek Conservation District
- Post Oak Savannah Groundwater Conservation District
- Rusk County Groundwater Conservation District
- Southeast Texas Groundwater Conservation District
- Starr County Groundwater Conservation District
- Trinity Glen Rose Groundwater Conservation District
- Uvalde County Underground Water Conservation District
- Wintergarden Groundwater Conservation District.

In 2005, Texas House Bill 1763 significantly changed the role of groundwater conservation districts in water management and the water planning process. Overall, the bill prescribes a process for managing groundwater regionally and gives districts more influence over the water planning process. It requires all districts within the same groundwater management area to collectively decide on a desired future condition, such as a maximum allowable water level drawdown, for each aquifer in the area. TWDB then uses groundwater availability models or other available information to estimate the volume of water that can be withdrawn from an aquifer annually while meeting this chosen condition. After these amounts, known as managed available groundwater, are defined, they will be used in future regional and state water plans as the maximum amount of water from an aquifer that can be used to meet water demands. Therefore, even in areas without districts, regional management philosophies will affect groundwater development by limiting eligibility for state funding to projects that will not conflict with the desired future conditions of districts in the groundwater management area (Mace and others, 2006).

1.10
GROUNDWATER AVAILABILITY MODELING

Groundwater availability models are tools that groundwater managers can use to predict how future changes in groundwater pumping and/or drought conditions might affect regional water levels and groundwater flow in aquifers. They are three-dimensional, numerical computer models that use available information about aquifers (such as measurements of water levels in wells, spring discharge, and the composition, structure, and permeability of the geologic formations that make up the aquifer) to simulate groundwater flow through them. Development of these models began in 1999 and continues today. In the future, there will be models for all of the major and minor aquifers in the state, and these models will be updated as future studies and monitoring provide more information about the aquifers.

Several groundwater availability models have been completed for the aquifers discussed in this report. Due to its size and the variation in its hydrogeologic characteristics, three models have been created for the Carrizo-Wilcox (Deeds and others, 2003; Dutton and others, 2003; Fryar and others, 2003). Because the Carrizo-Wilcox, Queen City, and Sparta aquifers are hydraulically connected, the models of the Queen City and Sparta aquifers were added to the Carrizo-Wilcox Aquifer models (Kelley and others, 2004). Models for the Brazos River Alluvium and Yegua-Jackson aquifers are currently under development.

1.11
SUMMARY

The population of the Upper Gulf Coast of Texas has more than doubled since 1950, and future population growth will increase the demand for water. In 2004, more than half of the water use in this region came from groundwater. The Carrizo-Wilcox Aquifer is the primary source of groundwater in the region and one of the most productive aquifers in the state. The Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Brazos River Alluvium aquifers are all sedimentary aquifers that provide significant sources of water to the region and are described in further detail throughout this report. Water users, groundwater managers, and water planners will depend on sufficient and accurate knowledge of groundwater resources in the region to ensure that future water needs are met.

1.12
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Chapter 2

Geology of the Carrizo-Wilcox Aquifer

Peter G. George, Ph.D., P.G.[1]

The Carrizo Wilcox Aquifer consists of rocks of the Wilcox Group that extend from Mexico, across Texas, into Louisiana, Arkansas, Mississippi, Alabama, Tennessee, and Kentucky (Figures 2-1, 2-2, 2-3, and 2-4). In Texas, the aquifer occurs in 66 counties over 11,186 square miles of outcrop and 25,409 square miles in the subsurface (TWDB, 2007). Based on its size and the large amount of water it supplies to the state, it is considered a major aquifer. Wilcox Group rocks are also important as a major oil and gas producer. This latter aspect is fortuitous in that Wilcox Group rocks have been the subject of numerous geologic studies, and this information is transferable to studies involving groundwater.

2.1
PREVIOUS WORK

The amount of information on the Wilcox Group is extensive, so this study will focus on work from inland areas where useable groundwater can be found, as well as other regional studies for context. Local onshore studies include Plummer (1933); Fischer and McGowen (1967); Edwards (1981); Bebout and others (1982); Galloway (1968); Halbouty and Halbouty (1982); Fiduk and Hamilton (1995); Xue and Galloway (1995); and Fiduk and others (2004). More regional studies on lower Tertiary stratigraphy include Galloway (1989a, 1989b); Worrall and Snelson (1989); Culotta and others (1992); Galloway and others (2000); Galloway (2005); Zarra (2007); and McDonnell and others (2008). Regional studies on the structural history of the Gulf of Mexico include Buffler (1991); Salvador (1991); Bradshaw and Watkins (1994); Diegel and others (1995); Peel and others (1995); Watkins and others (1996); Huh and others (1996); Jackson and others (2003); and Rowan and others (2005).

2.2
PHYSIOGRAPHY AND CLIMATE

The Carrizo-Wilcox Aquifer is located within the Interior Coastal Plains subprovince of the Gulf Coastal Plains physiographic province (Wermund, 1996). The Interior Coastal Plains are characterized by alternating sequences of unconsolidated sands and clays. The sands tend to be more resistant to erosion than the clay-rich soils, thereby producing numerous sand ridges paralleling the coast.

The Interior Coastal Plains subprovince has low topographic relief with ground surface elevations decreasing from about 800 feet to 100 feet toward the Gulf of Mexico.

Northwest- to southeast-flowing rivers, such as the Colorado and Brazos, cut across the Wilcox Group and younger rocks through broad terraced valleys.

Pine and hardwood forests predominate over the northeastern part of the aquifer, within a dense network of perennial streams. Toward the southwest, the number of trees decreases as they are replaced by chaparral brush and grasses (Wermund, 1996).

The aquifer is subject to three climatic zones: the Subtropical Humid division in the north, the Subtropical Subhumid division in the south, and the Subtropical Steppe division near the border with Mexico (Larkin and Bomar, 1983). Precipitation decreases east to west across the area of interest, from about 55 inches

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[1] Texas Water Development Board

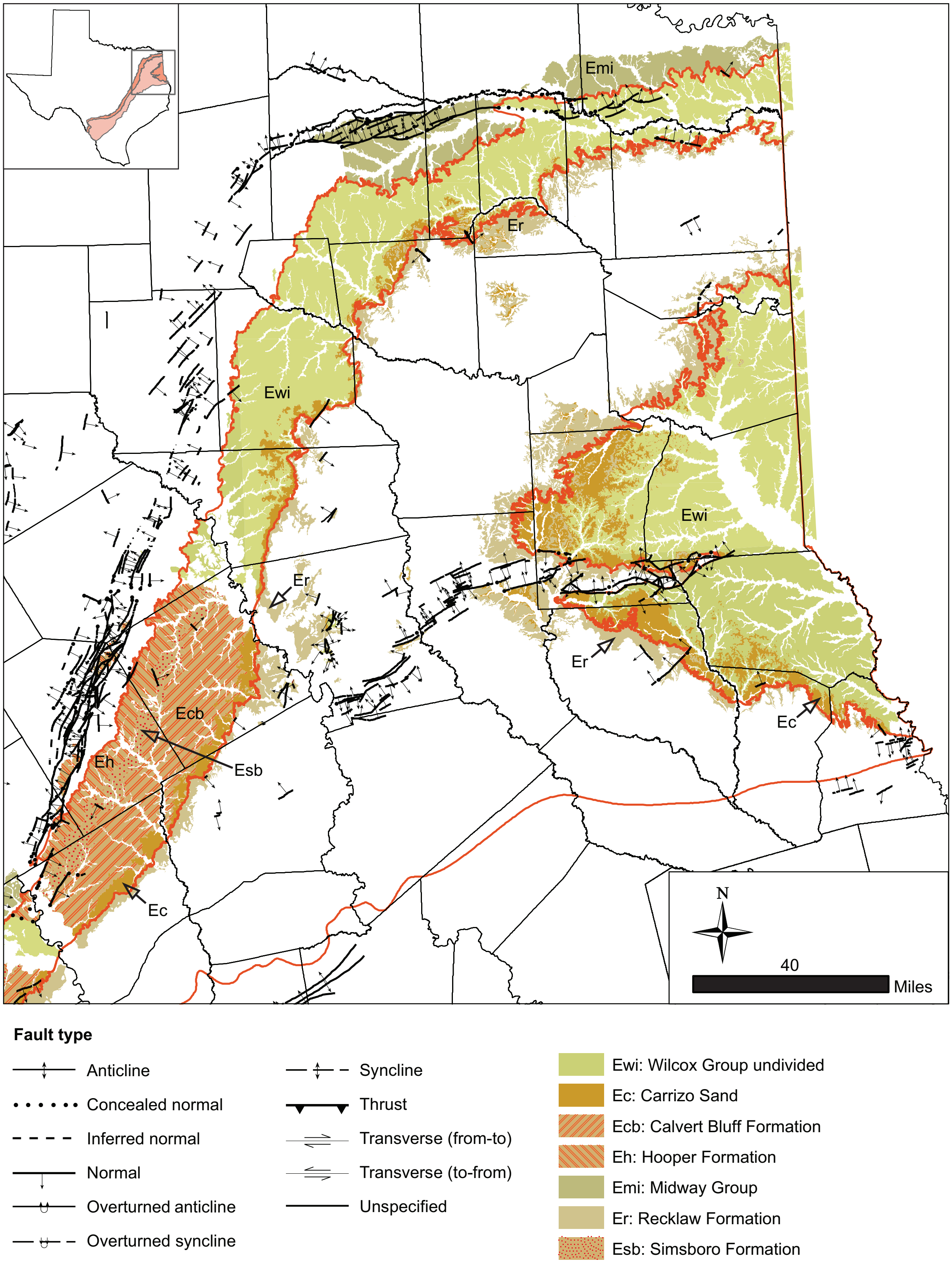

Figure 2-1. Partial geology of the northeastern part of the Carrizo-Wilcox Aquifer (outline shown in red), created using the 1:250,000 Digital Geological Atlas of Texas (USGS and TWDB, 2006).

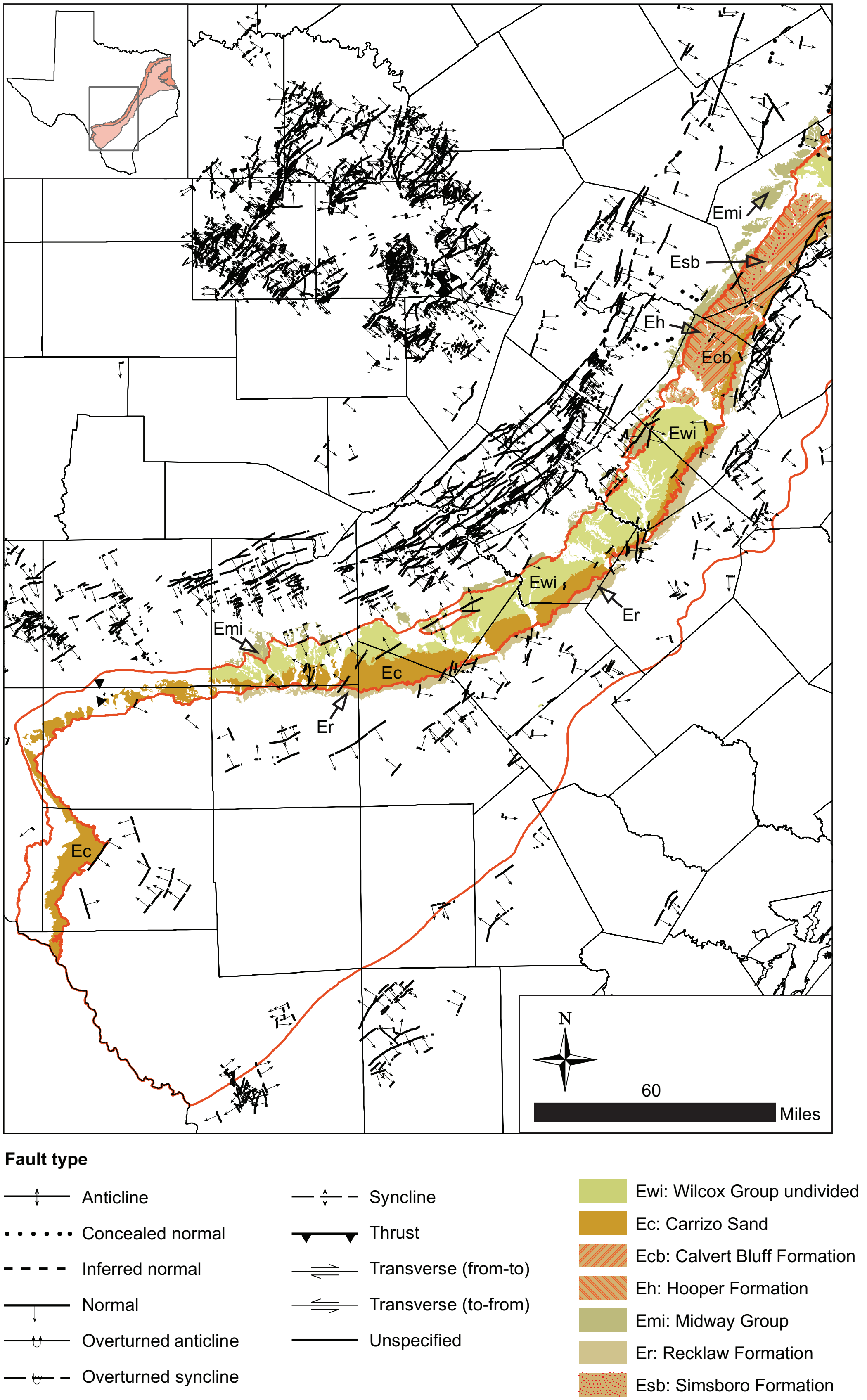

Figure 2-2. Partial geology of the southwestern part of the Carrizo-Wilcox Aquifer (outline shown in red), created using the 1:250,000 Digital Geological Atlas of Texas (USGS and TWDB, 2006).

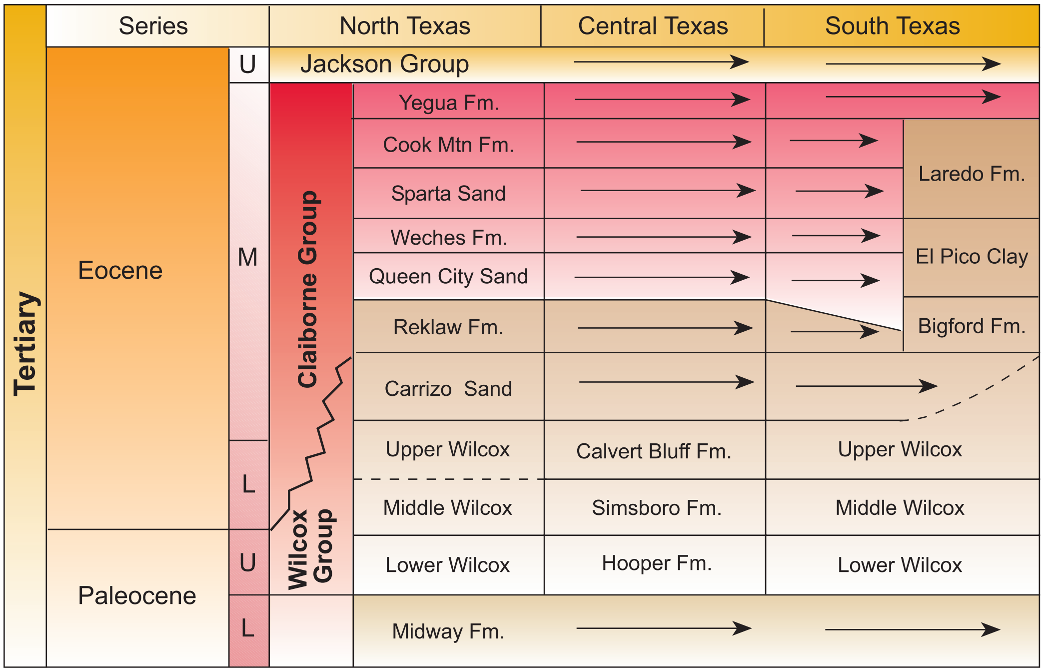

Figure 2-3. Generalized stratigraphic columns for the Carrizo-Wilcox Aquifer in Texas (from Fryar and others, 2003; after Ayers and Lewis, 1985; Hamlin, 1988; and Kaiser and others, 1978).

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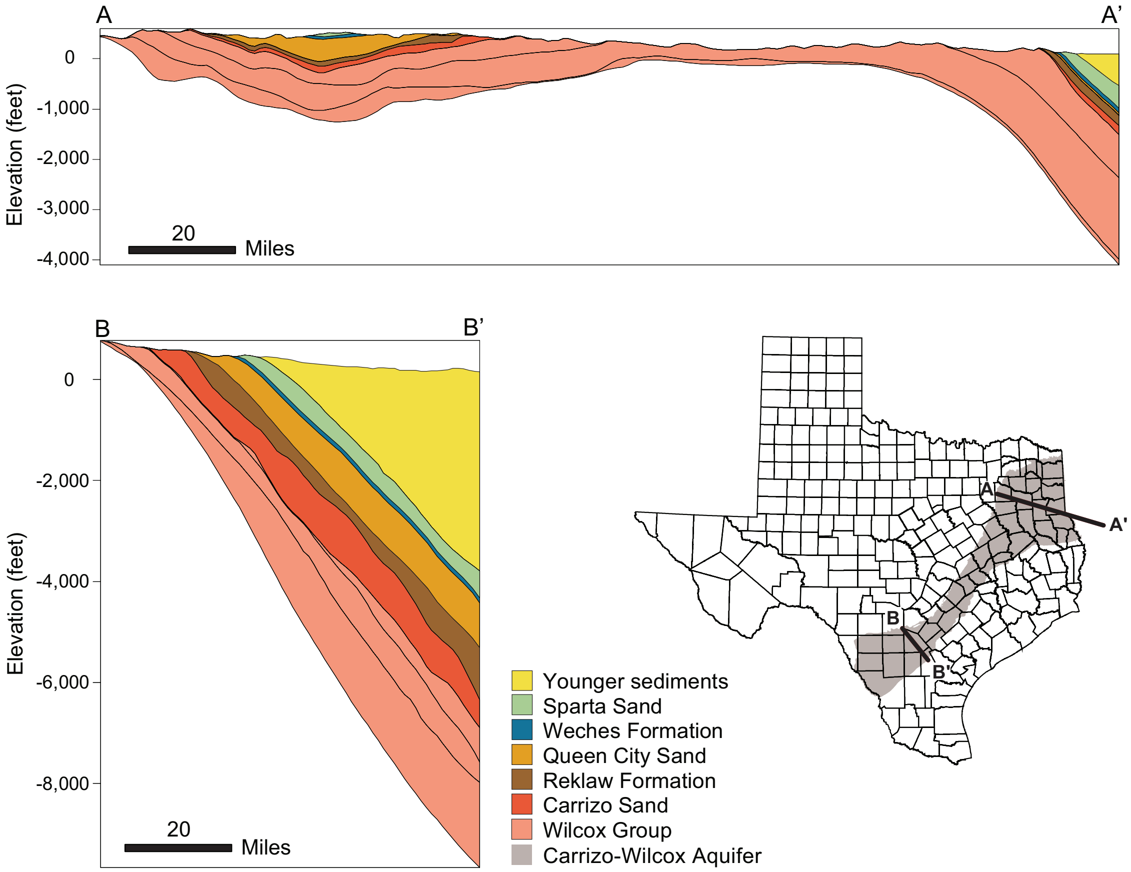

Figure 2-4. Structural cross section of the Carrizo-Wilcox Aquifer and overlying strata (modified from Kelley and others, 2004).

per year to about 20 inches per year along the Rio Grande (TWDB, 2007). The annual average lake evaporation rate increases to the southwest from about 45 inches per year to 85 inches per year (Larkin and Bomar, 1983).

2.3
GEOLOGY

The rocks that compose the Carrizo-Wilcox Aquifer represent the first major Cenozoic influx of clastic sediment into the west and central Gulf of Mexico Basin (Galloway and others, 2000). Late Paleocene and early Eocene tectonics, changes in eustatic sea level, and the nature of the underlying depositional surface influenced the deposition of sediment.

2.4
REGIONAL STRUCTURE

The regional setting of the Carrizo-Wilcox Aquifer includes a variety of structural features produced along the northern margin of the Gulf of Mexico since the break up of the Paleozoic supercontinent Pangaea and the opening of the North Atlantic Ocean in Late Triassic time (Byerly, 1991; Ewing, 1991; Figure 2-5).

2.4.1
Balcones Fault Zone

The Balcones Fault Zone borders part of the aquifer to the north (Figure 2-5). This fault zone formed along the northern margin of the Gulf of Mexico Basin and constitutes a divide between Cretaceous strata to the north and Tertiary sediments to the south. The zone overlies major crustal-scale faults of the Ouachita orogenic belt, which formed earlier in the late Paleozoic. It is characterized by down-to-basement normal faults with cumulative displacements of up to 1,600 feet (Ewing, 1991). To the southeast is the Luling Fault Zone with mostly up-to-basin normal faults, and together these two fault zones form a large graben system about 30 miles wide. The timing of faulting is not well constrained, but there is some evidence of Late Cretaceous and Miocene movement.

2.4.2
Karnes/Milano/Mexia and Talco fault zones

The Karnes/Milano/Mexia and Talco fault zones are part of a larger graben system linked by zones of en echelon left-stepping, down-to-basin normal faults extending from Central Texas to the Arkansas border (Jackson 1982; Ewing, 1991). There is evidence for Cretaceous to Eocene movement along the Karnes Fault Zone and Jurassic to Paleocene faulting in the East Texas Basin area (Rose, 1972; Jackson, 1982). Faulting in the East Texas Basin is associated with movement of Jurassic Louann Salt at depth (Jackson, 1982).

2.4.3
Elkhart Graben

The Elkhart Graben is located along the western end of the Elkhart-Mount Enterprise Fault Zone. It consists of parallel, normal faults with multiple offsets defining a graben about 25 miles long (Jackson, 1982). Jackson (1982) considers the graben to have been formed by crustal stretching and the collapse of salt-related anticlines. Most displacement along graben faults took place during the Early Cretaceous, although Eocene rocks were affected by faulting as well.

2.4.4
Mount Enterprise Fault Zone

The Mount Enterprise Fault Zone is located to the northeast of the Elkhart Graben. This fault zone is a regular array of parallel and en echelon normal faults that are largely downthrown to the north in a series of multiple offsets (Jackson, 1982). Unlike other faults in the East Texas Embayment, the Mount Enterprise Fault Zone is not obviously connected to salt-related structures or

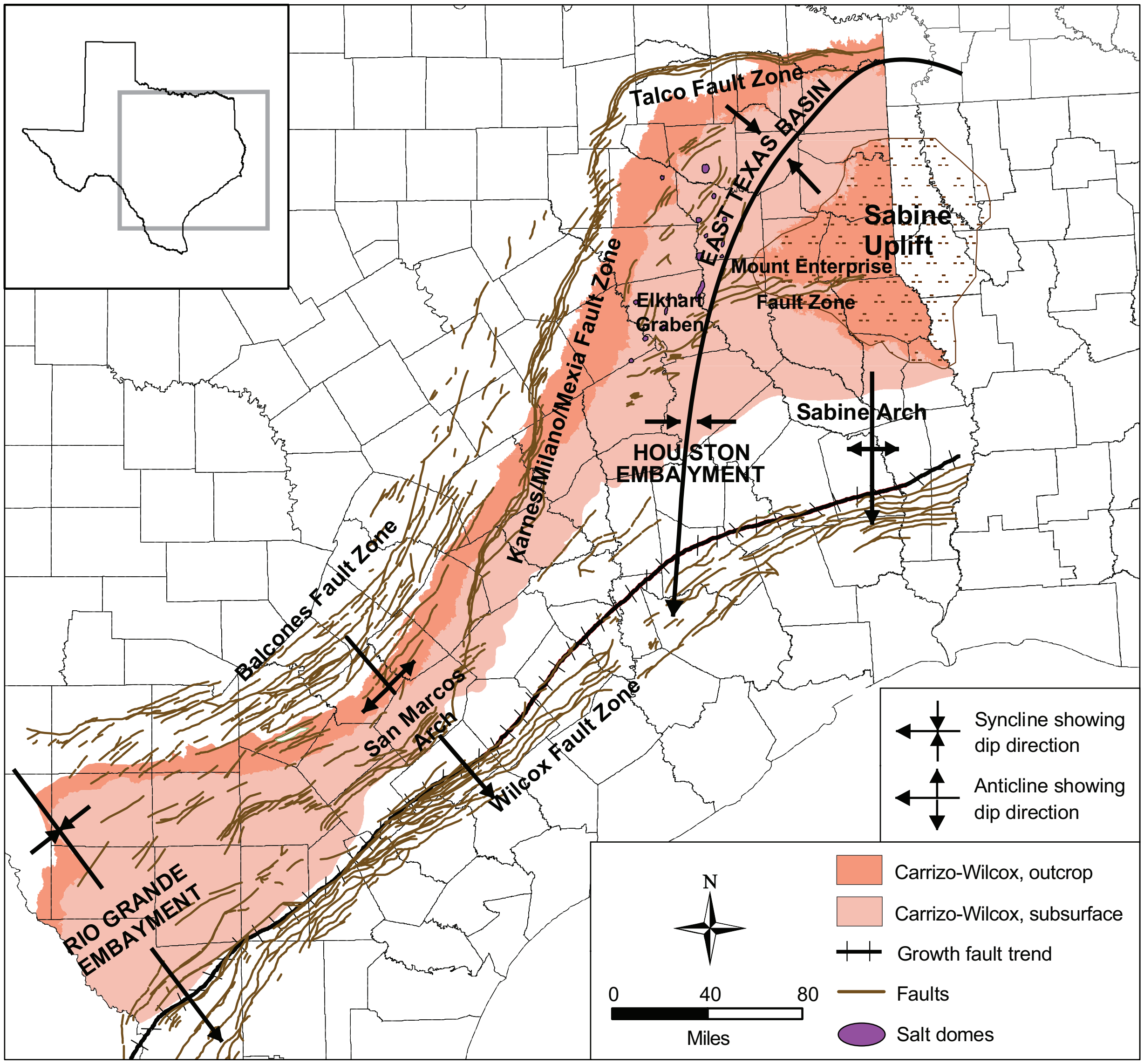

Figure 2-5. Map of major faults and structural features for the Texas Coastal Plain and East Texas Embayment in relation to the Carrizo-Wilcox Aquifer (modified from Kelley and others, 2004; Galloway and others, 2000; Ewing, 1990; Galloway 1982).

other basinal features. Also, even though the fault zone extends to the Sabine Uplift, it shows no geometric relationship to the structure. The fault zone was active in Early Cretaceous time, and some faulting was syndepositional with respect to the Wilcox Group.

2.4.5
Wilcox Fault Zone

The Wilcox Fault Zone parallels the Texas coastline south of the Carrizo-Wilcox Aquifer. The fault zone consists of closely spaced growth faults with a deep-listric character (Bruce, 1973; Ewing, 1991). Growth faults form in sedimentary rocks as deposition is occurring, where throw increases with depth and strata on the downthrown side are thicker than correlative strata on the upthrown side. Deep-listric growth faults are those that flatten into a deep, diffuse detachment level (probably in ductile shale), where vertical subsidence is greater than horizontal displacement (Ewing, 1988). In some cases, stratigraphic sections expand as much as three to five times across growth faults (Ewing, 1991). In South Texas, the Rosita Delta System thickens from about 600 feet to more than 3,000 feet across the fault zone. There, growth faults were activated by progradation of deltas over unstable prodelta-slope muds at the contemporary shelf margin (Edwards, 1981).

In the Houston Embayment, growth faults have been overprinted with salt diapir-related basins and uplifts (Ewing, 1983). In South Texas, a greater thickness of mobile, overpressured shale results in a complex structural style characterized by shale ridges and large antithetic faults (Ewing, 1986).

2.4.6
Sabine Uplift

The Sabine Uplift is a structural feature located between the East Texas and North Louisiana basins, and its present form is expressed in the outcrop patterns of Wilcox Group rocks (Figure 2-5). It has experienced several periods of uplift, but the causes of uplift are still unclear (Murray, 1945; Halbouty and Halbouty, 1982; Jackson and Laubach, 1988; Ewing, 1991). Uplift occurred in the mid-Cretaceous; Late Cretaceous (post-Woodbine, pre-Austin Chalk time); and in the Eocene. Halbouty and Halbouty (1982) estimated about 3,325 feet of uplift from Late Cretaceous to the present. During the deposition of Wilcox Group sediments, the Sabine Uplift region is thought to have been slowly rising (Moody, 1931).

2.4.7
San Marcos Arch

The San Marcos Arch is not considered an uplift in the traditional sense but more of a stable passive area where subsidence was less than within flanking "embayment" areas (Ewing, 1991). The arch appears to be an extension of the Llano Uplift to the northwest (Young, 1972). The stratigraphic influence of the San Marcos Arch can be detected in strata ranging in age from Jurassic to Miocene, extending from the Llano Uplift to the present shoreline (Halbouty, 1966).

2.4.8
East Texas Basin

The East Texas Basin accumulated a thick layer of salt during the Jurassic that later, during deposition of the Wilcox Group, strongly influenced sedimentation (Jackson, 1982; Jackson and Seni, 1983). From Early Cretaceous to Eocene time, salt structures in the basin evolved from pillow to diapir, and post-diapir geometries. Post-diapir growth produced mounds over salt domes that locally affected topography and subsequent distribution of sand and mud in fluvial deposits (Seni and Jackson, 1983).

2.4.9
Rio Grande and Houston embayments

Paleogene regional uplift and tectonism within the continental interior of western North America (Laramide Orogeny) provided the terrigenous clastic sediment deposited into the Gulf of Mexico Basin by way of the Rio Grande and Houston embayments. These embayments were areas of differential subsidence and sediment loading where thick sections of Wilcox Group sediment accumulated (Xue and Galloway, 1995; Xue, 1997).

The Houston Embayment lies north of the San Marcos Arch in a structural setting similar to that of the Rio Grande Embayment. It is a southern extension of the East Texas Basin and, as such, is characterized by salt diapirism and associated faulting and large salt withdrawal sub-basins (Jackson, 1982; Bebout and others 1978).

To the south across the San Marcos Platform and into the Rio Grande Embayment, underlying Jurassic salt is thin or absent, and long linear belts of growth faults and associated shale ridges, massifs, and diapirs dominate the structural style (Bruce, 1973). In the Rio Grande

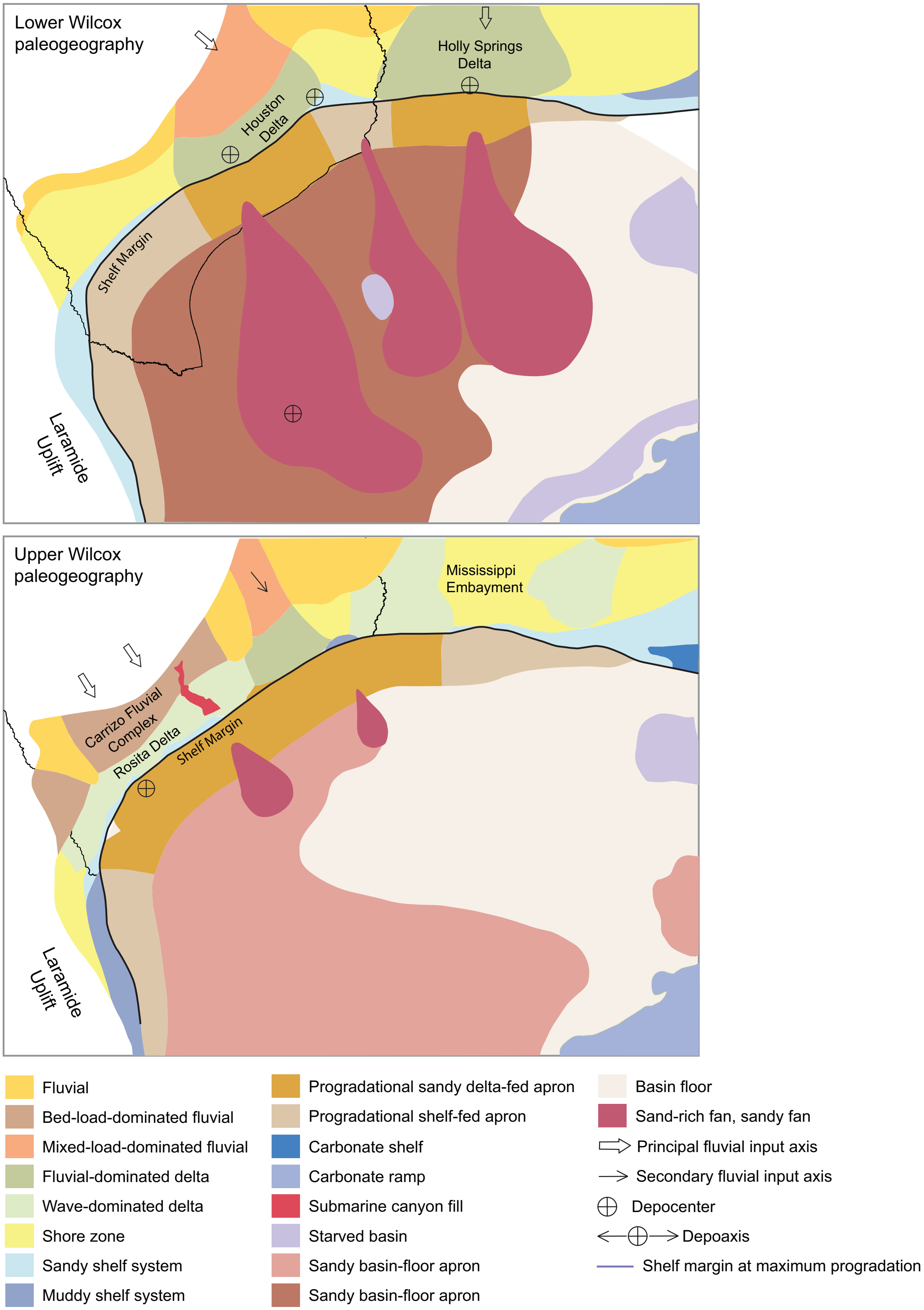

Figure 2-6. Paleogeographic maps during the times of Lower and Upper Wilcox deposition (modified from McDonnell and others, 2008).

Embayment, large but more discontinuous belts of growth faults and deep-seated shale ridges and massifs occur. South of the embayment in Mexico are northwest- to southeast-trending Laramide folds in Cretaceous rocks, such as the Peyotes-Picachos and Tamaulipas arches. Jurassic and Cretaceous sedimentation in the Rio Grande Embayment was nearly continuous, and later Tertiary deposition was influenced by the growth faulting and shale diapirism (Ewing, 1991).

2.5
REGIONAL STRATIGRAPHY

One method of describing the stratigraphic evolution of the Cenozoic Gulf of Mexico is through a series of paleogeographic maps. Two such maps, for the Upper and Lower Wilcox, are presented here (Salvador, 1991; Galloway and others, 2000; Figure 2-6).

2.5.1
Cretaceous

In Early and middle Cretaceous time, the Gulf of Mexico was characterized by carbonate shelves in the north and northwest and steep carbonate platforms in present-day Florida and Yucatan (Worrall and Snelson, 1989). Sedimentation was restricted to the basin margin where reefs developed, such as along the Sligo and Stuart City reef trends. Abyssal sediments accumulated in the deep Gulf of Mexico. The Sabine Uplift was a very broad, low-relief, often submerged structure during this period.

In the mid-Cenomanian, the tectonic stability that existed in the Gulf of Mexico Basin came to an end (Salvador, 1991). At this time, there was a profound change in the depositional setting over most of the basin. The change is represented by a regional unconformity that formed along the north flank of the basin to Florida and Yucatan. Also, the upper Albian to lower Cenomanian section on the western flank of the Sabine Uplift is truncated beneath the unconformity. This major episode of erosion ended most of the widespread carbonate deposition that characterized the Early and middle Cretaceous along the northern Gulf of Mexico Basin.

In the Late Cretaceous, following development of the regional unconformity, the basin accumulated chalk, marl, and shale over large areas. This sediment constitutes the majority of the Gulfian stratigraphy of the Gulf Coast.

2.5.2
Cenozoic

In Paleocene and Eocene time, as a result of increased plate motions, an immense volume of terrigenous clastic sediments eroded from uplifted areas of western North America during the Laramide Orogeny (Coney, 1972; Engebretson and others, 1985). A large amount of this sediment entered the Gulf of Mexico Basin, particularly along the northern and northwestern margins, causing rapid basinward migration of shoreline deposition across the shelves to positions far beyond the Cretaceous shelf margin (Galloway; 1989b; Galloway and others, 1991). The northern and northwestern Cenozoic basin margin prograded some 150 to 180 miles to the south and southeast (Galloway and others, 2000). The amount of progradation varied with respect to geographic location. The Rio Grande, Houston, and Mississippi embayments were three such locations, or depocenters, where major deltaic systems developed and supplied sand-rich sediment to the subsiding Gulf of Mexico Basin (Fisher and McGowen, 1967; Edwards, 1981; Galloway and others, 1982). In areas between depocenters, progradation of the Gulf Coast continental margin was slower since sedimentation occurred by longshore transport and deposition of suspended sediment.

An offlapping depositional style developed along the basin margin as sediments began to accumulate over the continental slope and into deeper parts of the basin. The center of the Gulf of Mexico Basin subsided as a result of sedimentary loading, rather than from thermal cooling of the oceanic crust (Galloway and others, 1991). Margin outbuilding was locally and briefly interrupted by hypersubsidence due to salt withdrawal and mass wasting.

Deposition, by way of the Cenozoic depocenters, produced successions of sandy wedges of coastal plain and marginal marine deposits that thicken and grade basinward into marine shelf and slope mud rocks (Galloway, 1989b). These sand-rich wedges are stratigraphically separated by updip tongues of marine shale deposited as a result of repeated transgression and marine flooding of the continental margin. These marine-shale bounded units provide the framework for systematic depositional analysis of the Cenozoic section (Galloway, 1989b).

2.5.3

Deposition of Lower Wilcox Formation

The large influx of clastic material associated with the Wilcox Group is generally attributed to two pulses of Paleogene tectonism, each of which produced a depositional cycle lasting from one maximum flooding event to the next (Chapin and Cather, 1981; Winker, 1982; Galloway and others, 1991; Xue, 1997). The first major pulse of Laramide uplift occurred in the southern Rockies at about 60 mega-annum (Ma) and is represented by late Paleocene (Lower Wilcox) strata.

The Lower Wilcox sediments were deposited between about 60 to 56.5 Ma (Xue, 1997). They overlie the Midway Group, which, in large part, is marine but at its upper part is thought to be prodelta marine facies of the lowermost Wilcox fluvial and deltaic facies (Bebout and others, 1982). Wilcox delta systems developed in Louisiana, Mississippi, and east of the Guadalupe River in Texas (Figure 2-6; Galloway and others, 1991). The major focus of deltaic sedimentation in Texas was located in the Rockdale Delta System, which is approximately equivalent in the literature to the Houston Delta or Houston Embayment (Fisher and McGowen, 1967; Xue, 1997). The Rockdale Delta System was nearly the same both in aerial extent and depositional style as the present-day Mississippi Delta, covering about 40,000 square miles (Figure 2-7; Fisher and McGowen, 1967; Galloway and others, 1991). It was characterized by extensive growth faulting and mobilized underlying salt and associated shale deposits, with major salt withdrawal basins constituting preferred and persistent depocenters. The system as a whole was about 2,500 feet thick on the older Cretaceous carbonate platform landward of zones of growth faulting and as much as 10,000 feet thick basinward. Where developed above the Cretaceous platform, delta-front and prodelta facies are relatively thin, and the bulk of the sediments consist of aggradational delta-plain facies. Downdip of the underlying Cretaceous shelf margin, progradational delta front and prodelta facies are stacked and generally associated with growth faults, and are thick and predominant as well (Fisher and McGowen, 1967; Galloway and others, 1991).

The Lower Wilcox delta systems consist of three constructional facies including delta plain, delta front, and prodelta. A fourth thin, but regionally extensive, destructional facies developed through local fluvial abandonment.

Lower Wilcox delta-plain facies sediments were deposited immediately downdip and basinward of feeding fluvial systems. These rocks are equivalent to some strata contained in the lower part of the Carrizo-Wilcox Aquifer. They are a complex of elongated, relatively straight but commonly thick, distributary channel deposits. The sands are generally uniform in texture, have sharp erosional lower boundaries, and have sharp upper boundaries due to stream abandonment (Fisher and McGowen, 1967; Galloway and others, 1991). The channel sands are associated laterally with levee silt deposits, local and thin interdistributary sand splays, extensive interdistributary or overbank muds, and numerous lignite seams.

The delta-front facies consist of channel mouth bar sands, frontally splayed sands, and varying amounts of wave-reworked sands. These are the progradational sand deposits of the Lower Wilcox Delta System. Above the Cretaceous platform, this facies is relatively thin where it underlies the thick aggradational delta-plain facies. Downdip the facies is stacked and thick, and basinward it grades into the shale facies of the prodelta. It is involved in growth faulting, as is the prodelta facies. Individual sequences of the delta-front facies display upward coarsening and increasing frequency of sands. They are separated from other sequences by thin, commonly glauconitic, delta-destructional beds (Fisher and McGowen, 1967; Galloway and others, 1991).

The distribution of the sandy delta-front sands delimits the extent of prograded delta lobes (Fisher and McGowen, 1967; Galloway and others, 1991). The Lower Wilcox delta systems, like the Holocene Mississippi Delta System, have two basic deltaic lobe geometries: a relatively narrow, elongated type and a more arcuate or lobate type. The different geometries are thought to be the result of varying degrees of marine reworking and coalescing of sand bodies by wave action.

The prodelta facies is the most basinward and thickest depositional facies.

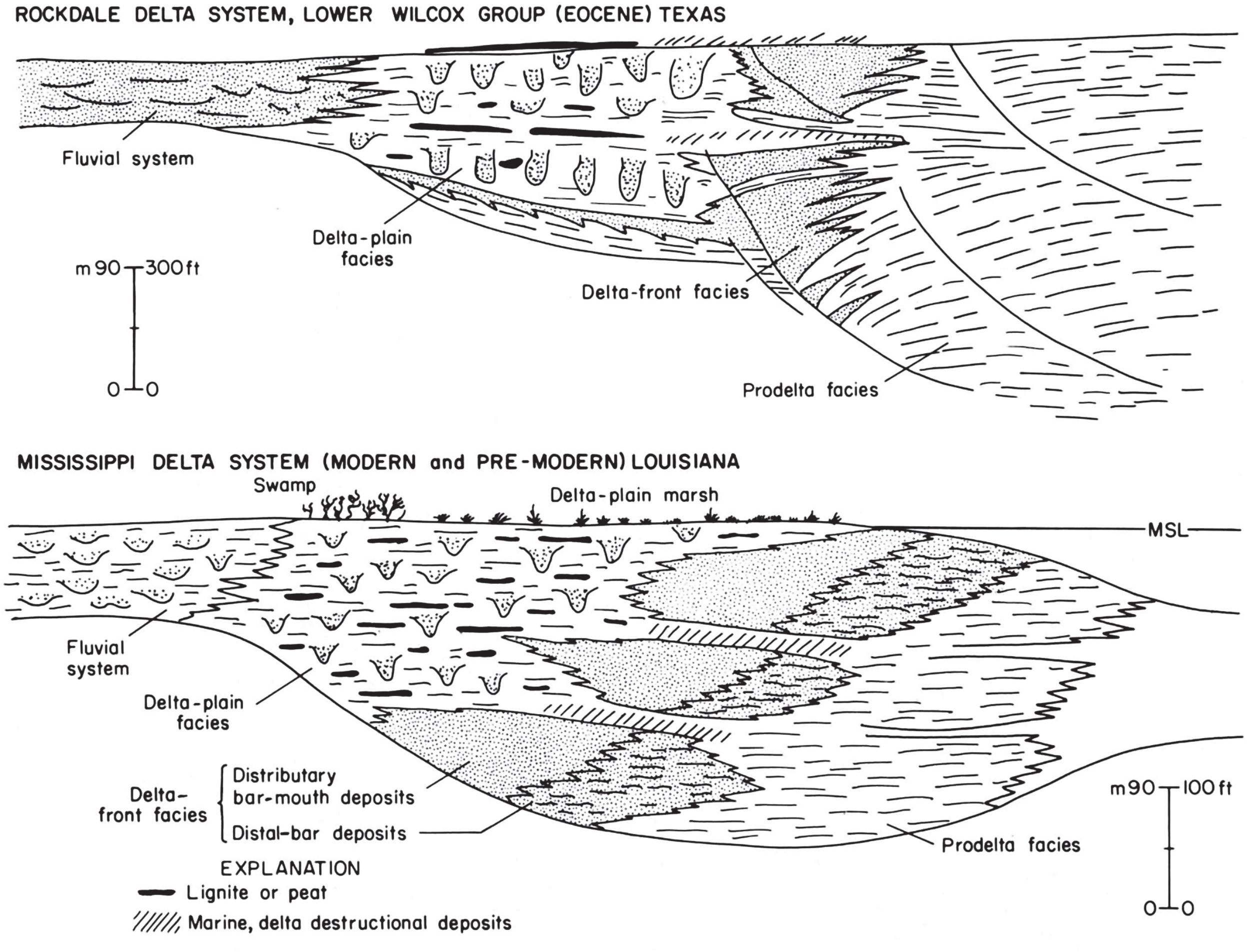

Figure 2-7. Comparison of facies of the Paleocene Lower Wilcox of Texas with the Holocene Mississippi Delta System (modified from Galloway and others, 1991; based on Fisher and McGowen, 1967, and Coleman and Gagliano, 1964).

MSL= mean sea level

Although not important in terms of water resources, it is significant in terms of growth faulting and structures associated with salt mobilization. The Lower Wilcox prodelta facies is mainly dark, organic shale. It grades basinward into deeper-water sediments of the continental slope.

Excessive loading of unstable prodelta muds triggered the extensive growth faulting associated with Lower Wilcox strata. Loading further served to extensively mobilize underlying salt and associated shale, commonly in the form of diapirs.

2.5.4
Deposition of Middle Wilcox strata

Middle Wilcox rocks are defined by maximum flooding surfaces associated with the Yoakum Shale (Central Texas) at their top and the Big Shale (Louisiana) at their base. These shales have been dated at 56.5 Ma and 54.3–55.0 Ma, respectively (Xue and Galloway, 1995). Two genetic stratigraphic sequences were deposited between these theses ages, representing only 1.5 to 2.2 million years. A genetic stratigraphic sequence is defined by Galloway (1989a) as being bounded by stratigraphic surfaces and correlative condensed marker beds that record the relative clastic-sediment starvation of the shelf and slope during transgression and the ensuing period of maximum marine flooding. The Middle Wilcox sequence boundaries are located at regionally continuous, low-resistivity marker beds within thin marine-shale beds. They lie stratigraphically between upward-fining, transgressive, and upward-coarsening, progradational facies successions. The boundaries are maximum flooding surfaces and correlative condensed sections in the platform environment. Basinward, across the growth-faulted shelf margin, the sequence boundaries lie within thick marine-shale wedges of the expanded downthrown sections (Xue and Galloway, 1995).

Isopach and net-sandstone distribution patterns of the Middle Wilcox sequences show no major sediment supply shift along strike during Middle Wilcox deposition (Xue and Galloway, 1995). Downward shifting of deposition beyond the shelf margins took place during slumping, which occurred when sea level fell or when there was rapid differential subsidence within growth-fault zones.

The older of the two sequences contains an updip fluvial belt, the Calvert Delta System, the Fayette Strand-Plain System, the San Marcos Barrier Lagoon System, the La Salle Delta System, and downdip muddy shelf-slope systems. The younger sequence is similar, including an updip fluvial belt, the Calvert Delta System, and the La Salle Delta System. However, its facies tracts prograded farther seaward, and the new Wilson Delta System localized in the San Marcos area replaced an interdeltaic barrier lagoon system in the underlying sequence.

2.5.5
Deposition of Upper Wilcox/ Carrizo strata

The primary locus of Wilcox Group deposition shifted to the southwest across the San Marcos Arch to the Rio Grande Embayment in early Eocene time (Edwards, 1981; Miller, 1989; Xue, 1997). There, an influx of Upper Wilcox Group sediments coincided with a period of north-south-directed constructional Laramide compression and uplift of the southern Rocky Mountains at about 55 Ma (Chapin and Cather, 1981; Winker, 1982, Galloway and others, 1991; Xue, 1997).

Following the Yoakum transgression associated with Middle Wilcox strata, there was renewed progradation into the basin (Edwards, 1981; Miller, 1989; Xue, 1997). The deltaic systems in the Rio Grande Embayment rapidly prograded to the shelf margin, as represented by the Rosita Delta System of Edwards (1981). The Rosita Delta System includes at least three delta complexes, each of which can be traced up to tens of miles along strike and up to approximately 15 miles downdip. Basinward, across the growth-fault zone, each delta complex thickens from about 600 feet to more than 3,000 feet. The growth faults were activated by progradation of deltas over unstable prodelta-slope muds at the contemporary shelf margin.

Each of the delta complexes of the Rosita Delta System consists of multiple lobes, some of which can be traced across deep zones where thicknesses increase by as much as tenfold, owing to progradation over active growth faults (Edwards, 1981). Characteristic coarsening-upward progradational units include prodelta shales, delta-front sandstones, distributary channel and channel mouth bar sandstones, and interdistributary shales and sandstones. Appreciable variability in sandstone distribution in the deltas may reflect changing importance of fluvial versus marine currents in distributing sediment along the delta front. However, all of the deltas prograded abruptly toward the shelf margin.

Updip of the deltaic complexes are two sand-rich fluvial depositional systems of the Carrizo Formation (Hamlin, 1988). The Carrizo Formation is part of a single, major regressive sequence, consisting of proximal high-sand fluvial systems. The Carrizo siliciclastics were deposited on a sand-rich humid coastal plain by rivers draining areas north, northwest, and west of the Rio Grande Embayment. Major fluvial channels were bed-load-dominated braided streams. These channels deposited broad belts and sheets of sand, miles wide and hundreds of feet thick (Hamlin, 1988). Deposits of mixed-load, meandering streams also occur in the Carrizo, interbedded with the bed-load system. Interchannel facies associated with the mixed-load deposits include natural levees, crevasse splays, floodplains, and coastal lakes.

The deltaic systems of the Houston Embayment expanded basinward and approached the shelf margin (Miller, 1989). Deposition within the growth-fault-bounded depocenter in South Texas continued, followed by aggradation of the depositional systems, which then slowly backstepped, resulting in deposition of the retrogradational deltas in South Texas (Edwards, 1981). Finally, transgressive shelf and shore-zone systems were deposited at the top of the Upper Wilcox rocks (Miller, 1989).

2.6

SUMMARY WITH SOME ADDITIONAL OBSERVATIONS

The tectonic histories of the source areas were the main driving mechanisms for the deposition of Wilcox Group sediments (Galloway and others, 1991). Changes in relative plate motions produced uplifts in the southern Rocky Mountains that supplied voluminous amounts of sediment to the Gulf of Mexico Basin at about 60 Ma and 55 Ma. The shift in the locus of primary sedimentation from the Houston Embayment to the Rio Grande Embayment was the result of a shift in the locus of uplift in the southern Rocky Mountains.

Eustatic changes in sea level produced regional flooding surfaces that can be traced along the Texas coast. They are particularly useful for correlation purposes and for placing Wilcox Group rocks in a sequence stratigraphic context. Short-term fluctuations in eustatic sea level may overprint first-order genetic stratigraphic sequences, but their signature, if present, is obscure (Galloway, 1989b).

Local deformation of Jurassic salt deposits in the form of salt diapirs influenced topography and, therefore, deposition of Wilcox strata (Seni and Jackson, 1983), especially in East Texas. Local deformation in southwest Texas in the Rio Grande Embayment was the product of rapid deformation of sand-rich sediment on shale-rich prodelta muds, producing growth faulting and shale diapirs.

The deltaic sediments of the Paleocene and Eocene Wilcox Group closely resemble those of the Holocene Mississippi Delta System (Galloway and others, 1991). This analog allows for a comparison between the two systems in terms of geohydrology and is a possible area for future research.

Cenozoic strata of the Gulf of Mexico Basin are possibly the most studied deposits in the world. As such, there is a great deal of information from oil and gas studies that can be of use to the water resource research occurring at more updip locations around the basin. Information on porosity and permeability from electric logs and other studies could help in refining groundwater availability models of the Texas Water Development Board. One such study already completed looked at the relationships between Carrizo deposition and the groundwater flow systems in South Texas (Hamlin, 1988).

2.7
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Chapter 3

Hydrogeology of the Carrizo-Wilcox Aquifer

Neil E. Deeds[1], Dennis Fryar[1], Alan Dutton[2], and Jean-Philippe Nicot[3]

The Carrizo-Wilcox Aquifer is composed of hydraulically connected sands from the Wilcox Group and the Carrizo Formation (Ashworth and Hopkins, 1995). The aquifer extends from northeast Mexico across Texas, from the Rio Grande in the southwest to the Sabine River in the northeast, and into Louisiana and Arkansas (Figure 3-1 shows the extent of the aquifer in Texas). The Carrizo-Wilcox Aquifer is classified as a major aquifer in Texas (Ashworth and Hopkins, 1995), ranking third in the state for water use (450,000 acre-feet per year) in 2003, behind the Gulf Coast Aquifer and the Ogallala Aquifer (TWDB, 2007). The Carrizo-Wilcox Aquifer provides water to all or parts of 60 Texas counties, with the greatest historical use being in and around the Tyler, Lufkin-Nacogdoches, and Bryan-College Station metropolitan centers and in the Winter Garden region of South Texas (Ashworth and Hopkins, 1995).

Comprehensive regional hydrogeologic descriptions of the Carrizo-Wilcox Aquifer were provided in the development of the conceptual models for the three groundwater availability models of the aquifer commissioned by the Texas Water Development Board (TWDB) in 2001 (Deeds and others, 2003; Dutton and others, 2003; Fryar and others, 2003). These studies considered the southern, central, and northern portions of the aquifer and built on the considerable existing literature describing the geology and hydrogeology of the Carrizo-Wilcox at various locations and scales.

This chapter provides a combined summary of those hydrogeologic descriptions, along with some new analyses of the aquifer as a whole. Some simulated results are presented in the current work, based on the updated Carrizo-Wilcox groundwater availability models that contain the Queen City and Sparta aquifers (Kelley and others, 2004).

3.1 GEOLOGY

The sediments that form the Carrizo-Wilcox Aquifer are part of a gulfward thickening wedge of Cenozoic sediments deposited in the Rio Grande and Houston embayments of the Gulf Coast Basin. Deposition in the Rio Grande Embayment was influenced by regional subsidence, episodes of sediment inflow from areas outside of the Gulf Coastal Plain, and eustatic sea level change (Grubb, 1997). Galloway and others (1994) characterized Cenozoic sequences in the Gulf Coast in the following three ways: (1) Deposition of Cenozoic sequences is characterized as an offlapping progression of successive, basinward thickening wedges. (2) These depositional wedges aggraded the continental platform and prograded the shelf margin and continental slope from the Cretaceous shelf edge to the current Texas coastline. (3) Deposition occurred along sand-rich, continental margin deltaic depocenters within embayments and was modified by growth faults and salt dome development.

Figure 3-2 shows a representative stratigraphic section for the study area. Minor changes in nomenclature and the nature of various formations occur across the state. In South Texas, the Carrizo-Wilcox Aquifer overlies the Midway

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[2] The University of Texas at San Antonio

[3] Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin

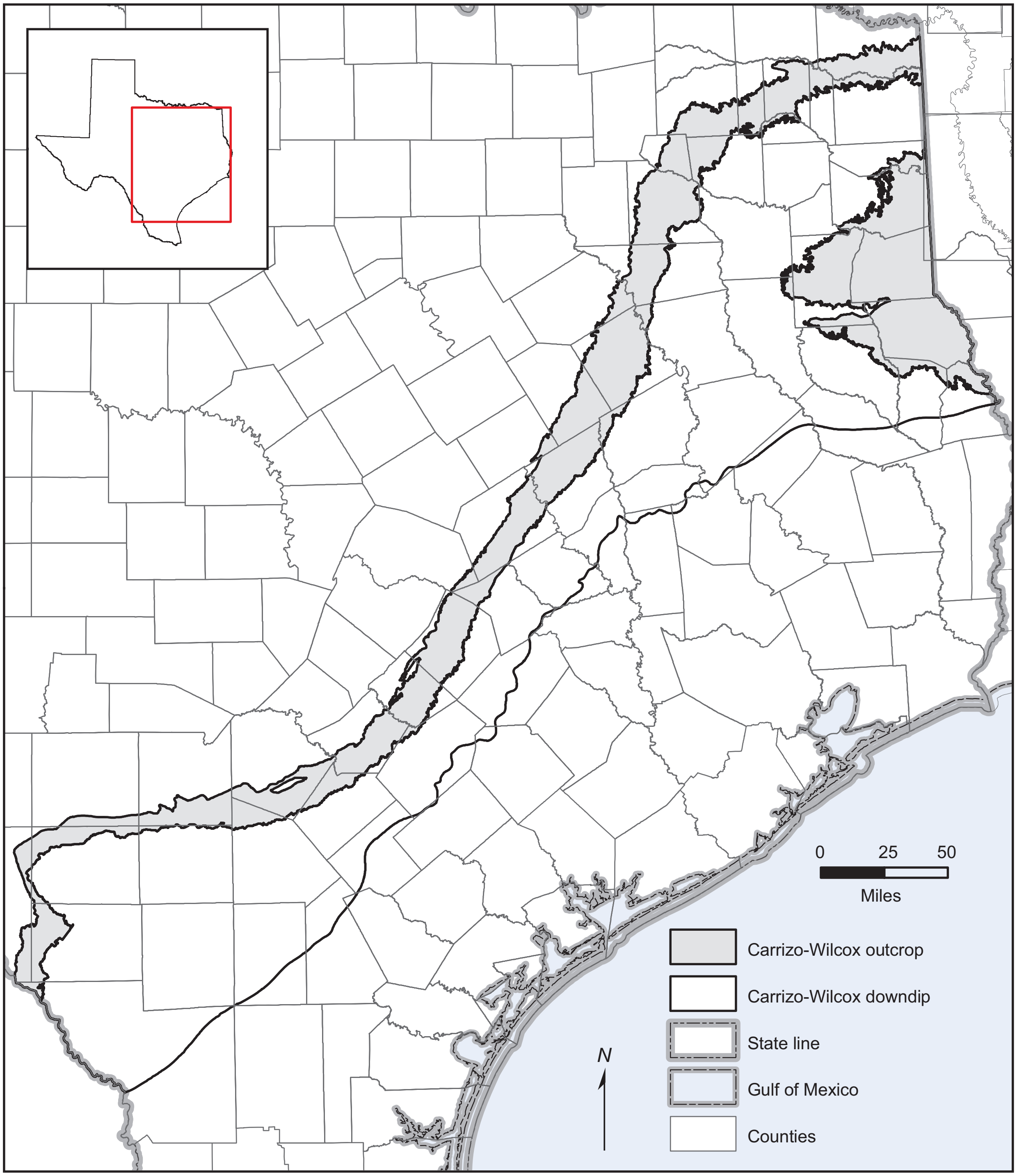

Figure 3-1. Location of Carrizo-Wilcox Aquifer in Texas.

Group, which is composed of marine clays. This portion of the aquifer consists of fluvial-deltaic sediments of the upper Paleocene and lower Eocene Wilcox Group Band Carrizo Sand. The Wilcox Group is subdivided into a lower, middle, and upper unit. The Lower Wilcox is composed of sands and clays deposited in a barrier bar and lagoon-bay system (Fisher and McGowen, 1967). The Middle Wilcox is not generally subdivided in the south but is typically described as a lower energy depositional sequence representative of a minor transgression.

The Carrizo Sand in the outcrop and shallow subsurface correlates with the upper part of the Wilcox Group in the deeper subsurface (Bebout and others, 1982; Hamlin, 1988). The Carrizo-Upper Wilcox predominantly consists of a fluvial sand facies that grades into more deltaic and marine facies farther downdip (Bebout and others, 1982). South and west of the Frio River, the Wilcox is sometimes referred to as the Indio Formation and is composed of irregularly bedded sandstone and shale.

Between the Colorado and Trinity rivers, the Wilcox Group is formally subdivided into the Hooper, the Simsboro, and the Calvert Bluff formations, corresponding to deltaic, fluvial, and fluvial-deltaic facies, respectively, which occur throughout east-central Texas (Kaiser, 1974). The Hooper Formation represents the initial progradation of the Wilcox Group fluvial-deltaic systems into the Houston Embayment of the Gulf of Mexico Basin and consists of interbedded shale and sandstones in subequal amounts, with minor amounts of lignite. The Simsboro Formation is predominantly a sand-rich formation composed of a multistory, multilateral sand deposit (Henry and others, 1980). The Calvert Bluff consists mainly of low-permeability clays and lignite deposits (Ayers and Lewis, 1985), which function like confining layers that retard the vertical movement of water within the Carrizo-Wilcox Aquifer across the study area.

In the Sabine Uplift area east of the Trinity River, the Simsboro Formation is no longer identifiable, and the Wilcox Group is divided informally into a lower and an upper unit (Kaiser, 1990). The Lower Wilcox represents the facies equivalent of the Hooper Formation, and the Upper Wilcox includes both of the Simsboro and the Calvert Bluff equivalent fluvial and fluvial-deltaic facies, respectively (Kaiser, 1990). The Carrizo Sand unconformably overlies the Wilcox Group and is separated from the Wilcox by a thin regional marine-transgressive unit, which is included as an informal member in the Upper Wilcox (Kaiser, 1990). The Carrizo Sand is composed primarily of relatively homogenous fluvial

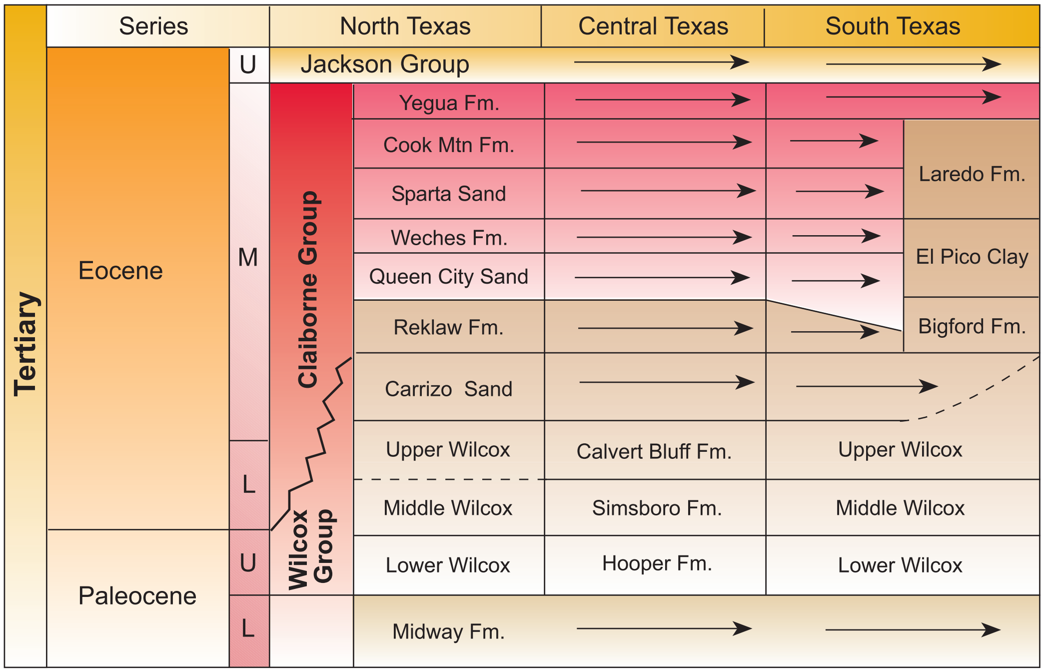

Figure 3-2. Generalized stratigraphic section for the Carrizo-Wilcox aquifer in Texas (after Ayers and Lewis, 1985; Hamlin, 1988; Kaiser and others, 1978).

Fm= formation

sands and only locally in the northernmost area contains a significant portion of interbedded muds. The Reklaw Formation consists of variable amounts of mud and sand and is considered the upper confining stratum of the Carrizo-Wilcox Aquifer. In the northeastern study areas, the Reklaw clays become discontinuous, providing a more permeable connection between the Carrizo Sand and the overlying Queen City Formation. In Marion and Harrison counties, the combined Wilcox, Carrizo, Reklaw, and Queen City units are collectively referred to as the Cypress Aquifer (Fogg and Kreitler, 1982). Above, the finer-grained Weches Formation separates the Queen City Sand from the overlying Sparta Sand that occurs only locally.

3.2
HYDROSTRATIGRAPHY

The Carrizo-Wilcox Aquifer consists of fluvial-deltaic sediments of the upper Paleocene and lower Eocene Wilcox Group and Carrizo Sand. The aquifer is bounded below by marine deposits of the Midway Group and above by the Reklaw and Bigford formations, which form a semi-confining unit between the Carrizo Sand and the Queen City Formation.

In the portion of the aquifer stretching from the Rio Grande to the Colorado River, the Wilcox Group is subdivided into a Lower, Middle, and Upper Wilcox. The Upper Wilcox in the deeper subsurface is correlated to the Carrizo Formation in the outcrop (Bebout and others, 1982; Hamlin, 1988). Bebout and others (1982) mapped the lower contact of the Upper Wilcox based on the lower regional marker identified in geophysical logs by Fisher and McGowen (1967). Hamlin (1988) also combined the Carrizo and Upper Wilcox and mapped the base of the Upper Wilcox as a distinct facies change from a fluvial (bed-load channel system) and mixed alluvial facies in the Upper Wilcox to a predominantly marine facies (delta, prodelta) in the Middle Wilcox. In comparison, Klemt and others (1976) lithologically picked the base of the Carrizo Aquifer as the top of the Wilcox Group by identifying the base of the major sand units of the Carrizo Formation. The Carrizo Formation mapped by Klemt and others (1976) correlates with the Carrizo Formation as mapped in Central Texas (Ayers and Lewis, 1985).

The southern portion of the Carrizo-Wilcox Aquifer is characterized by three distinct depositional systems, including a bed-load channel system, a mixed alluvial system, and a deltaic system (Hamlin, 1988). The bed-load channel system comprises the massive sand typically associated with the Carrizo Aquifer but also contains some sandy mud. The mixed alluvial system consists of interbedded sand and mud associated with channel sands and abandoned channel fill, levee and crevasse splay, floodplain, lacustrine, and delta-plain sediments. The deltaic system consists of delta-front sand, which changes to prodelta mud basinward. This change to marine facies was considered the boundary between the Upper and Middle Wilcox (Hamlin, 1988). The Middle Wilcox includes several transgressive flooding events and consists of various deltaic facies that form a partial hydrologic barrier between the fluvial-deltaic sediments of the Lower Wilcox and the predominant fluvial system of the Carrizo-Upper Wilcox (Galloway and others, 1994). The Reklaw Formation above the Carrizo Sand corresponds to a more extensive transgressive flooding event and consists predominantly of marine mud, which grades in the southwestern part of the study area to nonmarine mud and sands of the Bigford Formation.

Between the Colorado and Trinity rivers, the Carrizo-Wilcox Aquifer is composed of four hydrostratigraphic units with distinct hydraulic properties: the Hooper, Simsboro, and Calvert Bluff formations of the Wilcox Group and the Carrizo Sand of the Claiborne Group.

In general, the Simsboro and Carrizo formations contain thicker, more laterally continuous and more permeable sands and, therefore, are more important hydrostratigraphic units when determining groundwater availability. The Calvert Bluff and Hooper formations typically are made up of clay, silt, and sand mixtures, as well as lignite deposits. Because of their relatively low vertical permeability, the Hooper and Calvert Bluff formations act as leaky aquitards that confine fluid pressures in the Simsboro and Carrizo aquifers and restrict groundwater movement between the layers. Although the Hooper and Calvert Bluff formations contain sand units, they are generally finer and less continuous than the sands of the Simsboro and Carrizo formations. Above the Carrizo Formation, the low-permeability marine shale of the Reklaw Formation restricts vertical groundwater movement to the overlying Queen City Formation in the Claiborne Group.

In the Sabine Uplift area east of the Trinity River, the Simsboro Formation is no longer identifiable, and the Wilcox Group is divided into informal lower and upper units. The Lower Wilcox represents the facies equivalent of the Hooper Formation, and the Upper Wilcox includes both the Simsboro and the Calvert Bluff equivalent fluvial and fluvial-deltaic facies, respectively (Kaiser, 1990). Even though the structure and various sand maps in the Sabine Uplift area distinguish only the Upper and Lower Wilcox (Kaiser, 1990), a predominantly fluvial facies at the bottom and a fluvial-deltaic facies at the top can be identified within the Upper Wilcox, corresponding to the subdivision of the Wilcox Group in Central Texas as mapped by Ayers and Lewis (1985).

The Carrizo Sand unconformably overlies the Wilcox Group and is separated from it by a thin regional marine-transgressive unit, which is included as an informal member in the Upper Wilcox (Kaiser, 1990). The Carrizo Sand is composed primarily of relatively homogenous fluvial sands and only locally in the northernmost area contains a significant portion of interbedded muds. The Reklaw Formation consists of variable amounts of mud and sand and is considered the confining strata of the Carrizo-Wilcox Aquifer. However, in the northeastern part, the clay strata become more discontinuous making the Reklaw probably more pervious to vertical flow between the Carrizo and the overlying Queen City. In Marion and Harrison counties, the combined Wilcox, Carrizo, Reklaw, and Queen City units are referred to as the Cypress Aquifer (Fogg and Kreitler, 1982).

3.3
STRUCTURE

Depositional patterns of Claiborne Group sedimentation were influenced by the tectonic evolution of the Gulf of Mexico Basin. Early Mesozoic history of the basin included rifting and the creation of numerous sub-basins. During the Jurassic, marine flooding and restricted circulation resulted in the accumulation of halite beds in these sub-basins (Jackson, 1982). Subsidence continued as the rifted continental crust cooled. The sediment column records the effects of changes in relative rates of sediment progradation, basin subsidence, and sea level change. More than 50,000 feet of sediment has accumulated in the Gulf of Mexico Basin (Salvador, 1991). The Rio Grande and Houston embayments, East Texas Embayment (sometimes referred to as the East Texas Basin), Sabine Uplift, and San Marcos Arch are the main structural features underlying the onshore part of the Gulf of Mexico Basin (Jackson, 1982). Figure 3-3 shows the major faults and structural features for the Texas Coastal Plain and East Texas Embayment. The model outline shown on the figure shows the active extent of the TWDB groundwater availability models for the Carrizo-Wilcox Aquifer.

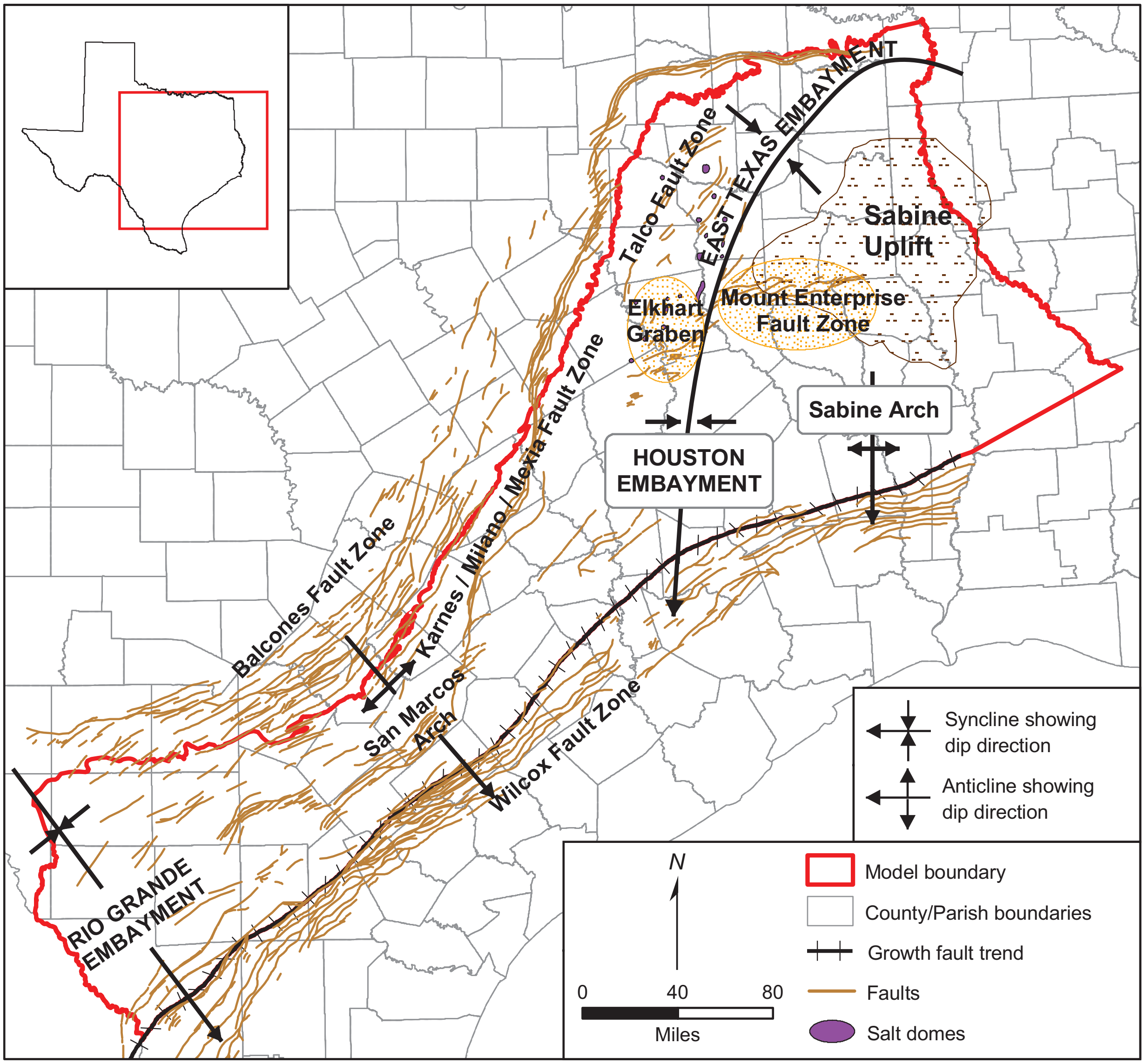

Figure 3-3. Map of major faults and structural features for the Texas Coastal Plain and East Texas Embayment. Faults modifed from Ewing (1990). Structure axes modified from Guevara and Garcia (1972), Galloway (1982), and Galloway and others (2000).

Various fault zones are associated with the basin history of crustal warping, subsidence, and sediment loading. From coastward to inland, these include (1) the Wilcox Growth Fault Zone (labeled Wilcox Fault Zone in Figure 3-3); (2) the Karnes Mexia Fault Zone (labeled Karnes/Milano/Mexia Fault Zone in Figure 3-3); (3) the Elkhart-Mount Enterprise Fault Zone (labeled Elkhart Graben and Mount Enterprise Fault Zone in Figure 3-3); and (4) the Balcones Fault Zone. The Wilcox Growth Fault Zone lies at the eastern or downdip limit of the study area. Saline water predominates in this area. The growth or listric faults formed as thick packages of Wilcox sediment prograded onto the uncompacted marine clay and mud deposited in the subsiding basin beyond the Cretaceous shelf edge. Continued downward slippage on the gulfward side of the faults and sustained sediment deposition resulted in the Wilcox Group thickening across the growth fault zone (Hatcher, 1995). Petroleum exploration drilling and geophysical studies within the study area have indicated that many of these large, listric growth faults can offset sediments by 3,000 feet or more. The listric fault planes are curved; the dip of the faults decreases with depth; and the faults die out in the deeply buried shale beds. Complex fault patterns evolved, with antithetic faults forming various closed structures. The major faults of the Wilcox Growth Fault Zone extend upward into the Claiborne Group.

The Karnes Trough Fault Zone, Milano Fault Zone, and Mexia Fault Zone (Jackson, 1982; Ewing, 1990) are collectively referred to as the Karnes Mexia Fault Zone in this chapter. The fault zone marks the updip limit of the Jurassic Louann Salt (Jackson, 1982). Displacement along the Karnes Mexia Fault Zone occurred throughout Mesozoic deposition along the Gulf Coast and continued at least through the Eocene, resulting in noticeable syndepositional features. Numerous faults with as much as 800 feet of displacement that exhibit no syndepositional features are also present throughout the Karnes Mexia Fault Zone (Jackson, 1982). In the central part of the study area, the Karnes Mexia Fault Zone displaces sediments by more than 1,000 feet in some areas, restricting the hydraulic communication between outcrop and downdip sections of aquifers.

The Elkhart-Mount Enterprise Fault Zone lies along the structural high between the East Texas Embayment and the Gulf of Mexico Basin. Flexure with subsidence in these two basins formed extensional faults and associated graben structures in the Queen City and Sparta formations. The Balcones Fault Zone consists of numerous fault strands that swing from northeasterly in the southern part of the study area to northerly in the central and northern parts of the area. Although the Balcones trend follows the thrust-fault trends of the late Paleozoic Ouachita Orogeny (Ewing, 1990), activity was mostly limited to the Late Cretaceous and Tertiary (Collins and Laubach, 1990). Some evidence points toward movement of this system as recently as Plio-Pleistocene times (Collins and Laubach, 1990). The zone results from tilting along the perimeter of the Gulf Coast Basin, flexure, and gulfward extension (Murray, 1961; Collins and others, 1992). Faults in this trend are of normal displacement, dominantly dipping to the southeast (basinward), although some northwest-dipping antithetic faults occur (Collins and Laubach, 1990).

Figure 3-4 shows two structural cross sections in the study area. Cross section A-A' shows the Tertiary formations from the Midway Formation through the Sparta Formation in East Texas. The primary structural features in the eastern part of the study area are the East Texas Basin, the Sabine Uplift, and the Houston Embayment. The Carrizo Formation has a narrow outcrop in the East Texas Basin and is eroded and not present over the Sabine Uplift, where the Middle Wilcox Formation is at the surface. South of the Sabine Uplift, the Carrizo and Wilcox formations outcrop in a narrow band parallel to the present day coastline. The entire Tertiary section steeply dips into the Gulf Coast Basin south of the Sabine Uplift and the East Texas Basin.

Westward through Central and South Texas, the Carrizo and Wilcox formations outcrop in a narrow band paralleling the present day coast and dipping strongly toward the Gulf Coast Basin. Cross section B-B' is representative of Central and South Texas, where the dip of the formations in the subsurface can reach 250 feet per mile in portions of those areas.

3.4
HYDRAULIC PROPERTIES

Information on hydraulic properties of the Carrizo-Wilcox Aquifer is based largely on data and sources provided by Mace and others (2003). They compiled and statistically analyzed transmissivity, hydraulic conductivity, and storativity data from numerous sources for the entire Carrizo-Wilcox Aquifer in Texas. They also analyzed spatial distributions in hydraulic properties in the Carrizo Sand and the Wilcox Group, suggesting regional trends in kriged transmissivities and hydraulic conductivities. The uneven data coverage and relatively large local-scale variability, expressed in a high nugget in the semivariograms, indicate significant uncertainty in the effective hydraulic properties of the aquifer systems. A relationship between hydraulic properties and sand thickness could not be established, even though more detailed local studies did indicate some correlations between different sand facies and hydraulic conductivities.

The Mace and others (2003) analysis depended on aquifer codes to determine whether wells were located in a particular formation. Although this approach works reasonably well, there are cases where the aquifer codes are missing, the codes are overly broad (for example, Carrizo-Wilcox undifferentiated), or the codes are inconsistent with the locations of the actual screens. For the current analysis, we used wells from the database that had screen location information and compared the screen locations to the model structure from the groundwater availability models. A well was considered to be screened in a particular formation if 75 percent of the screen intersected that formation. Additionally, the area comprising the footprint of the Carrizo-Wilcox Aquifer was divided into southern, central, and northern regions for the purpose of summary statistics. The

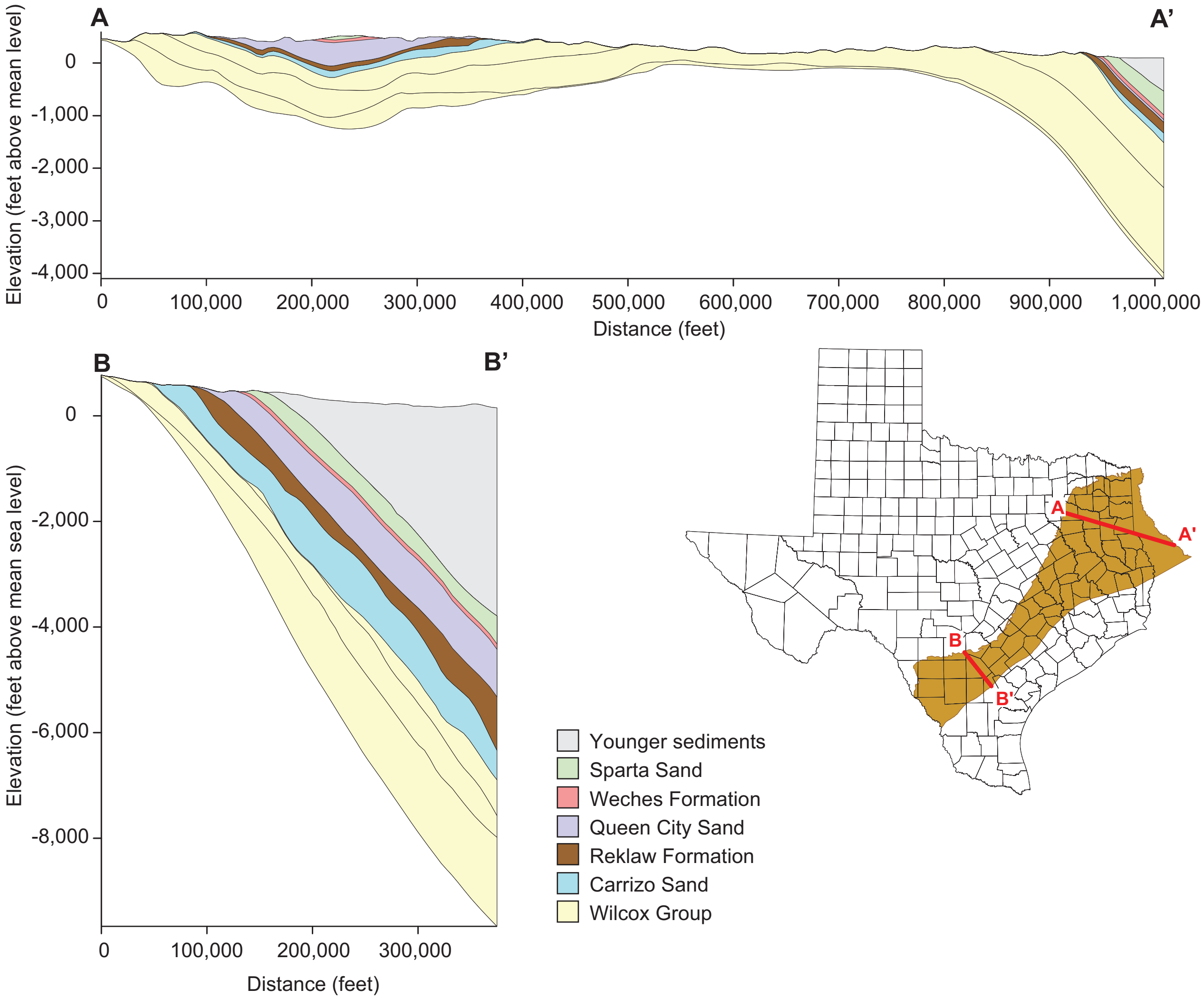

Figure 3-4. Structural cross sections for the Carrizo-Wilcox Aquifer and overlying sediments (Kelley and others, 2004).

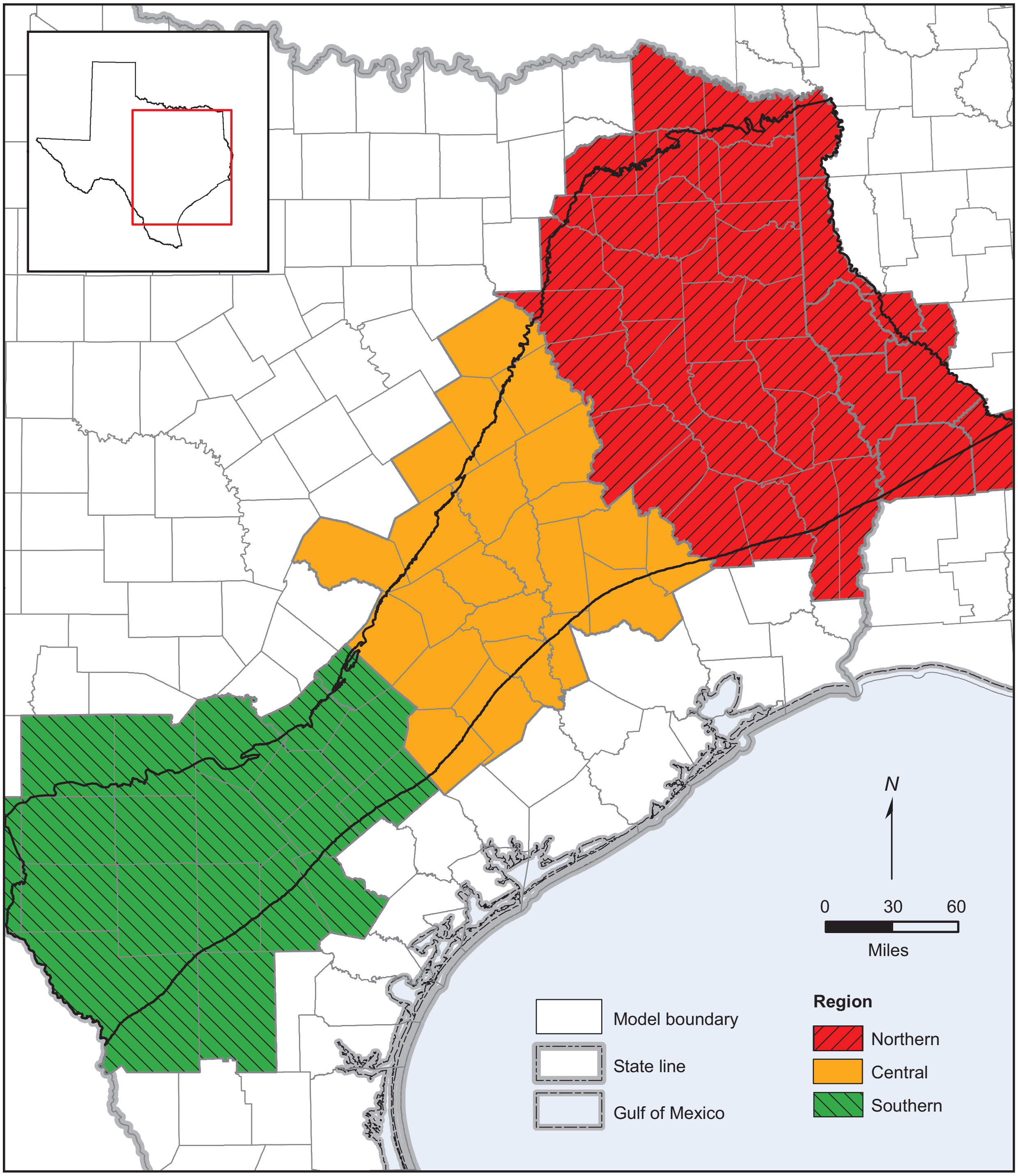

Figure 3-5. Regions used in summarizing hydraulic properties and simulated water budgets.

regions are non-overlapping (in contrast to the groundwater availability models, for which the overlap is necessary to buffer boundary effects) as shown in Figure 3-5. The central region was approximately defined by the limits of the Simsboro Aquifer between the Colorado and Trinity rivers. Table 3-1 shows the summary statistics for hydraulic conductivity based on this analysis. In the southern region, the mean hydraulic conductivity decreases with formation age, from 44.3 feet per day in the Carrizo to 13.3 feet per day in the Lower Wilcox. The same trend holds for the central region, where hydraulic conductivity ranges from 23.6 feet per day in the Carrizo to 8.3 feet per day in the Hooper. For the northern region, the mean hydraulic conductivity is identical between the Carrizo and Upper Wilcox at 12.2 feet per day and similar to the Middle Wilcox at 8.0 feet per day. This result is consistent with the generally undivided nature of the upper portion of the Carrizo-Wilcox in parts of the northern region.

The mean hydraulic conductivity generally decreases to the northeast for all of the formations. The decrease is most pronounced in the Carrizo Formation, from 44.3 feet per day in the southern region to 12.2 feet per day in the northern region. This trend is evident in Figure 3-6, which shows the point hydraulic conductivity values for those wells located in the Carrizo Formation. Figure 3-6 also shows the high spatial variability in the hydraulic conductivity estimates across the region.

The mean hydraulic conductivity of the Simsboro Formation is less in the central region than that of the Middle Wilcox in the southern region (Table 3-1). Most of the estimates for the Simsboro were from wells in the outcrop (or near outcrop) portion of the central region, as shown in Figure 3-7. Figure 3-7 appears to show a general decrease in hydraulic conductivity from south to north, even within the central region.

Figure 3-8 shows the hydraulic conductivity estimates in the Upper and Middle Wilcox formations in the northern region. The most productive wells appear more frequently in the outcrop areas of the Sabine Uplift. Wells in the downdip portions of the aquifer generally show measurements of less than 30 feet per day.

For all cases, the geometric mean is considerably lower than the arithmetic mean, indicating the disproportionate influence of a few high conductivity values on the arithmetic mean. When the hydraulic conductivity estimates were made for the groundwater availability models, interpolation was performed in log space, and the interpolated values were back-transformed to produce the final conductivity fields. Figure 3-9 shows an example of the effective conductivity for the Carrizo Formation. Effective conductivity in this case refers to the conductivity adjusted by the sand fraction. The conductivity generally decreases with depth, due to both decreasing estimated sand conductivity and decreasing sand fraction in the formation.

Table 3-1. Summary statistics for hydraulic conductivity determined using data from Mace and others (2003). All values in feet per day.

Metric	Region	Carrizo	Upper Wilcox/ Calvert Bluff	Middle Wilcox/ Simsboro	Lower Wilcox/ Hooper
Count	Southern	167	6	145	88
	Central	71	297	139	230
	Northern	195	477	759	163
Mean	Southern	44.3	30.7	27.7	13.3
	Central	23.6	16.6	16.3	8.3
	Northern	12.2	12.2	8.0	5.5
Geometric mean	Southern	13.5	8.5	8.8	5.5
	Central	6.7	4.3	6.4	3.4
	Northern	5.0	4.8	3.0	2.7

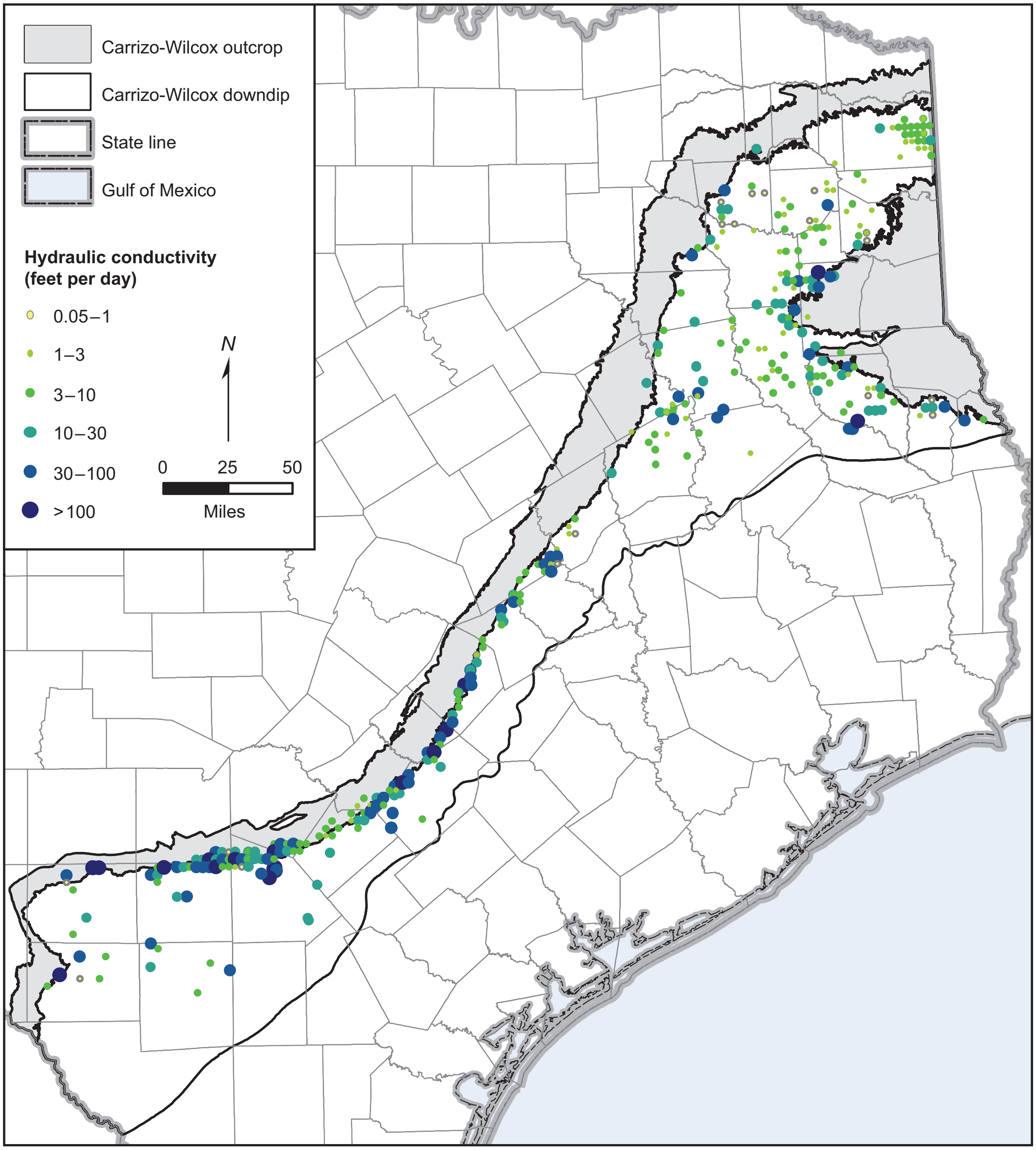

Figure 3-6. Hydraulic conductivity measurements in the Carrizo Formation.

3.5
WATER LEVELS AND REGIONAL GROUNDWATER FLOW

Water within the Carrizo-Wilcox Aquifer is under water table conditions in the outcrop areas and under confined conditions downdip of the outcrop. In many areas, confined pressures within the aquifer were originally above ground surface, and wells that were completed in these zones flowed. However, widespread groundwater development has significantly decreased the confined pressure, and flowing wells are generally absent, especially in the southern region (Moulder, 1957).

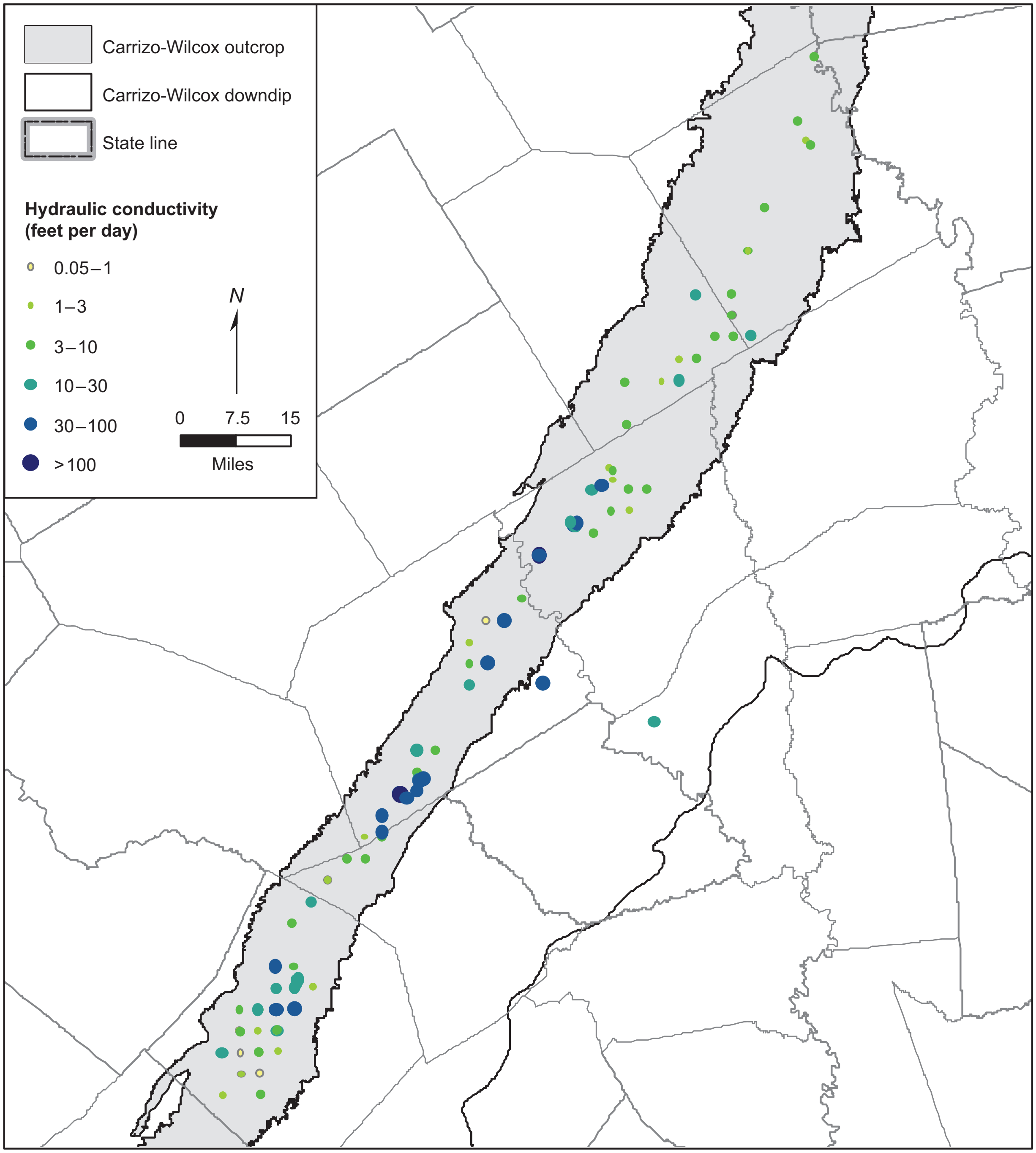

Figure 3-7. Hydraulic conductivity estimates in the Simsboro Formation.

Under non-pumping conditions, groundwater movement within the Carrizo-Wilcox Aquifer is significantly influenced by the topography and the structure of the units. Regionally, land surface elevation decreases along dip toward the coast. Groundwater flow in the subcrop follows this regional trend, flowing generally from the higher elevations in the outcrop downdip toward the coast. Locally, topographic lows are typically found in and around stream channels, and topographic highs occur along basin divides. In the outcrop, groundwater flow typically follows this local topography, with recharge in the local topographic highs moving toward the discharge areas in the local topographic lows. Because

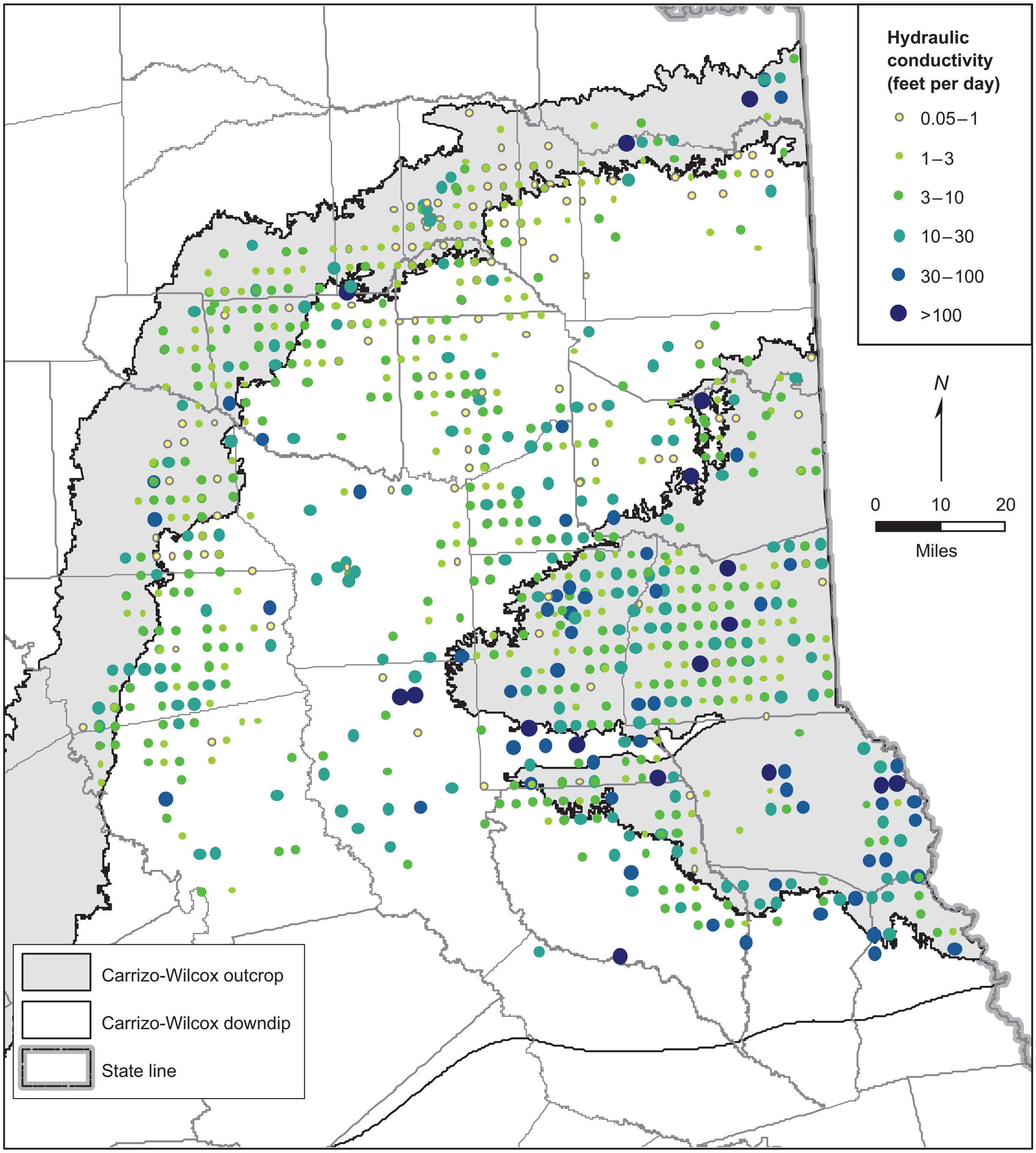

Figure 3-8. Hydraulic conductivity estimates in the combined Upper and Middle Wilcox formations in the northern region.

stream channels may run along the strike direction, shallow groundwater flow in the outcrop may also occur more along strike.

Figure 3-10 shows the simulated predevelopment head in the Carrizo Formation. In the southern region, the regional trend of decreasing head toward the coast is evident. Because the streams are either losing or weakly gaining in this region, little influence on heads from streams occurs until the Guadalupe River in the north. In the central and northern regions, the influence of the streams as discharge areas is much more pronounced. The confined portion

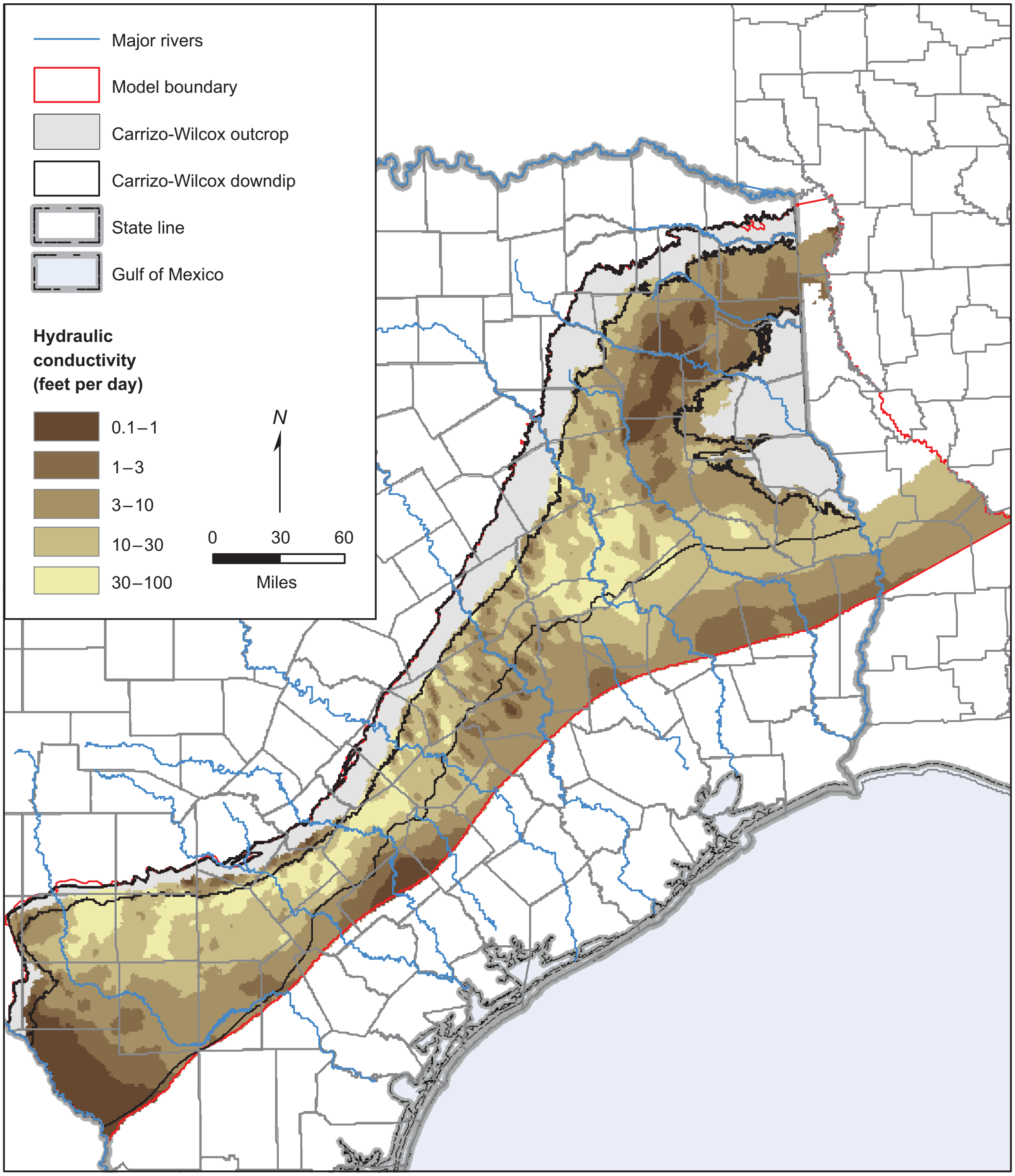

Figure 3-9. Effective hydraulic conductivity in the Carrizo Formation.

of the northern region again shows the more regional trend of decreasing head toward the coast.

Figure 3-11 shows the simulated drawdown from predevelopment to 1999 for the Carrizo and Simsboro formations for those areas where drawdown is greater than 100 feet. In the Winter Garden area in the south, drawdowns in excess of 300 feet are evident in Zavala and Frio counties. Figure 3-12 shows measured water level hydrographs for selected wells in the Winter Garden area. The general trend in the hydrographs is downward,

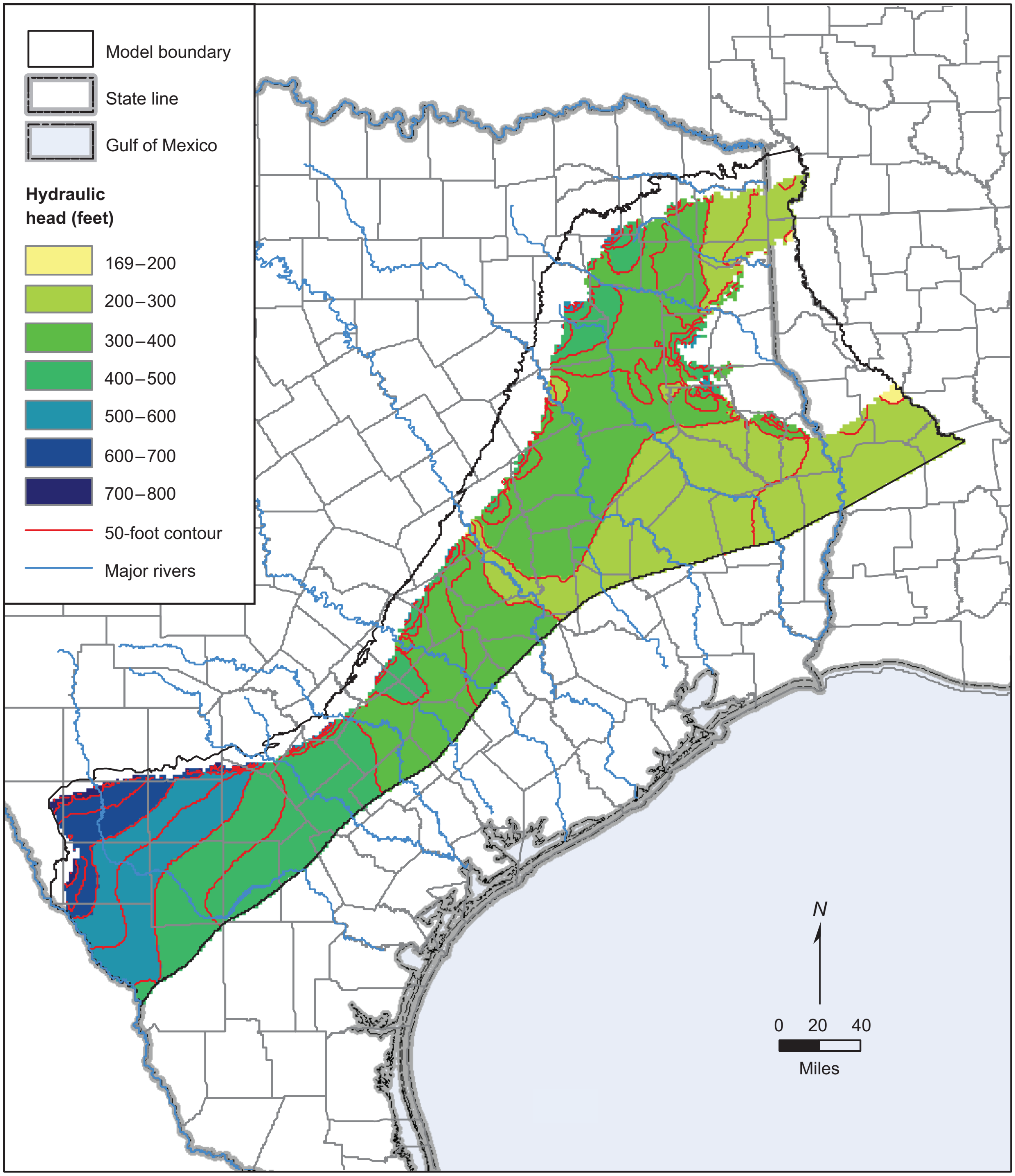

Figure 3-10. Simulated predevelopment head in the Carrizo Formation.

with some leveling off in the last decade. In the central region, Figure 3-11 shows a drawdown of over 100 feet in the Simsboro Formation due to pumping in Brazos County. Figure 3-13 shows a water level hydrograph for Brazos County in the Simsboro, with a measured decrease of about 150 feet from 1975 to 2005. For the northern region, Figure 3-11 shows the drawdown in the Carrizo Aquifer in excess of 300 feet for Smith, Angelina, and Nacogdoches counties. Figure 3-13 shows water level hydrographs for these three counties. In Smith County, the

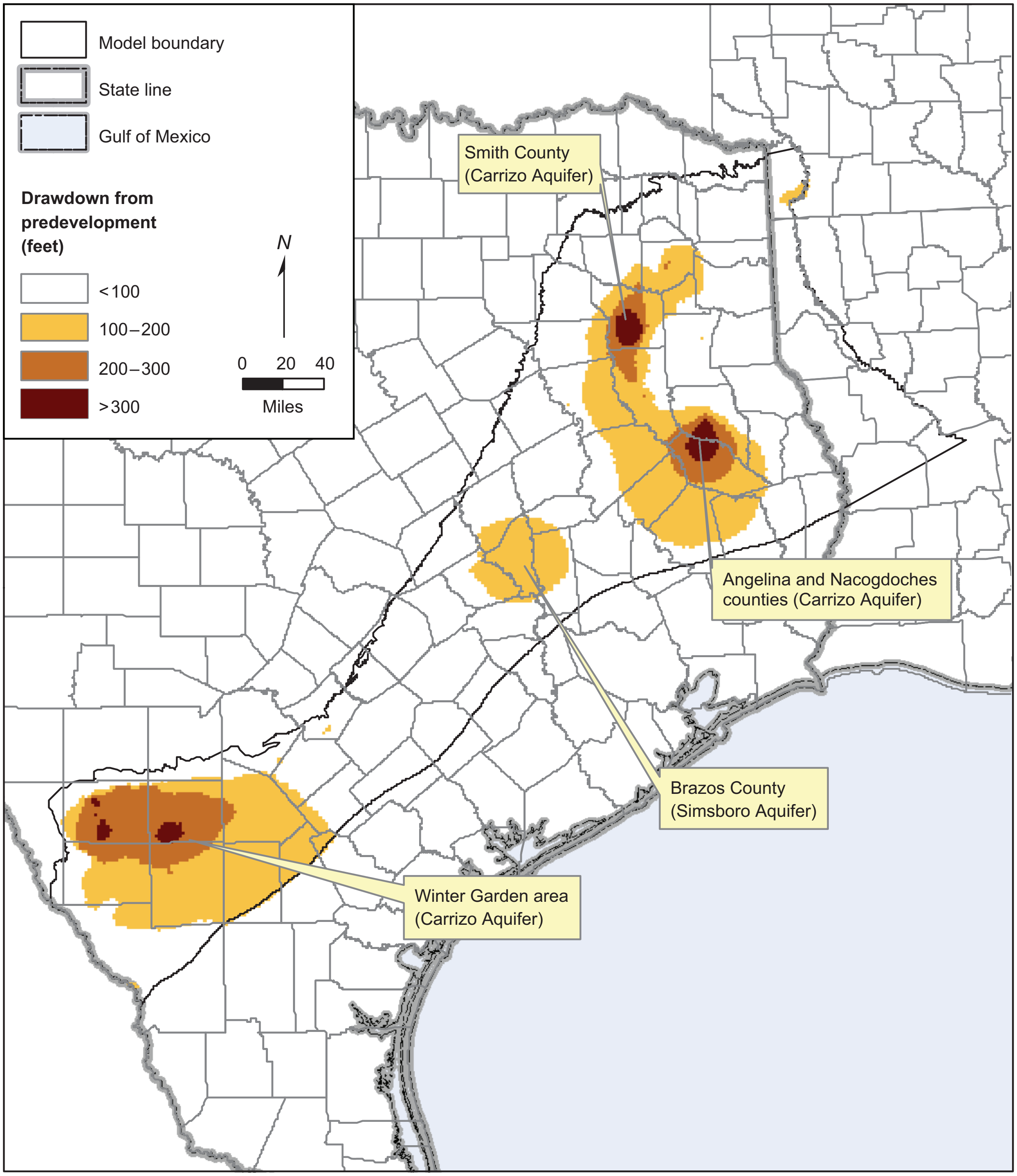

Figure 3-11. Simulated drawdown from predevelopment to 1999 in the Carrizo and Simsboro formations.

hydrograph shows a consistent downward trend covering about 150 feet of drawdown from 1965 to 2005. The water level hydrograph for Angelina County shows a drawdown exceeding 400 feet from 1945 to 2000, with a rebound of almost 300 feet from 2000 to 2005. The water level hydrograph for Nacogdoches County shows a similar trend, with a drawdown of almost 325 feet from 1940 to about 1980 and a rebound of approximately 100 feet from 1985 to 2000.

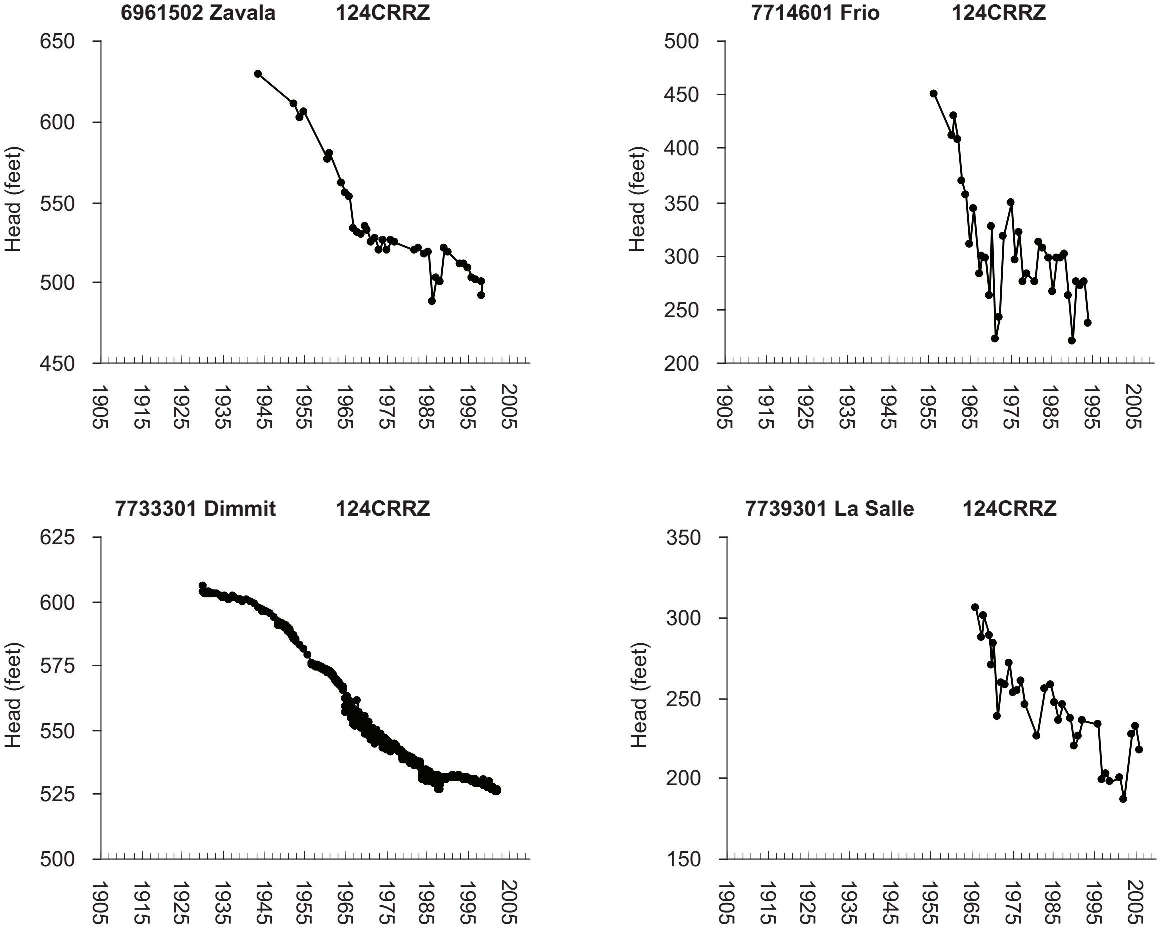

Figure 3-12. Measured water level hydrographs in Winter Garden area Carrizo wells.

3.6
WATER QUALITY

For a broad indication of water quality in the Carrizo-Wilcox Aquifer, we queried the TWDB groundwater database for the most recent measurements of total dissolved solids for wells completed in the aquifer. Figure 3-14 shows a plot of the resulting values. Note that the downdip limit of the aquifer as defined by TWDB is concurrent with the estimated milligrams per liter contour of 3,000 milligrams per liter total dissolved solids.

The common definitions for fresh, slightly saline, and moderately saline water are <1,000 milligrams per liter, 1,000–3,000 milligrams per liter, and >3,000 milligrams per liter, respectively. Figure 3-14 shows that in the southern region, the freshest water typically occurs in the shallowest portions of the subcrop. In the outcrop, the water quality is more mixed, with some occurrences of slightly saline water. Moving further downdip, the water quality begins to degrade in the deeper sections of the aquifer, with total dissolved solids increasing into the moderately saline range. In the northern region, the trends in water quality are less consistent. Overall, the majority of the measurements in this region indicate high quality (<500 milligrams per liter) water, regardless of whether the well is in the outcrop or near subcrop. This may be due to the higher precipitation in the northern region, compared to the central and southern regions, which would increase the recharge of meteoric

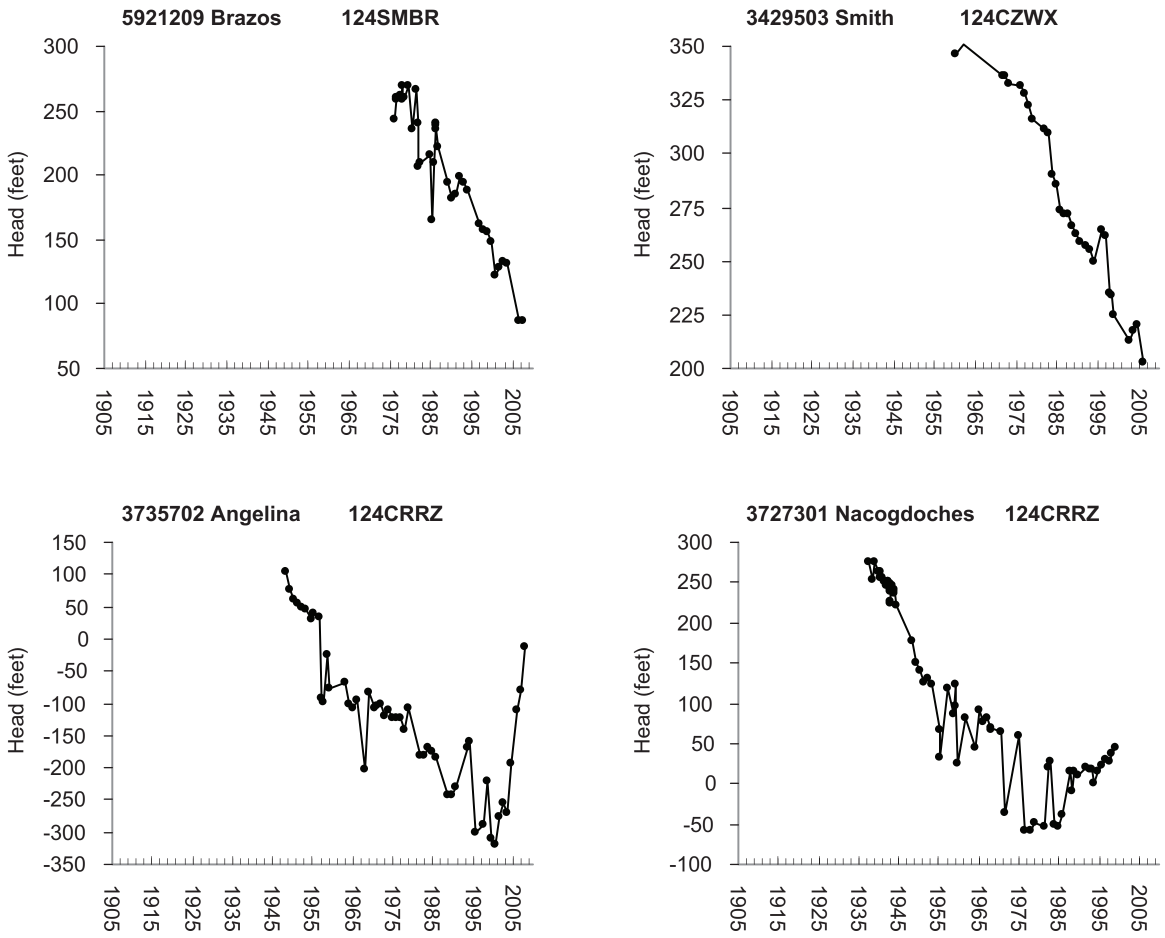

Figure 3-13. Measured water level hydrographs in the Carrizo and Simsboro formations.

water and generally improve the quality of water in the outcrop.

3.7
WATER BUDGET

The reports for the Carrizo-Wilcox Aquifer groundwater availability models detail the various mechanisms of recharge and discharge for each of the separate modeled regions (Deeds and others, 2003; Dutton and others, 2003; Fryar and others, 2003). However, the overall water budget of the aquifer, removing overlapping areas, has not been previously analyzed. In the following analysis, we used the regions shown in Figure 3-5 to define the areas for which the budget was calculated. We then summed the results to determine total budgets. The analyses were completed for both the steady-state and transient models. We chose 1999 as the transient year for which results are presented. Table 3-2 shows the results of the water budget expressed as net inflow or outflow for each component and region. Table 3-3 shows the same results expressed as a percent of net inflow or outflow for each component and region. For the purposes of this discussion, Wilcox refers to the Wilcox Group, undivided.

In predevelopment, the total inflow to the Carrizo Formation is 218,000 acre-feet per year, and total inflow to the Wilcox is 563,000 acre-feet per year. In general, recharge increases from the southern region to the northern region as precipitation increases. Nearly 100 percent of the inflow to the Carrizo and

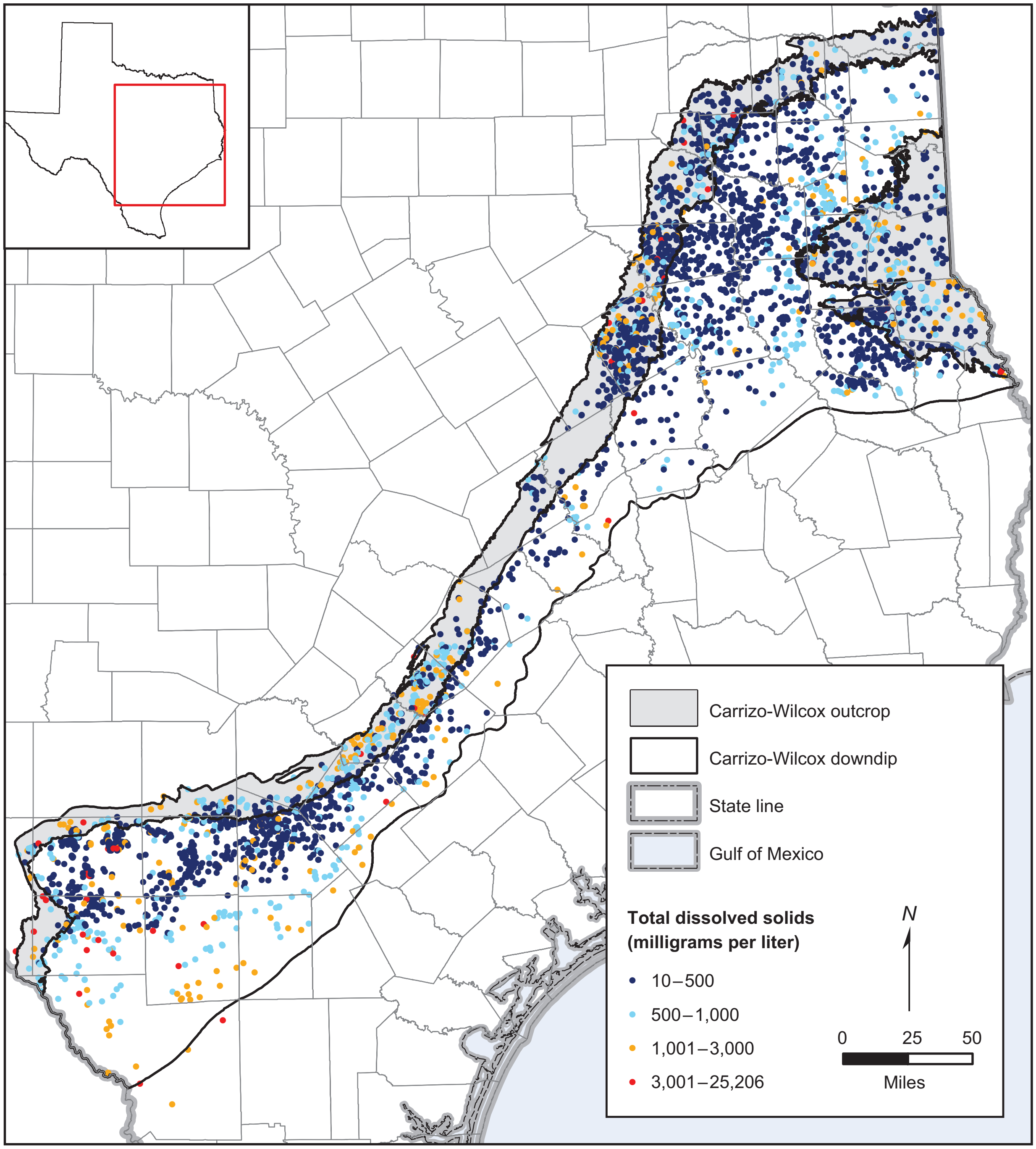

Figure 3-14. Measurements of total dissolved solids in the Carrizo-Wilcox Aquifer.

99 percent of the inflow to the Wilcox comes from recharge from precipitation. Outflow from the Carrizo occurs mainly through shallow discharge to streams and groundwater evapotranspiration, and deep discharge to cross-formational flow through the top of the formation. Top flow in the Carrizo represents flow to or from the Reklaw Formation, and bottom flow represents flow to or from the Wilcox. The fraction of discharge that is from groundwater evapotranspiration increases from the south to the north, as water tables are generally nearer to the surface in the northern region. For the southern region, over 50

Table 3-2. Simulated water budget for the Carrizo and combined Wilcox formations for predevelopment and year 1999. All values in acre-feet per year.

Region	Aquifer	Period	Recharge	Streams	ET	Drains	Top flow	Bottom flow	Reservoirs	Pumping	Storage	Net in	Net out
Southern	Carrizo	Pred	62,000	-32,000	-2,000	0	-39,000	8,000	n/a	n/a	n/a	70,000	-73,000
		1999	38,000	-9,000	0	0	57,000	-5,000	0	-222,000	143,000	238,000	-236,000
	Wilcox	Pred	43,000	-30,000	-4,000	-1,000	-8,000	0	n/a	n/a	n/a	43,000	-43,000
		1999	26,000	-10,000	-1,000	0	5,000	0	2,000	-57,000	35,000	67,000	-68,000
Central	Carrizo	Pred	40,000	-19,000	-14,000	-1,000	-10,000	4,000	n/a	n/a	n/a	44,000	-44,000
		1999	46,000	-23,000	-12,000	-1,000	-6,000	0	0	-10,000	9,000	55,000	-53,000
	Wilcox	Pred	117,000	-82,000	-29,000	-2,000	-4,000	0	n/a	n/a	n/a	117,000	-117,000
		1999	136,000	-99,000	-19,000	-4,000	0	0	3,000	-38,000	26,000	166,000	-160,000
Northern	Carrizo	Pred	116,000	-45,000	-57,000	-3,000	2,000	-15,000	n/a	n/a	n/a	118,000	-120,000
		1999	56,000	-32,000	-18,000	0	44,000	-30,000	0	-69,000	43,000	143,000	-150,000
	Wilcox	Pred	399,000	-219,000	-183,000	-14,000	15,000	0	n/a	n/a	n/a	414,000	-417,000
		1999	256,000	-162,000	-52,000	-13,000	30,000	0	13,000	-77,000	-5,000	299,000	-309,000
Total	Carrizo	Pred	218,000	-97,000	-72,000	-4,000	-47,000	-3,000	0	0	0	218,000	-223,000
		1999	141,000	-65,000	-30,000	-2,000	95,000	-36,000	0	-301,000	195,000	430,000	-433,000
	Wilcox	Pred	560,000	-332,000	-217,000	-17,000	3,000	0	0	0	0	563,000	-565,000
		1999	417,000	-271,000	-71,000	-17,000	36,000	0	18,000	-172,000	56,000	527,000	-532,000

Note: Positive numbers indicate inflows; negative numbers indicate outflows.

Pred = predevelopment; ET = evapotranspiration

Table 3-3. Simulated water budget as a percent of net inflow or outflow for predevelopment and year 1999.

Region	Aquifer	Period	Recharge	Streams	ET	Drains	Top flow	Bottom flow	Reservoirs	Pumping	Storage
Southern	Carrizo	Pred	89	-44	-3	0	-53	11	0	0	0
		1999	16	-4	0	0	24	-2	0	-94	60
	Wilcox	Pred	100	-70	-9	-2	-18	0	0	0	0
		1999	38	-14	-1	0	7	0	2	-85	52
Central	Carrizo	Pred	92	-45	-31	-1	-23	8	0	0	0
		1999	84	-45	-22	-3	-11	-1	0	-19	16
	Wilcox	Pred	100	-70	-25	-2	-3	0	0	0	0
		1999	82	-62	-12	-3	0	0	2	-24	16
Northern	Carrizo	Pred	98	-38	-47	-2	2	-12	0	0	0
		1999	39	-21	-12	0	31	-20	0	-46	30
	Wilcox	Pred	96	-53	-44	-3	4	0	0	0	0
		1999	85	-53	-17	-4	10	0	4	-25	-2
Total	Carrizo	Pred	100	-44	-32	-2	-21	-1	0	0	0
		1999	33	-15	-7	0	22	-8	0	-69	45
	Wilcox	Pred	99	-59	-38	-3	1	0	0	0	0
		1999	79	-51	-13	-3	7	0	3	-32	11

Note: Positive numbers indicate inflows; negative numbers indicate outflows.

Pred = predevelopment; ET = evapotranspiration percent of the discharge from the Carrizo occurs vertically through the top of the formation due to upward gradients in predevelopment.

The impact of groundwater development dramatically changes the budget in 1999 compared to predevelopment. In total, pumping accounts for 69 percent of outflow from the Carrizo Formation and 32 percent of the outflow from the Wilcox Group. With the addition of pumping, water removed from storage in the Carrizo accounts for 45 percent of the inflow to the Carrizo, but only 11 percent of the inflow to the Wilcox. Note that water removed from storage is considered an inflow component, and thus has a positive value in Table 3-2. Overall, capture occurs from streams, groundwater evapotranspiration, and cross-formational flow.

The effect of pumping in the southern region is most pronounced, with 94 percent of outflow in the Carrizo from pumping, of which 60 percent comes from storage. Much of the remainder of the inflow to the Carrizo (24 percent) flows from the top of the aquifer. Note the reversal from predevelopment, where about half of the outflow occurred through cross-formational flow. This reversal in cross-formational flow represents capture, where a discharge mechanism becomes a recharge mechanism under the influence of pumping.

In the central region, pumping makes up a much smaller percent of net outflow, with 19 percent and 24 percent from the Carrizo and Wilcox, respectively. Most of this outflow is balanced by a decrease in storage, with very little capture from streams, groundwater evapotranspiration, or cross-formational flow.

Because the flow system is shallower and recharge is greater in the northern region, storage does not contribute as significantly to the water budget, especially in the Wilcox, with its considerable outcrop in the Sabine Uplift area. Also of interest in the northern area is the source of capture for the pumping. The percent of outflow to the streams changes only slightly from predevelopment to 1999, but the percent of outflow to groundwater evapotranspiration decreases from 47 percent to 12 percent in the Carrizo, and 44 percent to 17 percent in the Wilcox. Both groundwater evapotranspiration and cross-formational flow are the major sources of capture in the northern region.

The distribution of pumping in the Carrizo-Wilcox Aquifer in 1999 is shown in Figure 3-15. In this figure, the pumping rates were plotted for each square mile. Rates of less than 10 acre-feet per year in a square mile were not plotted. This rate corresponds to about 10,000 gallons per day, or the production from a typical private domestic well. In the southern region, most of the pumping is in the Winter Garden area, which is consistent with the drawdowns shown in Figure 3-11. Similarly, Brazos County has the highest concentration of withdrawals in the central region. In the northern region, Angelina and Nacogdoches counties show the highest concentration of withdrawals, consistent with the drawdown cones shown in Figure 3-11

3.8

SUMMARY AND CONCLUSIONS

In this paper, we provided a basic summary of the hydrogeology of the Carrizo-Wilcox Aquifer in Texas. The Carrizo-Wilcox is a major aquifer in Texas, providing approximately 450,000 acre-feet of water in 2003 to users in the state. The Carrizo-Wilcox in Texas lies roughly parallel to the coast from the Rio Grande in the south to the Texas-Louisiana border in the northeast.

The sediments that form the Carrizo-Wilcox Aquifer are part of a gulfward thickening wedge of Cenozoic sediments deposited in the Rio Grande Embayment of the northwest Gulf Coast Basin. In the south, the Carrizo-Wilcox is composed of the Carrizo Formation and the Wilcox Group, with the Wilcox Group typically divided into upper, middle, and

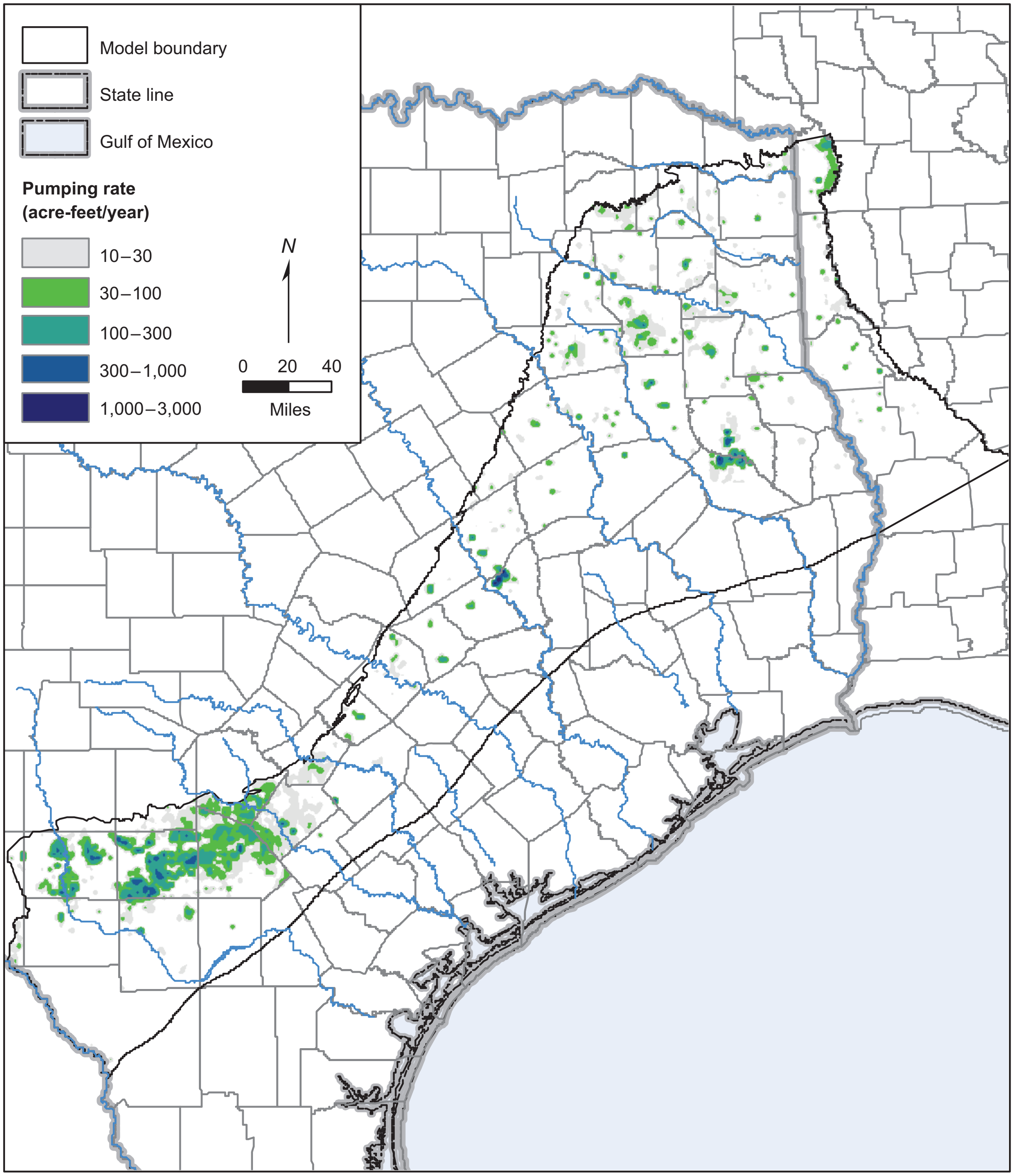

Figure 3-15. Estimated pumping rates in the Carrizo-Wilcox Aquifer in 1999.

lower units. In the central portion of the area, the three Wilcox units are called the Hooper, Simsboro, and Calvert Bluff formations, with the Simsboro being the most productive of the three. In the north, the contrast between the Carrizo and Wilcox can be poorly defined, with the combination collectively referred to as the Cypress Aquifer.

The Rio Grande and Houston embayments, East Texas Embayment, Sabine Uplift, and San Marcos Arch are the main structural features intersecting the Carrizo-Wilcox Aquifer. Various fault zones are associated with the basin history of crustal warping, subsidence, and sediment loading. From coastward to inland, these include the Wilcox Growth Fault Zone, the Karnes Mexia Fault Zone, the Elkhart-Mount Enterprise Fault Zone, and the Balcones Fault Zone.

We reanalyzed a database of hydraulic conductivity estimates from Mace and others (2003), locating the measurements in specific formations based on the structure of the groundwater availability models. The estimated mean hydraulic conductivity in the Carrizo Formation ranges from 44 feet per day in the south to 12 feet per day in the north. Hydraulic conductivity in the formations that make up the Wilcox generally decreases with depth of formation. Overall, the Carrizo Formation and portions of the Wilcox Group, including the Simsboro, can contain very productive sands.

Groundwater movement within the Carrizo-Wilcox Aquifer is significantly influenced by the topography and the structure of the units. Shallow groundwater flow is dominated by topography, with flow from the higher topographic areas toward the stream channels. In the subcrop, flow is generally downdip, which follows regional topography. Groundwater production has significantly affected water levels in the Carrizo-Wilcox, especially in the Winter Garden area in the southern region, Brazos County in the central region, and Smith, Angelina, and Nacogdoches counties in the northern region. Measured drawdowns of over 300 feet have been recorded in the Carrizo Formation. Water quality in the aquifer is generally good, with fresh water in most of the outcrop and subcrop (up to 30 miles in the dip direction) areas. Further downdip, the water transitions to slightly and moderately saline.

In predevelopment, the dominant source of inflow to the aquifer is recharge from precipitation. The dominant shallow discharge mechanism is through streams and groundwater evapotranspiration, with the relative importance of groundwater evapotranspiration increasing from south to north, as water tables rise closer to ground surface. The dominant deeper discharge mechanism is through upward cross-formational flow from the Carrizo Formation to younger sediments. Under current developed conditions, pumping makes up the majority of outflow in the Carrizo. In the south, much of the pumped water comes from storage along with significant capture from cross-formational flow, as vertical gradients are reversed. Moving to the northern region, capture from groundwater evapotranspiration increases, and the decrease in cross-formational flow is less significant.

3.9
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Chapter 4

Ecology of the Carrizo-Wilcox Aquifer

Chad W. Norris[1] and Daniel R. Opdyke, Ph.D., P.E.[1]

Groundwater is a major source of water in Texas, supplying almost 60 percent of the water used statewide in 2003 (TWDB, 2007). As the development of land and water resources has increased over the last several decades and the availability of suitable surface water development locations has diminished, increased pressure has been placed on groundwater resources to meet future needs. However, the connection between groundwater and surface water resources is often overlooked as they are developed.

Many surface water features, including lakes, streams, reservoirs, wetlands, and estuaries, interact with groundwater to some extent (Winter and others, 1998). In some situations, surface water bodies gain water from groundwater systems, and in others, the surface water body is a source of groundwater recharge. As a result, the withdrawal of water from streams can reduce groundwater recharge, and in other situations, groundwater pumping can deplete water in lakes, streams, and wetlands. Thus, there is concern about the potential impact groundwater withdrawals will have on surface water habitats supported by groundwater. To manage land and water resources effectively, the hydrogeologic linkages between groundwater and surface water must be understood.

The most apparent linkage between groundwater and surface water is the expression of springs, which are defined as the natural flow of groundwater to the land surface. Springs have long been recognized as valuable ecological (Danielopol, 1989; Williams and Danks, 1991), natural (Bowles and Arsuffi, 1993; TPWD, 2005), and cultural (Brune, 1975; Brune, 1981; Weniger, 1984) resources. They are an important natural feature that played a major role in the lives of early inhabitants and settlers, determining the location of trails, providing power for mills, and supplying water for domestic, municipal, agricultural, and recreational uses.

The unique aquatic and wetland habitats formed by springs represent the interface between hypogean (subterranean) and epigean (surface water) habitats. These habitats are recognized for their high proportion of unique biota that often include rare, endemic, and relict species. The presence of such species is often owed to the hydrologic stability displayed by many springs in terms of the quantity and quality of water discharged over time (Hynes, 1970; Ward 1992). Because of their relative stability (as compared to streams and reservoirs), springs play a vital role in ensuring that common (non-game) aquatic species remain common. Springs provide the base flows to rivers and streams that sustain aquatic, wetland, and riparian habitats during drought and often support disjunct headwater habitats that serve as isolated refuges. In addition, springs often maintain downstream aquatic and riparian habitats, enhance and/or sustain surface water supplies, provide recharge to downstream aquifers, and offer a natural, relatively inexpensive means of monitoring groundwater quality.

Despite the ecological and hydrological significance of springs, a paucity of data exists on the vast majority of springs that occupy the Texas landscape. Moreover, many springs in the state have not been assessed by biologists

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or hydrologists, and a large proportion of the data that exist on spring systems are from a relatively small number of springs (Brune 1981; Ourso and Hornig, 1999). Because the loss and decline of Texas springs has been well documented (Brune, 1975, 1981; Bowles and Arsuffi, 1993), it is likely that remaining spring systems, the habitats they support, and the biota that rely on them will be negatively impacted to some extent by human activities as the population continues to increase. A significant and obvious threat to spring habitats is groundwater withdrawals that directly impact springflows. Other less obvious threats include contamination, development within recharge zones, introductions of exotic species, and poor land management practices.

4.1
CARRIZO-WILCOX AQUIFER

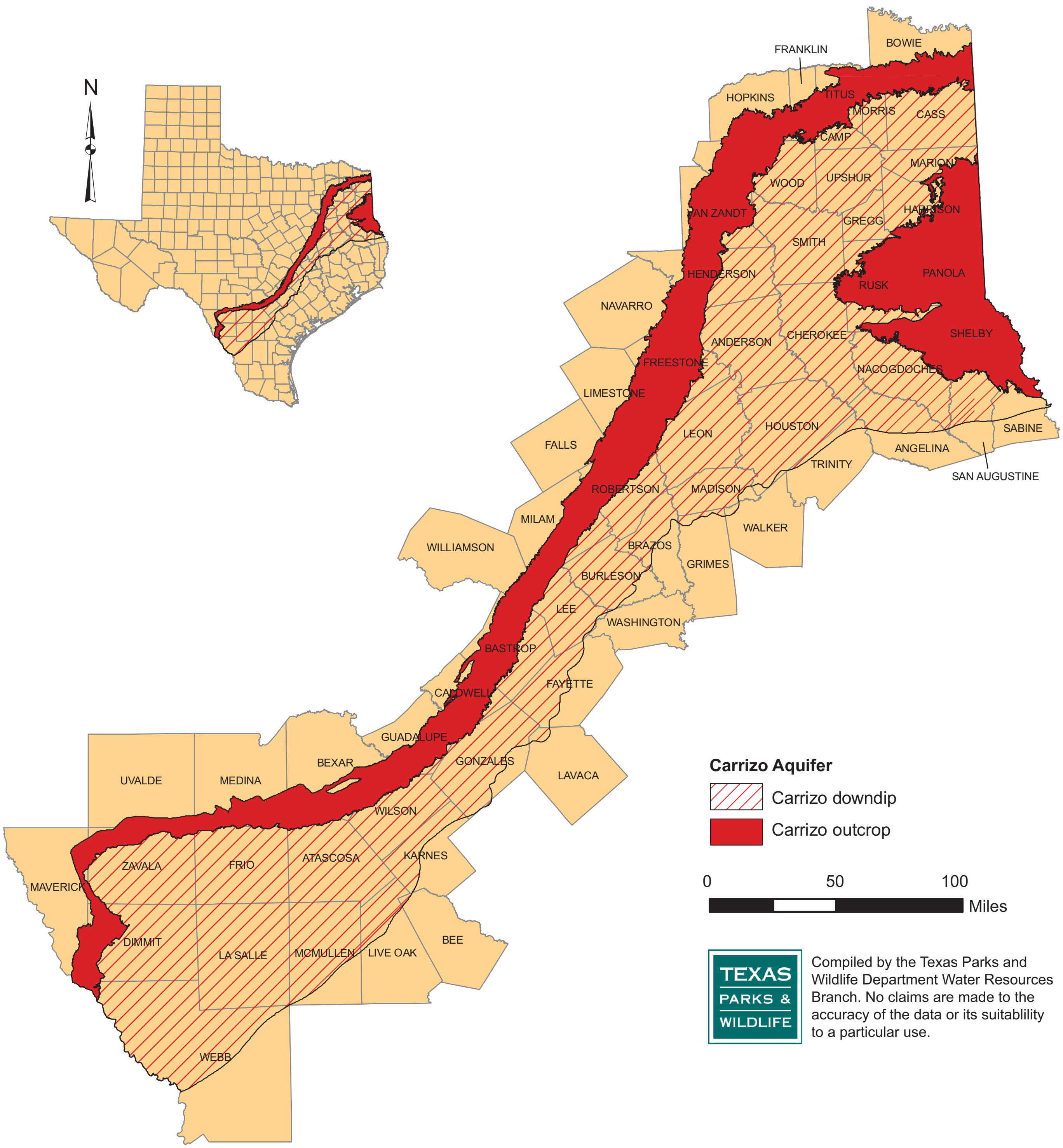
The Carrizo-Wilcox Aquifer is a major aquifer in Texas that ranges from the Rio Grande in South Texas northeastward into the Piney Woods of East Texas (Figure 4-1). The aquifer consists of the Wilcox Group and Carrizo Formation. These geologic units crop out in a narrow band that extends from the Sabine River in northeast Texas to the Rio Grande in southwest Texas.

The aquifer is composed primarily of hydraulically connected sands locally interbedded with gravel, silt, clay, and lignite deposited during the Tertiary Period. The Carrizo is a homogeneous sand unit overlying the thicker, more heterogeneous Wilcox Group (Deeds and others, 2003; Dutton and others, 2003; Fryar and others, 2003). In most of Central Texas, the Wilcox Group is divided into three distinct formations: the Hooper, Simsboro, and Calvert Bluff formations. This division cannot be made north of the Trinity River and south of the Colorado River due to the absence of the Simsboro Formation as a distinct unit.

Groundwater in the Carrizo-Wilcox Aquifer exists under both water table (unconfined) and artesian (confined) conditions. Water table conditions usually occur in the outcrop areas, and artesian conditions occur where the aquifer is overlain by confining beds with lower hydraulic conductivity rates. The major water-bearing units of the Carrizo-Wilcox Aquifer are the Carrizo and Simsboro formations, which contain more permeable and thicker sand deposits. In contrast, the Calvert Bluff and Hooper formations are made of clay, silt, sand, and lignite mixtures and generally have a low vertical permeability, which make them act as leaky aquitards that confine fluid pressures in the Carrizo and Simsboro and restrict groundwater movement between the layers (Dutton and others, 2003).

The Carrizo-Wilcox Aquifer is in communication with several minor aquifers that overlie its confined portion, including the Queen City, Sparta, and Yegua formations (Figure 4-2). In this chapter, these minor aquifers will be referred to as associated minor aquifers. These aquifers represent sediments from contrasting depositional environments. Water is pumped from these aquifers to some extent for various uses, and they also support various spring habitats. More information on the Carrizo-Wilcox and associated aquifers is presented by Ashworth and Hopkins (1995).

Groundwater is pumped from the Carrizo-Wilcox in about 60 counties in Texas for various uses. Irrigation pumping occurs throughout the aquifer and accounted for 43 percent of the total groundwater removed in 2003. Approximately 35 percent of the total groundwater removed from the aquifer in 2003 was for municipal water supply (TWDB, 2009). Public water supply systems in Bryan-College Station, Lufkin-Nacogdoches, and Tyler make up a large portion of the municipal percentage as they are population centers in the region and receive significant amounts of their water from the Carrizo-Wilcox Aquifer (TWDB, 2007; TWDB, 2009). Lignite mining operations also remove a



Compiled by the Texas Parks and Wildlife Department Water Resources Branch. No claims are made to the accuracy of the data or its suitablility to a particular use.

Figure 4-1. Map of Carrizo-Wilcox Aquifer (aquifer data from the TWDB database, www.twdb.state.tx.us/data/data.asp).

significant portion of groundwater from the central area of the aquifer (Deeds and others, 2003; Dutton and others, 2003; Fryar and others, 2003).

As the population of Texas continues to grow at a rapid rate, increased pressure is being placed on groundwater resources. The proximity of the Carrizo-Wilcox Aquifer in relation to many urban areas and estimates of water availability from the aquifer have made it a target for various entities seeking to obtain future water supplies. As such, there is concern about the potential impact groundwater withdrawals will have on surface water habitats that rely on groundwater contributions from the aquifer. Under natural conditions (no wells pumping), aquifers approach a state of dynamic equilibrium where recharge to the aquifer essentially equals the natural discharge (Theis, 1940). Discharge from wells alters this equilibrium by reducing aquifer storage, inducing additional recharge, and decreasing natural discharge. The location of the well in relation to the source area of induced recharge and/or the natural discharge areas plays a major role in the significance of the impacts.

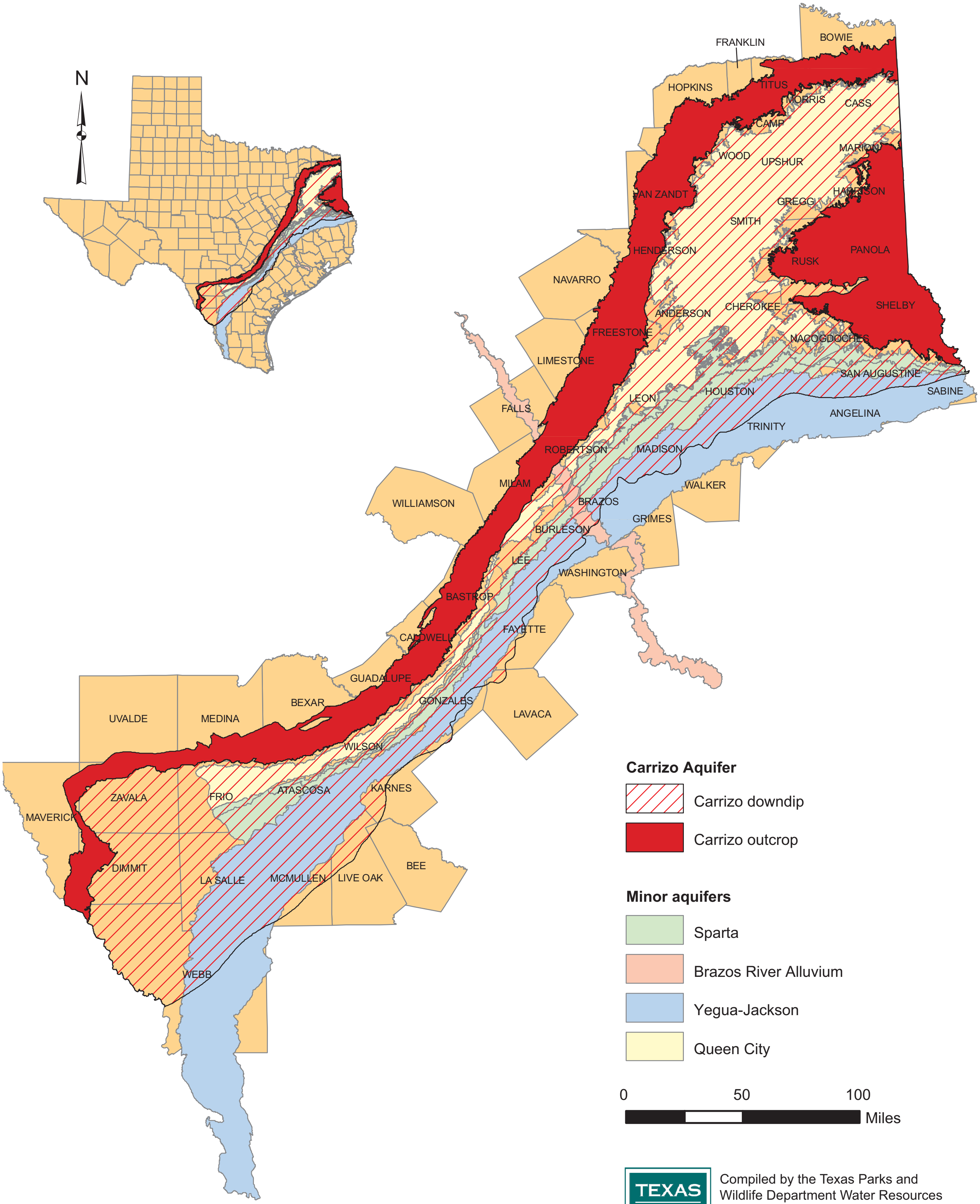
4.2

NATURAL DISCHARGE OF THE CARRIZO-WILCOX AQUIFER

Groundwater in the Carrizo-Wilcox Aquifer moves slowly under the influence of gravity from areas of recharge to areas of discharge. Recharge to the Carrizo-Wilcox Aquifer occurs primarily in the outcrop portion and is derived mainly from direct precipitation and losses from surface water bodies. Recharge rates vary during seasonal, annual, and longer time periods and differ across the outcrop according to vegetation, slope, soils, and other factors. Estimates of the recharge rate for the Carrizo-Wilcox Aquifer range from 0.1 to more than 5 inches per year (Ryder and Ardis, 1991; Thorkildsen and Price, 1991; Dutton, 1999; Scanlon and others, 2002). In general, only a small amount of annual rainfall reaches the water table because most rainfall runs off or is evapotranspired. Dutton (1990) estimated that only about 10 percent of precipitation may end up as recharge.

Springs are natural discharge points for aquifers. They emerge through natural openings in rock or soil under gravity or artesian conditions. Gravity springs commonly occur in the unconfined portion of the Carrizo-Wilcox and associated minor aquifers in one of two ways. The first type of gravity spring occurs when groundwater percolates downward, moves laterally due to underlying impermeable strata, and emerges at the land surface, often on hillsides or in headwater streambeds. Springs of this type are often apparent and are commonly fed by seepage from isolated hills or topographic highs, such as the Yegua Knobbs in Lee County. The second type of gravity spring represents water that enters the water table in the unconfined portion of the aquifer but emerges as discharge to seeps and springs in valleys, base flows to rivers and streams, and evapotranspiration in bottomland areas. This is often referred to as rejected recharge. These springs may form in alluvial deposits and be apparent along streams and rivers, such as Bastrop Springs. However, these types of springs more commonly issue subaqueously in stream and river bottoms as they traverse aquifer outcrops and form gaining reaches of streams.

Groundwater that does not emerge as gravity springs and seeps and makes its way to the confined portion of the aquifer is discharged naturally through artesian springs and cross-formational leakage as well as artificially through wells. Artesian springs form where groundwater confined by relatively impermeable beds and/or faults is forced to the surface, which is relatively uncommon in the Carrizo-Wilcox and associated aquifers. One example is the springs associated with the Elkhart Graben-Mount Enterprise fault system that provide flow to Elkhart Creek (Brune, 1975). Many, if not



Compiled by the Texas Parks and Wildlife Department Water Resources Branch. No claims are made to the accuracy of the data or its suitablility to a particular use.

Figure 4-2. Map of Carrizo-Wilcox and associated minor aquifers (aquifer data from the TWDB database, www.twdb.state.tx.us/data/data.asp).

most, of the artesian springs historically documented from the Carrizo-Wilcox and associated aquifers ceased to flow decades ago as development of the aquifer reduced the hydraulic head or artesian pressure (Brune, 1981). Alterations to the hydraulic head may also impact the relationship between adjacent aquifers and cross-formational flow.

Cross-formational leakage is the movement of water from one aquifer to an underlying or overlying aquifer, depending upon the vertical gradient in hydraulic head. Several studies have found that the Carrizo-Wilcox Aquifer discharges water upward to younger, overlying aquifers such as the Queen City Aquifer (Kreitler, 1979; Fogg and others, 1983; Hamlin, 1988). This is significant because as the Carrizo-Wilcox Aquifer has been developed, the natural balance of recharge and discharge (such as cross-formational flow and springflow) has changed (Dutton and others, 2003). In areas experiencing heavy groundwater pumping, the hydraulic gradient between aquifers has been reversed, resulting in cross-formational flow from overlying younger units (for example, the Queen City Sand) to the Carrizo-Wilcox Aquifer. The resulting reduction in upward flow from the confined portion of the Carrizo-Wilcox Aquifer may ultimately have an indirect impact on the quantity and reliability of water produced by springs issuing from the Queen City Aquifer and other minor aquifers as dynamic equilibrium is further impacted.

4.3
SPRINGS OF THE CARRIZO-WILCOX AND ASSOCIATED AQUIFERS

Information on Texas springs is largely limited to that collected by the U.S. Geological Survey and the Texas Water Development Board (TWDB) while inventorying and studying groundwater supplies across the state. As such, the information is scattered in various reports, and the springs documented are primarily limited to those that were or are used for domestic, livestock, or agricultural purposes. Moreover, the data contained in the reports were generally limited to location, geologic formation, and one or more discharge estimates. Very little data have been gathered on the vast majority of Texas springs. In fact, information as basic as the location, distribution, and extent of springs in Texas is lacking, as no thorough inventory has been performed.

Gunnar Brune, a geologist for TWDB, compiled much of the information available on springs in state and federal reports and gathered some additional data. Brune (1975) first identified some 281 major and historical springs in Texas, only 11 of which reportedly issue from the Carrizo-Wilcox and associated aquifers. Later, Brune (1981) compiled existing data and gathered some additional information on slightly more than 2,000 springs from 183 of the 254 Texas counties. The work of Brune essentially documented the loss and decline of Texas springs but provided little ecological information.

In 2003, the U.S. Geological Survey, in cooperation with TWDB, published a database of historically documented springs and springflow measurements in Texas (Heitmuller and Reece, 2003). Approximately 2,000 springs were identified and are in the database. Approximately 217 of these springs are reported to issue from the Carrizo-Wilcox and associated aquifers. Analysis of the distribution of springs contained in the database reveals clusters of springs in the eastern portion of the Panhandle, southwestern portion of the Big Bend region, in a band that follows the Carrizo-Wilcox and associated aquifers from south central Texas northeasterly toward Texarkana, and throughout the Edwards Plateau. The density of springs issuing from the Carrizo-Wilcox and associated aquifers is greatest in the central and northern part of the aquifer systems, with few documented springs occurring southwest of Wilson County (Figure 4-3).

In general, the density of springs appears greatest in headwater regions and is remarkably low in the lower reaches of large river basins. This may be due to physiographic differences between headwaters and lower reaches of river systems. Of course, many springs issuing into streams from sandy and alluvial aquifers, such as the Carrizo-Wilcox or Gulf Coast aquifers, do so subaqueously. They are often not readily apparent, may occur over great distances of aquifer outcrops, and may move to some extent in relation to river processes. As such, these springs have been largely neglected in mapping, documenting, and studying springs. Most subaqueous springs are identified as gaining reaches of rivers in various reports, much of which was compiled by Slade and others (2002).

Another source for identifying springs is the 7.5 minute U.S. Geological Survey topographic maps. Stevens and Meretsky (2008) searched these maps for named springs and developed a georeferenced database for those in the western United States, including Texas. A total of 745 named springs were identified in Texas. This is surprisingly low considering the number of springs identified by Brune (1981) and Heitmuller and Reece (2003). However, many of the springs identified by Brune (1981) and Heitmuller and Reece (2003) are either unnamed or are not depicted on U.S. Geological Survey maps.

Without question, the number of springs that actually exists in the state, including those associated with the Carrizo-Wilcox Aquifer, is much greater than what is currently documented. For example, analysis of U.S. Geological Survey topographic maps and state and federal databases revealed only six springs in Gonzales County. With the assistance of the local groundwater conservation district and landowners, Helen Besse (personal communication 2009) identified 20 springs in the county. This represents a threefold increase in the number of springs documented in the county and highlights the need for more on-the-ground research.

4.4
CHARACTERISTICS OF CARRIZO-WILCOX SPRINGS

The geology and characteristics of an aquifer (for example, parent material, permeability, and porosity) from which a spring flows dictate the location of the spring outflow, the physical and chemical properties of the water it discharges, and the type of habitat formed by the spring outflow. From the perspective of spring ecology, the most important hydrogeological distinction may be between springs fed by slow seepage through small pore spaces and those fed by rapid flow through wide openings in rock. For example, springs issuing from the Carrizo-Wilcox Aquifer differ greatly from those in Central Texas that issue from karst limestone aquifers such as the Trinity and Edwards. Carrizo-Wilcox springs are typically smaller, younger, and less stable than those of the Edwards or Trinity aquifers.

Springs issuing from the Carrizo-Wilcox and associated minor aquifers, including the Queen City, Sparta, Weches, and Yegua formations, tend to be smaller in size both in terms of the actual orifice and the volume of discharge produced and often rise discretely as a group or series of seeps that coalesce into a stream. The sands that form these aquifers were deposited during the Tertiary Period (65 to 1.8 million years ago). However, because of the unconsolidated nature of sand, springs produced from it are typically young, rarely surviving 100 years (Brune, 1981). They are easily destroyed or altered by natural and human means, but new springs will appear in the same general area as long as the water table remains above the spring orifice. The relatively low transmissivity of sand as compared to the

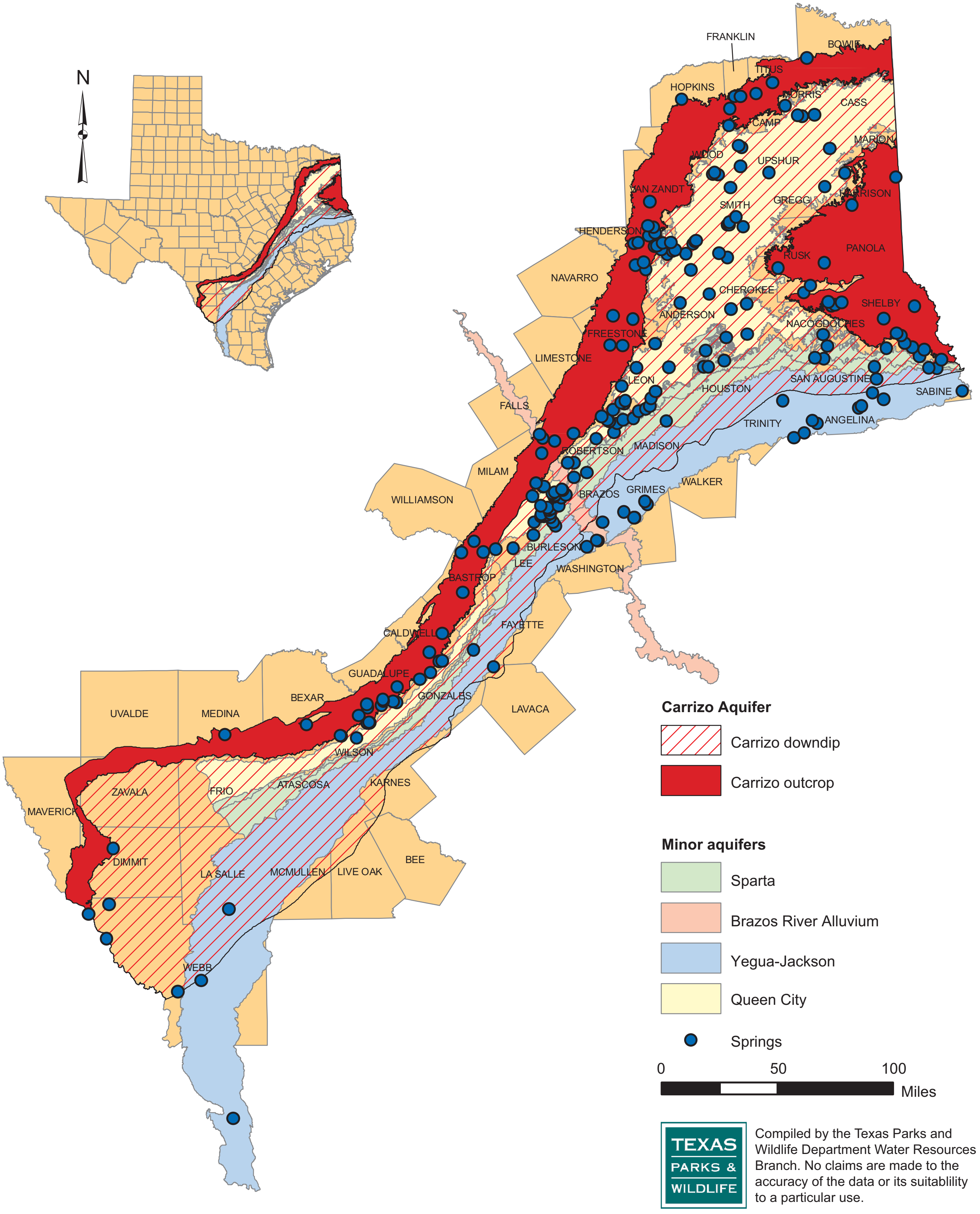


Figure 4-3. Carrizo-Wilcox and associated aquifers with springs (Heitmuller and Reece, 2003; aquifer data from the TWDB database, www.twdb.state.tx.us/data/data.asp).

karstic limestone aquifers of Central Texas imparts less variability in flow and allows flow to persist for many months to years without rainfall in the recharge zone (Brune, 1981). However, the relatively small pore spaces that impart less variability in flow also limit the distribution of hypogean species, which result in a lower proportion of rare, endemic, and relict species as compared to the limestone springs of Central Texas.

Water traveling through a carbonate aquifer system, such as the Edwards-Trinity Aquifer, becomes charged with calcium bicarbonate and loses carbon dioxide, resulting in an increased pH. In these types of aquifers, calcium carbonate, aided by photosynthesis, is deposited in the groundwater (Hynes, 1970). Because of the freshwater input from and stable substrate of limestone springs, algae, mosses, and other higher plants, referred to as hydrophytes, are often well developed (Ward, 1992). Hydrophyte communities provide a mosaic of habitat patches in springs (Minckley, 1963: Ward and Dufford, 1979) and can be a major source of organic detritus (Ward, 1992). As a result, the primary productivity of these springs is principally autochthonous, or derived from within the system (Thorup, 1966; Ward and Dufford 1979).

Carrizo-Wilcox springs are more acidic with fewer aquatic macrophytes and more allochthonous (derived from outside the system) sources of energy as compared to springs from the Edwards or Trinity aquifers. Shading from the canopy prevents extensive hydrophyte production, and the influx of terrestrial leaf litter contributes greatly to the composition of woodland spring habitats (Minshall, 1968; Ward, 1992).

As a result of the acidity, groundwater from Carrizo-Wilcox springs tends to leach iron, resulting in high concentrations of ferrous bicarbonate in solution. As the spring water reaches the surface and acquires oxygen, the deposition of ferric hydroxide occurs. As a result, the spring orifices are often covered with masses of siderophile (iron-loving) bacteria. The downstream reaches of the spring habitats generally clear up as the water acquires inorganic ions.

Several characteristics of groundwater that separate it from surface water are important in the ecology of spring habitats. Spring water is usually derived from water that has infiltrated at many locations over a range of time periods. Infiltration can occur a great distance from the site of discharge, and residence times can vary from days to thousands of years (Kamp, 1995). The solutes present and their relative concentrations are largely determined by the geology of the strata through which the water has passed (Freeze and Cherry, 1979). The water quality of the discharged spring water is important because it is also a major determinant for the ecology of a spring system.

4.5
ECOLOGY OF CARRIZO-WILCOX SPRINGS

Typically, physicochemical characteristics of spring systems are less variable than in surface water systems such as streams or reservoirs. Spring systems generally provide uniform conditions in contrast to surface water, which is generally subjected to more seasonal variation (Hynes, 1970). As a result, many springs harbor taxonomically or ecologically interesting organisms including rare, endemic, and relict species (Nielson, 1950; Edwards and others, 1989; Bowles and Arsuffi, 1993), which are adapted to and dependent upon the thermal and hydrologic stability of these environments (Hynes, 1970; Hubbs, 1995). Compared with higher-order streams, most springs have greater physical and chemical stability, smaller and more isolated habitat areas, fewer large predators, and presumably shorter durations in geologic time (Glazier, 1991; Kamp, 1995). All of these factors, and possibly others, are important determinants of the distinctive spring fauna.

Perhaps the most ecologically important feature of many springs is the thermal and hydrologic consistency they display through the year (Hynes, 1970; Ward, 1992). The average water temperature of a typical spring is very nearly equal to the average mean air temperature in the area. As a result, spring environments in the temperate zone are generally cooler than other natural surface waters in the summer months and warmer in the winter months. Variations in temperature generally result from either shallow flow areas near the spring or from very rapid infiltration and flow through cavernous formations (local flow systems with short residence times) (Kamp, 1995).

Although the temperature requirements of many aquatic animals are not known, cold spring inhabitants, in general, are known to have narrow limits of tolerance to variation (Hynes, 1970; Hubbs, 1995), which probably accounts for the restriction of typical spring fauna to a narrow zone below the spring source where temperature variance is minimal. Such species are generally unable to maintain populations in habitats with greater thermal variability.

From a biological perspective, the most important factor related to the flow of a spring is the persistence of the flow (Danks and Williams, 1991; Kamp, 1995). Also of great importance, and closely related to persistence, is the variability of the flow. In general, the most permanent springs can be expected to be those fed by long flow systems with a moderately permeable material and with high porosity at the water table. Springs discharging from sand aquifers tend to display persistent flow as they are fed by slow seepage through small pores with strong filtration. In some cases, many years may be required for water to travel from areas of recharge to areas of discharge (springs), resulting in a delayed action that allows springs to flow persistently for many months to a year without significant rainfall in the recharge zone.

The persistence of flow is important in terms of dispersal from and the colonization of spring habitats. As a spring habitat begins to dry up, aquatic organisms will generally either disperse to find a favorable habitat, enter a dormant stage to avoid dessication, exploit hyporheic or hypogean habitats, or be extirpated from the habitat (Ward, 1992). Some common spring inhabitants such as amphipods, isopods, and snails have limited dispersal capabilities as they lack the ability to fly. Dispersal efforts by such species are likely complicated by the fact that many spring habitats are isolated from other suitable habitats by great distances or by inhospitable habitats that they are unable to traverse. The greatest impact from the cessation of flow is likely to occur in springs with historically persistent flow as these are the springs that commonly harbor rare and interesting species.

The variability of flow from a spring is also a major determinant in shaping the spring community. In some cases, the stable flow conditions allow colonization by certain species that are unable to maintain populations in streams with highly variable discharge (Ward, 1992). In other cases, it may preclude species that require variable discharges to complete their life cycle.

4.5.1
Spring fauna

The fauna of springs is generally dominated by macroinvertebrates but also commonly includes amphibians, reptiles, and fish. The diversity in spring habitats is often reported to be depressed (Odum, 1957; Minshall, 1968; Ward and Dufford, 1979). Depressed diversity in spring habitats has been attributed to many factors, including poor water quality at the source area, the lack of heterogeneity in certain factors (such as temperature and flow) that are needed by some species to complete their life cycle, and the geographic isolation of many springs (Ward, 1992). These factors not only affect the overall diversity of organisms present at a particular spring, but also the diversity within specific taxonomic groups. In most streams, there is a progressive increase in numbers of fish (Matthews, 1998) and macroinvertebrate (Ward, 1992) species downstream as habitat heterogeneity increases.

The organisms present at a particular spring usually include species restricted and adapted to springs and common species with a broader distribution that find conditions favorable in spring habitats. Organisms restricted to springs include those that are unable to maintain populations in streams with highly variable conditions. These organisms commonly include rare, endemic, relict, and hypogean organisms with specific life history requirements related to spring habitats. Organisms restricted to springs often form an important component of the spring fauna and, although they persist in sheltered places for some distance downstream, are commonly absent from downstream reaches. Common stream-dwelling species appear further downstream but may also penetrate up to the spring orifice. In some cases, they may find conditions in spring habitats more favorable at certain times of the year or following certain environmental extremes.

For example, the Mexican tetra (*Astyanax mexicanus*) is a common, widespread species found in a variety of habitats (Thomas and others, 2007). The northern distribution of the Mexican tetra is apparently limited by its lack of cold tolerance (Edwards, 1999). During winter months when spring habitats are relatively warm, Mexican tetras are often more abundant as compared to other times of year and are commonly the dominant fish species (Norris, 2009, unpublished data). Similarly, other common fish species, such as the channel catfish (*Ictalurus punctatus*) and black bass (*Micropterus* sp.), are often found in greater abundance in headwater spring habitats following flood events (Norris, 2009, unpublished data). This suggests they found refuge in the isolated spring habitats when a hydrologic connection during flood stage allowed entry to the habitat. Over time, these species are generally lost from the community.

The fish community of headwater spring habitats is generally quite limited, and the presence of fish is often restricted to larger spring systems with dependable flow (Matthews and others, 1983; Pflieger, 1982). Many fish species endemic to spring habitats are now extinct, endangered, or of special concern due to a myriad of environmental changes, such as exotic species introductions, dam construction, and instream flow alteration, that have altered habitats (Anderson and others, 1995; Miller and others, 1989). Few, if any, endemic fish species found in East Texas are restricted to spring habitats associated with the Carrizo-Wilcox and associated aquifers. This is not surprising as the proportion of endemic fish species is much lower in East Texas as compared to West Texas (Hubbs and others, 1991).

Springs issuing from the Carrizo-Wilcox and associated aquifers, especially subaqueous springs, play an important role in sustaining downstream fish populations by providing perennial aquatic habitat during drought. Subaqueous springs also serve as a vital source of prey items for downstream communities. These springs often issue through extensive alluvial deposits overlying larger regional aquifers. At the interface of these alluvial aquifers and surface water habitats where groundwater and surface water readily mix is the hyporheic zone. A distinct fauna, referred to as the hyporheic meiofauna, inhabits the interstitial spaces between sediments. The hyporheic meiofauna includes a diverse group of organisms between 50 and 1,000 micrometers in size from a wide range of taxa, including crustaceans, insects, rotifers, oligochaetes, nematodes, and tartigrades. However, considerable differences exist in the percent composition of these taxa in different streams. Coarse sediments often contain more crustaceans and insects, and sandy sediments often contain more rotifers, nematodes, and tartigrades (Hakenkamp and Palmer, 2000). This difference is likely due to size differences as crustaceans and insects are at the upper size range of meiofauna but may be an artifact of the protocol and gear used in sampling the two substrates.

The hyporheic meiofauna are important for several reasons. They are the link between microbial communities and higher trophic levels (as prey) and can be a significant food source for predators such as macroinvertebrates and fish (Pope and Brown, 1996; Hakenkamp and Palmer, 2000). The distribution of the hyporheic meiofauna is greatly influenced by both the unidirectional flow of streams and the upwelling or downwelling of water vertically. Both forces influence whether the fauna are flushed from sediments (induced into drifting) or can settle from the water column. In fact, distinct species assemblages have been identified within the hyporheic zone in relation to the magnitude and direction of vertical water flux (Boulton and others, 1992; Williams, 1993). Because many fish species are known to feed on drifting invertebrates, areas of upwelling that induce invertebrates to drift likely serve as feeding hot spots. This may explain why it is common to see fish congregating in areas where springs emerge into stream bottoms.

The invertebrate community of spring headwaters tends to be dominated by noninsect fauna such as amphipods, isopods, triclads, and mollusks, especially in the spring source area (Glazier and Gooch, 1987; Gooch and Glazier, 1991; Webb and others, 1995; Williams and Williams, 1998). Hynes (1970) delineated four faunal components of spring macroinvertebrate communities: 1) groundwater forms—primarily noninsect taxa restricted to the spring source, 2) marginal forms—species normally inhabiting wet margin habitats that become more fully aquatic in the uniform conditions of rheocrenes, 3) crenon forms—relict species of previously widespread populations that found refuge in spring habitats and species normally occurring in headwater reaches of streams that inhabit and are restricted to springs at lower elevations, and 4) stream forms—members of the normal stream fauna that find conditions favorable in springs and springbrooks.

In general, much like fish communities, the diversity of the macroinvertebrate community tends to increase downstream from spring sources due to increasing thermal and habitat heterogeneity (Minckley, 1963; Minshall, 1968; Ward and Dufford, 1979; Ward, 1992). Depressed macroinvertebrate diversities at spring sources have been attributed to thermal constancy (Ward and Stanford, 1982), habitat persistence and structure (Erman and Erman, 1984; Glazier, 1991; Smith and others, 2003), and water quality (Strayer, 1994). These characteristics or properties may eliminate or exclude species with life history requirements related to these factors, such as those species that require changes in temperature to complete their life cycle (Hynes, 1970; Ward, 1992). Interestingly, species that inhabit springs typically display a higher fecundity (number of offspring per generation) and multi-voltinism (number of generations per year) than closely related species or even the same species that inhabit other natural surface waters (Hynes, 1970; Ward, 1992).

The macroinvertebrate communities of 34 sandy East Texas springs were studied by Gibson (2000). He found that springs issuing from the Carrizo-Wilcox and associated aquifers have low endemicity as compared to springs of the Edwards Plateau and that the fauna was dominated by nearctic taxa restricted to colder stream headwaters. Most of the invertebrate taxa collected were relatively common, but some rare species, including hypogean species, were found. Gibson (2000) identified the following nine macroinvertebrate species as indicative and expected in permanent, sandy springs of East Texas: *Synurella* near *bifurcata* (Amphipoda), *Crangonyx pseudogracilis* (Amphipoda), *Calopteryx maculata* (Odonata), *Argia immunda* (Odonata), *Cordulegaster maculata* (Odonata), *Diplectrona modesta* (Trichoptera), *Molanna tryphena* (Trichoptera), *Tipula* sp. (Diptera), and *Bittacomorpha clavipes* (Diptera).

4.5.2

Spring flora

Springs often support a diverse vegetative community that occupies both aquatic and riparian habitats. Aquatic vegetation includes flowering plants, mosses, liverworts, and large algal species collectively referred to as macrophytes. Macrophytes are commonly classified as floating, emergent, or submerged based on growth habits. They are usually found in both lotic and lentic habitats but generally obtain their greatest diversity and density in lentic habitats. Riparian vegetation occupies the streambank and portions of the floodplain periodically inundated by floods. This includes both woody and herbaceous plants. Both aquatic vegetation and riparian vegetation washed into the stream as detritus are important for providing energy and habitat heterogeneity to aquatic ecosystems, among other aspects. This is especially true in headwater habitats where inputs of coarse particulate matter (such as woody debris, leaves, and aquatic macrophytes) are often greatest (Vannote and others, 1980).

Much of the energy that drives aquatic foodwebs is derived from aquatic and terrestrial vegetation. This vegetation serve as a source of non-living organic matter that is broken down by microorganisms (bacteria and fungi) into particulate and dissolved organic matter. As this matter is broken down, energy is released and made available to higher trophic levels. Aquatic and terrestrial vegetation washed into streams also provides shelter and foraging opportunities for macroinvertebrate and fish species. In general, greater diversity of vegetation and detritus in an aquatic ecosystem results in a more complex habitat, which, in turn, means more niches available for aquatic organisms to occupy. Greater diversity in aquatic macrophytes often results in greater diversity of fish and macroinvertebrate species.

The floral community of springs issuing from the Carrizo-Wilcox and associated aquifers is perhaps the most unique aspect of these habitats. Much like the fauna associated with spring habitats, the floral community generally includes both rare and endemic species restricted to spring-influenced waters as well as common species with a broader distribution. Many of these species are disjunct from other populations or are at the geographic limit of their range. For example, *Symphyotricum puniceum* var. *scabricaule* (rough-stemmed aster) is the southwesternmost member of its complex, with none of its close relatives occurring in Texas. It is only known from eight counties in Texas where it occupies deep muck stream valley bogs (Bridges and Singhurst, 2007).

4.5.3

Spring habitats

Springs are among the most structurally complicated, ecologically and biologically diverse, productive, evolutionarily provocative, and threatened ecosystems on earth (Danielopol, 1989; Williams and Danks, 1991; Bowles and Arsuffi, 1993; Stevens and Meretsky, 2008). They are transitional habitats that represent the interface between groundwater and surface water habitats. The myriad of habitats supported by springs ranges from apparent isolated springs that form the headwaters of streams or wetlands, such as hillside seeps, bogs, and fens, to discrete springs that emerge subaqueously in river and stream bottoms.

In their zonation scheme for running waters, Illies and Botosaneanu (1963) recognized the distinctiveness of spring habitats and the organisms that inhabit them and termed the spring-fed headwaters as crenal. Crenal habitats were further divided into the eucrenal for spring sources and the hypocrenal for springbrooks, or spring runs. The boundary of the eucrenal zone with the hypocrenal zone is generally defined as the point where the annual variation in water temperature does not exceed 2°C (Illies and Botosaneanu, 1963; Erman and Erman, 1984). The distance over which this change occurs varies depending on the volume of flow, the shape of the spring run channel, the degree of shading by riparian vegetation, and the prevailing ambient air temperature, among other factors.

The extent and type of habitat formed at a particular spring is directly related to the quantity and persistence of water it discharges. Spring sources are generally recognized as being one of three types: rheocrenes, limnocrenes, or helocrenes (Illies and Botosaneanu, 1963; Hynes, 1970). Rheocrenes are springs that emerge as running water or lotic ecosystems and are commonly referred to as springbrooks or spring runs. Limnocrenes are springs that emerge to form ponds or lakes, which generally then outflow to form a stream. Helocrenes are marshy areas formed by springs that generally emerge as diffuse seepage. All three of these habitat types exist at outflows of the Carrizo-Wilcox Aquifer. However, this classification system for headwater spring habitats does not address alluvial springs that emerge from streambanks and into stream and river bottoms. These springs are a vital component of the groundwater-surface water interactions that occur with the Carrizo-Wilcox and associated aquifers. Following is a brief description of selected springs issuing from the Carrizo-Wilcox and associated aquifers that represent these habitat types.

4.5.3.1
Streams (Rheocrenes)

A majority of the research performed on springs in Texas and, in general, has concentrated on rheocrenes. Rheocrenes are generally characterized by a relatively constant flow regime, clear water, and stable substrate conducive to establishing a well-developed hydrophyte community (Ward, 1992). As mentioned previously, sandy springs often lack a well-developed hydrophyte community; their major source of energy is derived from terrestrial vegetation; and they rarely emerge from an apparent orifice to form a flowing stream. They are often better described as a series of seeps that coalesce to form a flowing stream. However, true rheocrene springs that issue from a relatively large, single orifice do exist. Gibson (2000) offered the following descriptions of several rheocrenes:

> Edie's Spring is located in Leon County, three miles north of Flynn off State Highway 39. Water trapped by an impermeable layer of clay is forced up through coarse sand forming a large tunnel with an average depth of four feet and width of three feet. The tunnel walls are formed by loosely packed sand and the bottom is clay. This large permanent spring bubbles up out of Sparta sand forming a shallow pool and flowing into the beginnings of a small, fast flowing, shallow, sandy creek. This creek widens and deepens as the banks are cut deeper further downstream with the added flow of another much smaller spring and several small seeps. The pH (6.2) and dissolved

oxygen (7.3 mg/l) are moderate with the conductivity (52.8 µS) being relatively low.

Red Moore Spring is located in Wood County, one mile north of West Mineola. This spring, issuing from Queen City sand, emerges from under a soft sandstone deposit, eroding back into this formation. This spring is the beginning of a large, fast flowing, sandy creek with a moderate allochthonous material component and little iron flocculate. The conductivity (53.3 µS) is low and the dissolved oxygen (14 mg/l) is high and the pH (7.02) is neutral. The richness (of invertebrate taxa) here is high due to the size of this spring. Fauna such as Baetidae and Coleoptera, which often occur in temporary pools, large streams, and lakes, are found here because of the permanence and large size of the many pools and backwaters.

Tonkawa Springs is located in Nacogdoches County, seven miles southeast of Mount Enterprise off State Highway 1087. This spring, issuing from Queen City sand, emerges from a sandstone cave eroded by the flow of the spring itself. This is the largest spring sampled with a flow of 11 liters/second in 1978, and is perhaps the largest sandy spring that still exists in Texas. Chemical analysis at the springhead showed the temperature (18°C), pH (4.4), and dissolved oxygen (5.6 mg/l) to be relatively low, with the conductivity (109.3 µS) to be moderate. The flow outside the cave is channeled within cement walls and fills a manmade pond. This spring, once used as a mill, has been dammed since before the Civil War. It has also been, and now is in the process of being extensively used as a resource for bottled water. Changes made to increase the flow have resulted in erosion further into the sandstone extending the length of the cave and speeding up the inevitable collapse of this formation. Large amounts of sand pushed out of the spring are slowly inching down the channel like a glacier. The depth of the water emerging from the cave is about two feet, which then doubles about 40 feet down the channel at the end of this migrating sand bank. Large filamentous algae blooms were observed from this point in the channel continuing downstream and filling up the pond. The pond reaches depths up to 15 feet and probably averages near 7 feet. The overflow of the dam produced a more typical sand spring habitat forming a large, shallow stream winding through piney woods. This stream had large amounts of allochthonous material and some small areas of iron flocculate. The temperature (23.1° C), conductivity (93.9 µS) and dissolved oxygen (6.6 mg/l) were all found to be moderate here, with pH (4.78) still relatively low.

4.5.3.2
Hillside seeps and bogs (Helocrene)

Wetland habitats supported by springs, such as hillside seeps and bogs, are perhaps the most biologically diverse of the spring habitats found at outflows of the Carrizo-Wilcox and associated aquifers. Among the most unique and specialized natural communities of the Post Oak Savanna Ecoregion of Texas are the hillside seepage slopes and deep muck bogs (Sphagnum-Beakrush series; East Texas Bogs) (Bridges and Singhurst, 2007). These communities are permanently saturated by diffuse groundwater seepage from the adjacent upslope sandhill savannas. They support very diverse and restricted assemblages of plant species, many of which are at their western range limits and in some cases disjunct from populations much farther north or east.

Despite their biodiversity value, very few studies have examined the ecological or botanical significance of these communities. Most studies have focused on only one or a few sites each (Rowell, 1949a, 1949b; Kral, 1955; Starbuck, 1984; MacRoberts and MacRoberts, 1998; Singhurst and others, 2003). There has been no systematic overview of these communities as to their geographic range, variation over this range, and the effect of differences in seepage hydrology on the composition of the plant community. Data gathered by Bridges and Singhurst (2007) indicate there is a strong case for recognizing these communities as distinct from the hillside seepage slopes of southeastern Texas and southwestern Louisiana. Such a distinction results in the definition of a community type alliance, which is endemic to the Post Oak Savanna Ecoregion of Texas and, consequently, a high priority for inventory and protection in the state (Bridges and Singhurst, 2007).

Bogs and seepage slopes are most common in the Northern and Central Post Oak Ecoregion areas. Within the Northern Post Oak Ecoregion, the highest concentration of sites are in Henderson and Anderson counties, with perhaps the greatest concentration of extant sites occurring on the Queen City Sand Formation between Athens and Cayuga. A second concentration is in the Central Post Oak Ecoregion in Leon and southern Freestone counties, mostly on the Sparta Sand and Queen City Sand formations. There are probably more extant bog and seepage slope sites in Leon County than in any other county in the Post Oak Ecoregion, and they are distributed through most of the county rather than being concentrated in a narrow band. However, even in Leon County, intact or well-developed examples of bogs and seepage slopes are still very rare (Bridges and Singhurst, 2007).

In the southern Post Oak Ecoregion, bogs and seepage slopes become increasingly rare and more restricted to specialized geologic and hydrologic situations. Only a few sites are known in Robertson, Milam, Burleson, Bastrop, and Lee counties. Sites in Gonzales and Guadalupe counties represent a unique community type in a naturally rare geologic context, and it is very unlikely that many more examples of this type exist. The small seepage sites in Wilson County may represent the extreme southwestern limit of Coastal Plain deep sand seepage-influence on natural community composition. It is likely that seepage from the surficial sandy aquifers is not constant enough or strong enough to support seepage-dependent wetland plants in the increasingly arid climate, except in a few isolated situations. If areas of stronger seepage influence were found south and west of this region, they would be highly significant and very rare.

Many of these bogs have been destroyed by mining activity, impoundments, drainage, overgrazing, and competition by invasive or exotic species. Very few examples of these communities are permanently protected, with only 248 acres of this community series statewide on state-owned conservation lands. Bridges and Singhurst (2007) estimate that bogs and seepage slopes represent only a small fraction of 1 percent of the total land area in the Post Oak Ecoregion. Despite their limited distribution, these habitats represent a significant feature of the biodiversity of the Post Oak Savanna Ecoregion as they contain a high proportion of plant species that are either rare in general (*Symphyotrichum puniceum* var. *scabricaule* [rough-stemmed aster], *Eriocaulon koernickianum* [small-headed pipewort], and *Xyris chapmanii* [Chapman's yellow-eyed grass]); rare in Texas although common in other states (*Cladium mariscoides* [smooth sawgrass], *Cinna arundinacea* [sweet redwood], *Rhynchospora scirpoides* [longbeak beaksedge], and *Burmannia biflora* [northern bluethread]); or rare in the Post Oak Ecoregion but common in other regions of the state (*Lachnocaulon anceps* [whitehead bogbutton], *Aletris aurea* [golden colicroot], *Lycopodiella caroliniana* [slender clubmoss], *Magnolia virginiana* [sweetbay], *Paspalum monostchyum* [gulfdune paspalum], and *Rhynchospora nitens* [shortbeak beaksedge]).

4.5.3.3
Ponds (Limnocrenes)

Many spring-fed ponds exist as outflows of the Carrizo-Wilcox and associated aquifers. However, many of these are not natural features but manmade. The very nature of spring hydrology, being mostly permanent even in droughts, makes them a successful location for constructing small ponds. It has been quite common over the last several decades to dredge wetland areas, such as those described above, or convert small flowing springs to form ponds for agricultural or livestock uses. Gibson (2000) reported that most of the previously reported springs he visited no longer flowed and many of these had been converted to ponds.

When discussing spring-fed ponds, many think of small upland pasture ponds. However, they may include lakes, such as oxbow lakes, as well. Horseshoe Lake is a perennial oxbow lake associated with the Brazos River. The lake was determined to be largely disconnected from the Brazos River during summer months for the period 1984–2004. Through water chemistry and isotope analysis, the origin of water to the lake was determined to be hyporheic upwelling or groundwater (Chowdhury, 2004; Osting and others, 2004). Furthermore, models predicted the oxbow was only connected to the river six times between 1940 and 2000. Thus, groundwater contributions are key to maintaining the perennial nature of this habitat and the organisms that inhabit it.

4.5.3.4
Base flow springs

Base flow is an important component of the natural flow regime in many streams that represents the contribution of groundwater to gaining reaches of a stream or river. When runoff from storm events has drained away, the natural surface water flow that continues often represents base flow contributions from groundwater. Streams can have an intermittent or perennial base flow component. In general, surface water bodies with relatively thick unsaturated zones in arid areas, such as the southern Carrizo-Wilcox, lose water, and surface water bodies in humid areas, such as the northern Carrizo-Wilcox, are more typically gaining (Scanlon and others, 2002). Because base flow contributions represent a significant portion of the natural flow regime in many of our state's major rivers, it is important to identify those sections of rivers that interact with groundwater.

Two methods are commonly used to characterize the interaction of surface water and groundwater in streams: gain/loss studies and base flow separation. Gain/loss studies involve the manual measurement of streamflow at various locations along the length of a stream. Streamflow gains and losses are then identified by comparing the streamflow values measured at a given location to those measured at the next downstream location. Base flow separation is a standard technique applied to historical streamflow data that provides an estimate of groundwater discharge. Both of these methods can provide an estimate of gains or losses to streamflow from a particular aquifer outcrop if the spatial resolution is sufficient.

In many cases, alluvial deposits act as a transition zone or aquifer that conveys water between larger, regional aquifers and streams. For example, groundwater in the bedrock Carrizo-Wilcox Aquifer moves into the Quaternary alluvial deposits that floor the valleys of the Colorado, Brazos, and Trinity rivers (Dutton and others, 2003).

Numerous low-flow studies have been performed on streams that cross the outcrops of the Carrizo-Wilcox and associated aquifers. Slade (2002) compiled information on a total of 47 studies that identified reaches of streams and rivers gaining or losing water from the Carrizo-Wilcox Aquifer. Streams identified as gaining water as they cross the Carrizo-Wilcox outcrop include the Colorado River, Leona River, Cibolo Creek, West Bowles Creek, Little Cypress Creek, and the Sabine River, among others.

In many cases where base flow springs exist, springs and seeps issue from alluvial and terrace deposits on the banks. This is the case with Bastrop Springs along the Colorado River and Sutherland Springs along Cibolo Creek. Bastrop Springs issues from terrace deposits on the northeast bank of the Colorado River. These springs have been altered to some extent by human activity as they are located adjacent to the town square. It is likely the springs once formed a bog or other wetland habitat, but they now form small pools. The Colorado River in this area has been recognized as a gaining section for many years.

In 1918, the flow of the Colorado River increased from about 61 to 97 cubic feet per second, an increase of 59 percent, as the river crossed the outcrop of the Carrizo-Wilcox Aquifer. Flow at the Smithville gage during this period was 101 cubic feet per second. That flow rate is exceeded 99.9 percent of the time at the Smithville gage (Dutton and others, 2003), indicating that this section of the Colorado River has been a gaining reach across the outcrop of the Carrizo-Wilcox Aquifer even during times of extreme drought.

Another example of base flow springs occurs along Cibolo Creek as it crosses the outcrop of the Carrizo-Wilcox Aquifer at Sutherland Springs. Sutherland Springs is composed of numerous springs, including White, Sulphur, Cold, Sour, and Alligator springs, which issue from the Carrizo Sands (Brune, 1981). Historically, the springs were much used by the Coahuiltecan Indians, served as a stop on the Chihuahua Road, and had the old town of Sutherland Springs built around them. Sutherland Springs, Texas, was a resort town billed as the "most beautiful spot in Texas" with the "largest group of mineral springs in America." In the mid to late 1800s, the springs, reportedly with 27 flavors, were known for their medicinal qualities and supported a resort community (Brune, 1981). Like many springs in Texas, Sutherland Springs have been severely altered over the last 100 years by a variety of human and natural activities, including increased use demands placed on aquifers and surface waters by an increasing population and siltation caused by flooding.

Approximately nine springs were observed during a reconnaissance trip to Cibolo Creek at Sutherland Springs on March 15, 2005, when groundcover was moderate. Springs observed along the banks of Cibolo Creek at Sutherland Springs were primarily seeps emerging from holes in the steep, muddy bank. Spring orifices were much more difficult to locate during a return visit on May 31, 2005, as ground cover was dense and covered many of the spring orifices. Among the springs observed on March 15, 2005, was a sulphur spring that once provided flow to what was billed as the "largest sulphur bathing pool in America." Alterations to this spring are evident and dramatic. In 1913, the creek reportedly flooded over its banks and filled the spring-fed pools with mud. The stone wall and dam that formed the pool are now buried below mud and flood debris, and the spring has been reduced to a trickle that supports a small, shallow pool. Based on these observations, it appears as though sedimentation from flood events may have contributed to reduced springflows by filling spring orifices.

Gains and losses in the flow of Cibolo Creek have been addressed by several studies (Holland and Welborn, 1965; Reeves and Kunze, 1970; Buzan, 1982) and provide some insight to flows derived from Sutherland Springs. Holland and Welborn (1965) identified areas of gain and loss along Cibolo Creek and offered probable sources of input. According to their measurements, most of the base flow of Cibolo Creek at its mouth was derived from about a 20-mile stretch that encompasses Sutherland Springs, the Carrizo Aquifer outcrop, and numerous faults that transect Cibolo Creek. The maximum flow measured by Holland and Wellborn (1965) was 18.2 cubic feet per second, and the Carrizo Sand was identified as the source of most of this water. The results of Holland and Wellborn (1965) were generally confirmed by Reeves and Kunze (1970) despite differing antecedent rainfall. Reeves and Kunze (1970) measured a net streamflow gain of 8.6 cubic feet per second over approximately 8.5 river miles as Cibolo Creek transects the Carrizo Sand outcrop in the vicinity of Sutherland Springs. Rainfall in the months preceding the measurements of Reeves and Kunze (1970) was above average, so some portion of the gain in streamflow is likely attributable to increased base flow from bank storage. However, a recent study initiated by the U.S. Geological Survey has confirmed that Cibolo Creek near Sutherland Springs gains water but has also shown even more substantial gains in streamflow from the downstream Gulf Coast Aquifer (Darwin Ockerman, personal communication, 2009).

4.6

DISCUSSION

Despite the interconnected nature of surface and groundwater, Texas water law treats the two separately and offers no protection for spring habitats. Surface water is publicly owned and governed by the "prior appropriation" doctrine. It can only be used with permission of the Texas Commission on Environmental Quality under provisions of the Texas Water Code. In contrast to surface water, groundwater in Texas is governed by the rule of capture, except in those areas where management is accomplished through local groundwater conservation districts. All confirmed groundwater conservation districts in Texas are required to develop and implement a management plan and rules for managing their groundwater resources, which may include modifying or eliminating the rule of capture. Most groundwater conservation districts require new wells to be registered and keep records of the production and use of groundwater, and they may also make and enforce rules to conserve, protect, and recharge groundwater. Such rules may include limiting production based on tract size or the spacing of wells. Some groundwater conservation districts have developed management plans and rules that protect springflow (for example, Barton Springs/Edwards Aquifer Conservation District).

In Texas' regional and state water planning, management goals for aquifers in different areas of the state range from sustainability to eventual (planned) depletion (TWDB, 2007). However, the definition of sustainability can be elusive (Devlin and Sophocleous, 2005). Potential environmental impacts from these various management strategies are difficult to predict. When a well is pumped, the water comes from various proportions of captured recharge, captured discharge (seeps and springs), and storage depletion. Although the relative volumes from these three sources is highly site specific and varies with time, "it is usually the groundwater discharge that is captured during groundwater development" (Bredehoft, 2007). Alterations to surface flows due to groundwater pumping can have serious impacts to aquatic and aquatic-dependent habitats by reducing instream habitat diversity and availability, altering trophic and community structure, reducing assimilative capacity and water quality characteristics, and reducing overall stream productivity (Annear and others, 2002). Additional research related to the impacts of groundwater pumping on surface water resources and ecosystems is needed to promote sound management as population and water demands grow. When such information is available, groundwater conservation districts have the authority to manage for the protection of springflows, and some already do so.

As mentioned previously, the use of groundwater resources results in the withdrawal of groundwater from storage, a reduction in natural discharge, and an increase in recharge. The effects of declining groundwater levels and subsequent reduced springflows on surface water flow could greatly affect the availability of surface water supplies since springflows often compose a significant proportion of streamflow. Feliciano (1985) estimated that approximately 30 percent of the nation's surface water flow is provided by groundwater. More locally, a recent streamflow gain/loss study concluded that "appreciable increases in streamflow, apparently the result of increases in base flow, occur in the reach of the Brazos River that crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers" (Turco and others, 2007). If broken down by season, it is likely groundwater accounts for a much more significant proportion of surface flow during drier summer months, as springflows often sustain base flows. Although recognizing that springflows had declined considerably, Brune (1981) estimated the total flow of Texas' springs to be in excess of 4,132 cubic feet per second, or almost 3 million acre-feet per year. This volume of water equals about 33 percent of the estimated 9 million acre-feet per year of total surface water available for use in 2010 (TWDB, 2007) and constitutes a significant contribution to the surface water supplies of the state. Because surface water availability analysis in Texas is generally based on historical streamflows, groundwater pumping may reduce the historical groundwater contribution to streams and effectively reduce actual streamflows to levels below that predicted (TNRCC, 1995). During extended drought conditions, this could have a significant impact on the availability of surface water for municipal, industrial, agricultural, and other uses.

4.7
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Chapter 5

Hydrogeology of the Queen City and Sparta Aquifers with an Emphasis on Regional Mechanisms of Discharge

Van Kelley[1], Dennis Fryar[1], and Neil E. Deeds[1]

The Queen City and Sparta aquifers are classified as minor aquifers in Texas (Ashworth and Hopkins, 1995). Groundwater use for the Queen City and Sparta aquifers is relatively minor, with reported water uses of 16,000 and 10,000 acre-feet per year in 2003, respectively (TWDB, 2007). However, these two minor aquifers are important water resources in the state, with groundwater availability estimates of 300,000 acre-feet per year for the Queen City Aquifer and 51,000 acre-feet per year for the Sparta Aquifer under drought conditions in the year 2000 (TWDB, 2007). These aquifers extend from the Frio River in South Texas to East Texas, with the Sparta Aquifer continuing into Louisiana and Arkansas (Figure 5-1). The Queen City Aquifer provides water to all or parts of 42 Texas counties and is used primarily for livestock and domestic purposes, with significant municipal and industrial use in northeast Texas (Ashworth and Hopkins, 1995). The Sparta Aquifer provides water to all or parts of 25 Texas counties and is used for livestock and domestic needs along its extent, with some municipal, industrial, and irrigation uses locally (Ashworth and Hopkins, 1995).

Pumping from the Queen City and Sparta aquifers to date has been generally low as evidenced by relatively stable groundwater levels. However, development has been significant in select locales, resulting in significant drawdown in these areas. In these regions, impacts of the high pumping include decreased groundwater storage, decreased stream base flow, decreased springflow, and decreased shallow groundwater evapotranspiration. Cross-formational flow would also be altered in response to the localized high pumping.

This chapter will review the hydrogeologic characteristics of the Queen City and Sparta aquifers. The chapter will end with an emphasis on a review of the recharge-discharge mechanisms in the two aquifers and their significance and relation to future aquifer development.

5.1
SETTING

The Queen City and Sparta aquifers are classified as minor aquifers in Texas (Ashworth and Hopkins, 1995). They are composed of sediments of the Tertiary Claiborne Group, which extend from South Texas northeastward through East Texas. Figure 5-1 shows the surface outcrop and downdip subcrop of the Queen City and Sparta aquifers as defined by the Texas Water Development Board (TWDB). The outcrop areas of the Queen City and Sparta aquifers lie between the Carrizo-Wilcox Aquifer and the Yegua-Jackson Aquifer in a band subparallel to the Gulf Coast from South Texas to East Texas. The outcrop area of the Sparta Aquifer occurs in isolated locations in the East Texas Basin. The Queen City and Sparta aquifers are not recognized southwest of the Frio River because of generally poor water quality. However, these aquifers do exist west of the Frio and to the Rio Grande and were included in the state groundwater availability models completed in 2004 (Kelley and others, 2004). The

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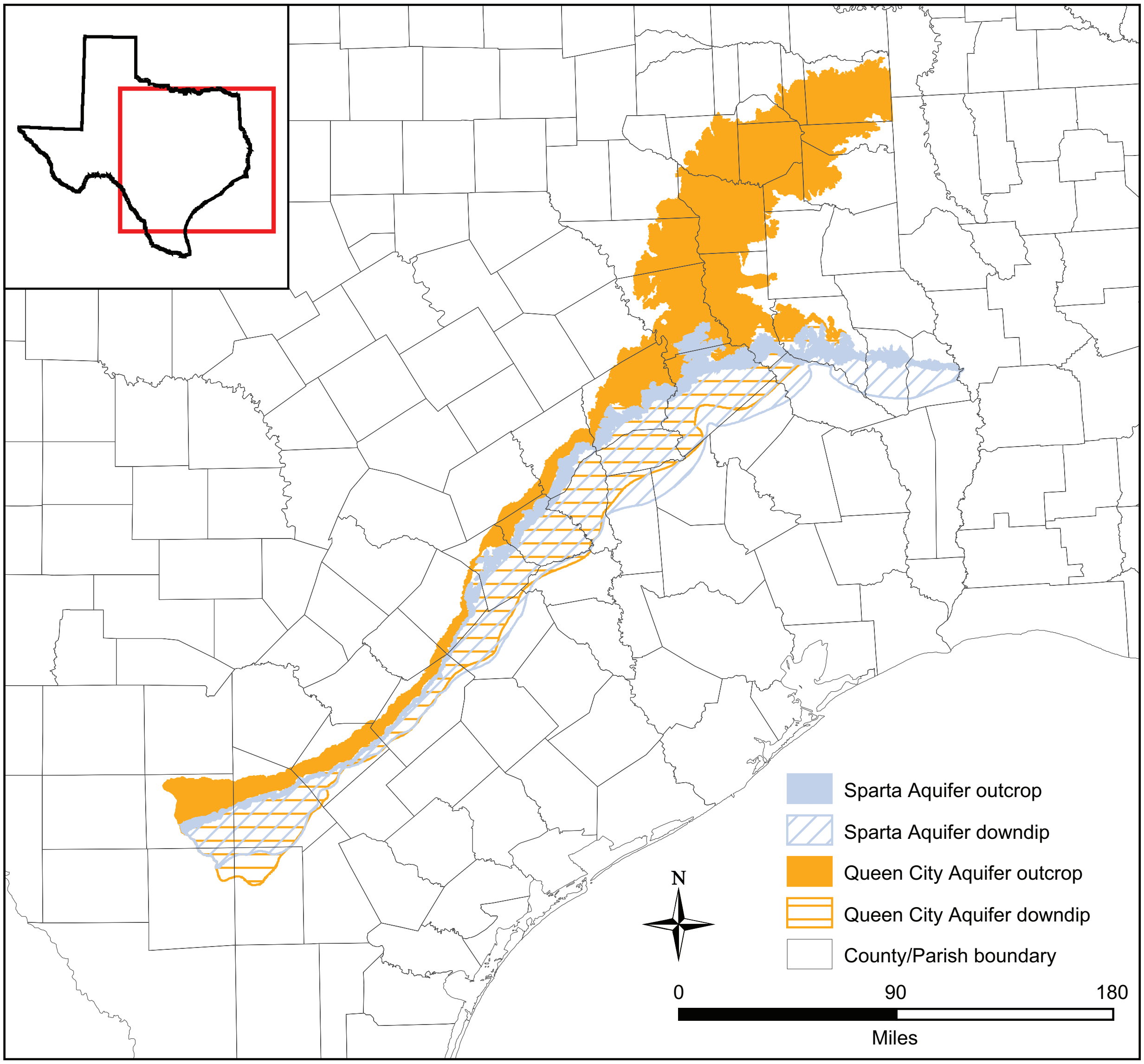

Figure 5-1. Outcrop and subcrop of Queen City and Sparta aquifers.

Sparta Aquifer continues to the east of Texas into Louisiana and Mississippi, whereas the Queen City loses productivity and is generally not recognized east of Texas. This paper will focus on these aquifers in Texas and east to the Red River in southwestern Arkansas and western Louisiana.

The Queen City and Sparta aquifers are located within the Interior Coastal Plains subprovince of the Gulf Coastal Plains physiographic province (Wermund, 1996). The Interior Coastal Plains comprise alternating sequences of unconsolidated sands and clays. The sands tend to be more resistant to erosion than the clay-rich soils and, as a result, the province is characterized as having sand ridges paralleling the coast. Figure 5-2 provides a topographic map that includes the outcrop of the aquifers. Generally, the study area is characterized as having low relief, with ground surface elevations gently decreasing from the southwest to the northeast and southeast. Ground surface elevation varies from over 800 feet above sea level in the far western portion of the study area to less than 100 feet above sea level in river valleys and in the southeastern-most regions of the

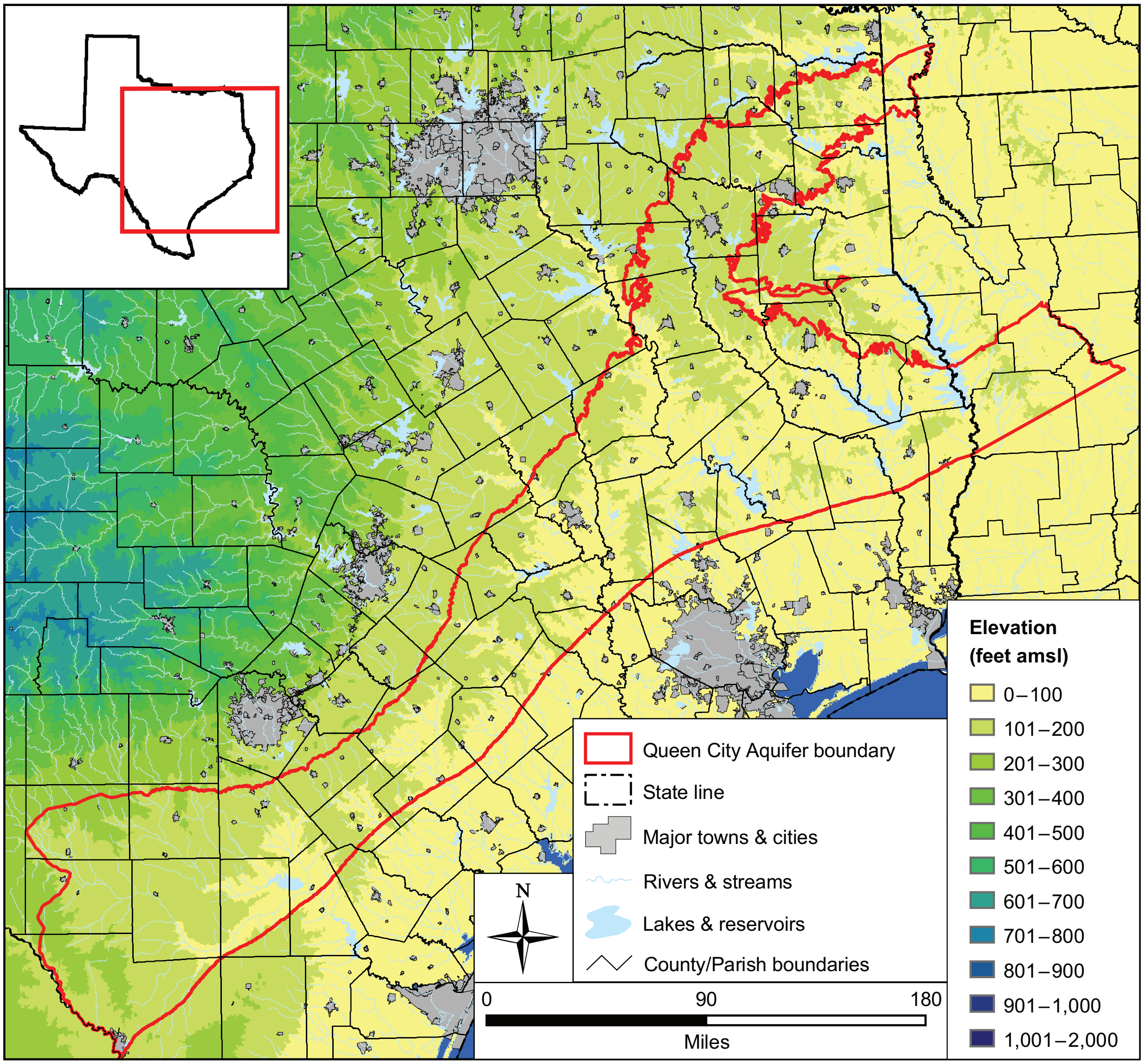

Figure 5-2. Topographic map of the study area.
amsl = above mean sea level

study area. The gentle gulfward decrease in ground surface elevation is interrupted by resistant Tertiary sandstone outcrops. River valleys are broadly incised with terraced valleys hundreds of feet lower than the surface basin divide elevations.

The study area is characterized by pine and hardwood forests in the northeast, with a dense network of perennial streams. The density of trees in the study area decreases from the north to the south and south of San Antonio, where the landscape is dominated by chaparral brush and grasses (Wermund, 1996). The study area resides in the cool portion of the Temperate Zone of the Northern hemisphere and intersects two climatic zones in Texas: the Subtropical Humid division and the Subtropical Subhumid division (Larkin and Bomar, 1983). Most of the study area has a Modified Marine climate termed Subtropical, which is dominated by the onshore flow of humid tropical air from the Gulf of Mexico. The amount of moisture decreases as it flows from the east to the west and as continental air masses intrude from the north, resulting in the climate subdivisions of humid, semihumid, and semiarid. The Subtropical Humid climate zone extends from the Texas/Louisiana border in the northeastern part of the study area to approximately Guadalupe and Wilson counties to the southwest. This climate is characterized as having warm summers and mild winters. The Subtropical Subhumid climate zone exists between Guadalupe and Wilson counties and Zavala and Dimmit counties in the southern study area. This climate zone is characterized as having hot summers and dry winters.

Precipitation is greatest in the northeast, and historical averages range from a low of 20.9 inches at Eagle Pass to a high of 59.9 inches in Jasper County. Generally, the average annual precipitation decreases from the east to the west. In the northern half of the study area, precipitation also increases with proximity to the coast. The average annual net pan evaporation depth in the aquifer outcrop area ranges from a low of 38.3 inches per year in the far northeast portion of the study area to a high of 65.9 inches per year in the southwest. In general, the pan evaporation rate exceeds the annual average rainfall. Annual rainfall exceeds the pan evaporation rate in limited portions of the study area in far northeastern Texas, contrasting with the greatest rainfall deficits with regard to the net evaporation rate occurring in the far southwestern portions of the aquifer system.

5.2
GEOLOGY

The sediments that form the Queen City and Sparta aquifers in Texas are part of a gulfward thickening wedge of Cenozoic sediments deposited in the Rio Grande Embayment and Houston Embayment of the northwest Gulf Coast Basin. Deposition has been influenced by regional crust subsidence, episodes of sediment inflow from areas outside of the Gulf Coastal Plain, and eustatic sea level change (Grubb, 1997). Galloway and others (1994) characterized Cenozoic sequences in the Gulf Coast in the following three ways: (1) Deposition of Cenozoic sequences is characterized as an offlapping progression of successive, basinward thickening wedges. (2) These depositional wedges aggraded the continental platform and prograded the shelf margin and continental slope from the Cretaceous shelf edge to the current Texas coastline. (3) Deposition occurred along sand-rich, continental margin deltaic depocenters within embayments (Rio Grande, Houston, and Mississippi embayments) and was modified by growth faults and salt dome development. The primary Paleogene depositional sequences in ascending stratigraphic order are the Lower Wilcox, the Upper Wilcox, the Carrizo, the Queen City, the Sparta, the Yegua-Cockfield, the Jackson, and the Vicksburg-Frio (Galloway and others, 1994). Each of these depositional sequences is bounded by marine shales and finer-grained sediments representing transgressions (for example, the Reklaw and Weches formations).

Figure 5-3 shows a generalized stratigraphic section for the study area. The Recklaw Formation, composed of marine clays deposited in a major marine transgression, represents the base of the Queen City Aquifer. The Queen City, Weches, and Sparta formations overlie the Reklaw and Carrizo formations and the Wilcox Group. The Queen City Formation is composed of several fluvio-deltaic depositional systems. In the northern study area, the Queen City Formation was deposited as part of a high-constructive, lobate delta system (Guevara and Garcia, 1972). The deltaic sands of the Queen City Formation thin toward the southeastern portion of the study area near the Texas/Louisiana line. In south-central Texas (western Fayette to Wilson County), the dominant depositional facies for the Queen City Formation is the stand-plain facies, which is characterized as having strike-oriented sand trends (Guevara and Garcia, 1972). In South Texas, the Queen City Formation was deposited as part of a

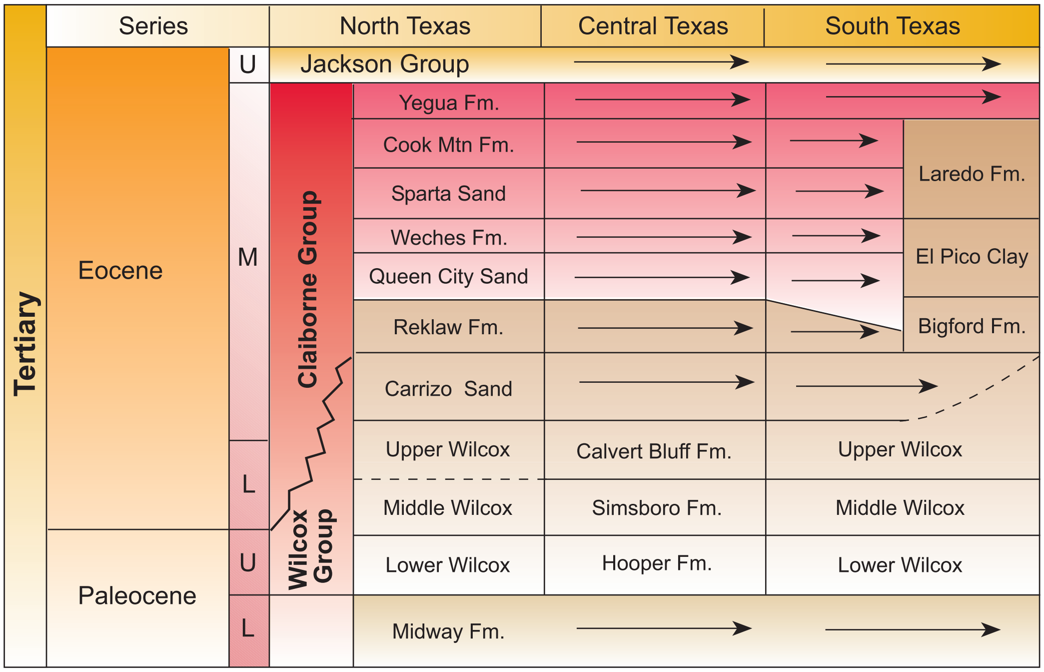

Figure 5-3. Generalized stratigraphic section for the Wilcox and Claiborne groups in Texas (after Ayers and Lewis, 1985; Hamlin, 1988; Kaiser, 1978; Ricoy and Brown, 1977; Guevara and Garcia, 1972; and Payne, 1968).
Fm = formation

high-destructive, wave-dominated delta system (Guevara and Garcia, 1972). The Queen City sands thicken in the western part of the study area and extend southward into Mexico along the Rio Grande Embayment. West of the Frio River, the Reklaw thins significantly and is equivalent to the base of the Bigford Formation. The Queen City Formation thickens and correlates to the Bigford Formation and the lower part of the El Pico Clay. The Bigford can be composed of up to 75 percent sands. West of the Frio River, the upper Queen City and the Weches formations become indistinguishable and interfinger with the clays of the El Pico Clay.

The Queen City Formation is overlain by the Weches Formation, a marine unit composed of glauconitic muds. This formation represents a marine transgression between Queen City and Sparta deposition. The Weches is a thin formation, generally less than 100 feet thick. West of the Frio River, the Weches Formation becomes indistinguishable from the underlying Queen City and is considered part of the El Pico Clay.

Overlying the Weches Formation is the Sparta Formation. Ricoy and Brown (1977) identified three principal depositional facies within the Sparta: (1) a high-constructive delta facies in East Texas, (2) a stand-plain/barrier bar facies in Central Texas, and (3) a high-destructive wave dominated deltaic facies in South Texas. The Sparta is very identifiable in Texas as a sand-rich unit overlain and underlain by marly marine transgressive units, the Cook Mountain and Weches formations, respectively. The sources of sand to the Sparta delta systems were primarily from East and South Texas, with the stand-plain facies being fed by longshore currents in Central Texas. The Sparta is significantly thicker east of the study area in Louisiana, Arkansas, and Mississippi and also thickens southwest of the study area in northeastern Mexico (Ricoy and Brown, 1977). The Sparta and overlying Cook Mountain grade into the Laredo Formation west of the Frio River.

5.3
AQUIFER STRUCTURE AND CHARACTER

The Rio Grande and Houston embayments, East Texas Embayment (sometimes referred to as the East Texas Basin), Sabine Uplift, and San Marcos Arch are the main structural features underlying the onshore part of the Gulf of Mexico Basin (Jackson, 1982; Galloway and others, 2000). Sediment input for the Queen City Formation was focused in the Rio Grande Embayment, whereas for the Sparta Formation the main sediment input was to the east in the central Mississippi axis (Galloway and others, 2000). The East Texas Embayment is one of the major sub-basins formed early in the Mesozoic, and it had significant thicknesses of halite deposition. Subsidence, tilting, and differential loading by Cenozoic sediments caused the displacement of halite beds and the formation of various salt-tectonic features such as salt ridges and salt diapirs or domes (Jackson, 1982). The Sabine Uplift, which lies at the eastern edge of the study area and extends into Louisiana, is a broad structural dome. Its topographic expression influenced sediment deposition in the East Texas Embayment during the Tertiary (Fogg and others, 1991). The San Marcos Arch is a structurally high basement feature beneath the central part of the Texas Coastal Plain, separating the East Texas and Rio Grande basins, areas that had greater rates of subsidence. The Queen City and Sparta formations drape over the San Marcos Arch.

As part of the development of the TWDB groundwater availability model for the Queen City and Sparta aquifers, Seay Nance (Jackson School of Geosciences) developed additional structural control and net sand picks for the Queen City and Sparta aquifers across Texas. Construction of structural contour surfaces of the Queen City and Sparta aquifers required compiling and digitizing structural information from a number of sources. Sources on subsurface structure included Payne (1968), Garcia (1972), Guevara and Garcia (1972), Guevara (1972), Ricoy (1976), Ricoy and Brown (1977), unpublished data from an East Texas groundwater model developed by TWDB, and data from the U.S. Geological Survey's Regional Aquifer-System Analysis (Wilson and Hossman, 1988). The groundwater availability model development effort used a subset of the original logs used from the work of Guevara (1972), Garcia (1972), and Ricoy (1976) to develop the structure. These were augmented by additional geophysical logs gathered at the Texas Commission on Environmental Quality Surface Casing Unit.

Figure 5-4 shows two structural cross sections in the study area. Cross section A-A' shows the Tertiary formations from the Wilcox Group through the Sparta Formation in East Texas. The primary structural features in the eastern part of the study area are the East Texas Basin, the Sabine Uplift, and the Houston Embayment. The Queen City Formation outcrops in the East Texas Basin (Figure 5-4). In portions of the East Texas Basin, the Weches and overlying Sparta formations are still present and confine the Queen City Formation. The Queen City, Weches, and Sparta formations are eroded and not present over the Sabine Uplift. South of the Sabine Uplift, these formations outcrop in a narrow band parallel to the present-day coastline. The entire Tertiary section steeply dips into the Gulf Coast Basin south of the Sabine Uplift and the East Texas Basin. Westward through Central and South Texas, the Queen City, Weches, and Sparta formations outcrop in a narrow band paralleling the present day coast and dipping strongly toward the Gulf Coast Basin. Cross section B-B' (Figure 5-4) is representative of Central and South Texas. The dip of the formations in the subsurface can reach 250 feet per mile in portions of South and Central Texas.

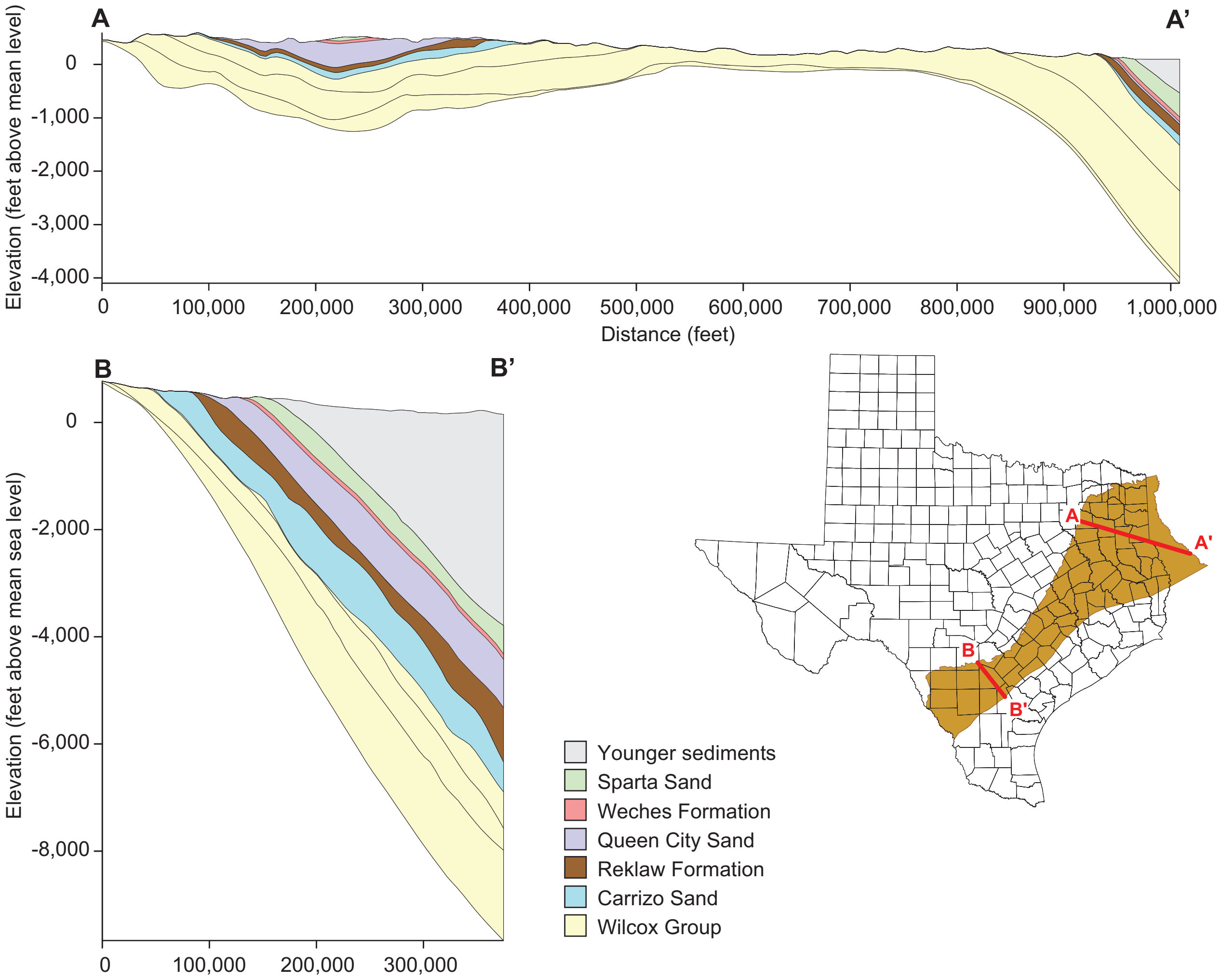

Figure 5-4. Generalized structural cross sections for the Queen City and Sparta aquifers (Kelley and others, 2004).

Figures 5-5 and 5-6 show the isopach surfaces for the Queen City and Sparta aquifers, respectively. The thickness of the Queen City Formation and its stratigraphic equivalents increases considerably from almost nothing at the Louisiana state line to more than 2,000 feet at the Mexican border (Figure 5-5). In East Texas and west of the Sabine Uplift along the East Texas Embayment, the Queen City Formation is in outcrop and is generally between 200 and 400 feet thick but locally reaches more than 500 feet in Smith County. The Queen City Formation as a deltaic sandy aquifer pinches out south of the Sabine Uplift where its stratigraphic equivalent is part of the marine Cane River Formation. Toward the southwest, the thickness gradually increases from about 400 feet in Leon County to about 800 feet in Wilson County. Further south, approaching the center of the Rio Grande Embayment, the thickness of the Queen City Formation increases dramatically to more than 1,200 feet and becomes more clayey, transitioning to its stratigraphic equivalent west of the Frio River, the El Pico Clay.

The thickness of the Weches Formation is generally under 100 feet and reaches more than 200 feet only in the deep confined sections of the aquifer system. In Louisiana and south of the Sabine Uplift, the stratigraphic equivalent of the Weches Formation is the Cane River Formation, which also includes the stratigraphic equivalent of the Queen City and

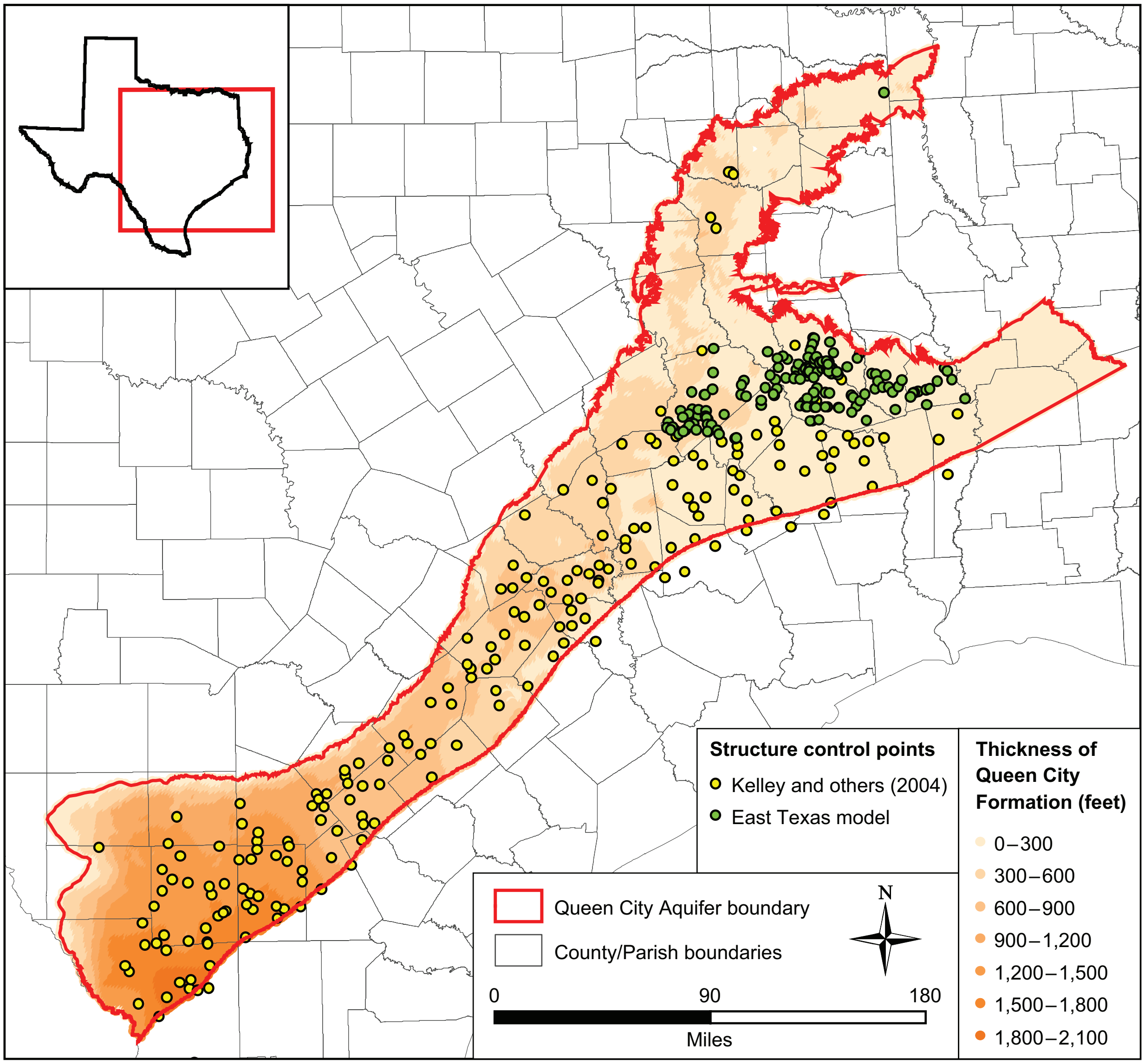

Figure 5-5. Thickness of Queen City Aquifer.

Reklaw formations. The thickness of the Sparta Formation varies gradually from more than 700 feet at the Red River in Louisiana to about 200 feet in the updip subsurface in South Texas (Figure 5-6). The thickness of the formation generally increases with depth and also varies locally along strike, correlating with the axes of the fluvio-deltaic deposition centers. In particular, the expression of the San Marcos Arch is visible in Gonzales County, with a local decrease in both the formation thickness and net sand thickness. West of the Frio River, the Sparta Formation merges into the Laredo Formation, which is the stratigraphic equivalent to the Cook Mountain Formation.

Figures 5-7 and 5-8 plot net sand maps for the Queen City and Sparta aquifers. These maps were developed and documented as part of the development efforts of the TWDB groundwater availability model (Kelley and others, 2004) and based upon maps published in Guevara and Garcia (1972) and Ricoy and Brown (1977), respectively, and the work of Payne (1968), Ricoy (1976), Garcia (1972), and

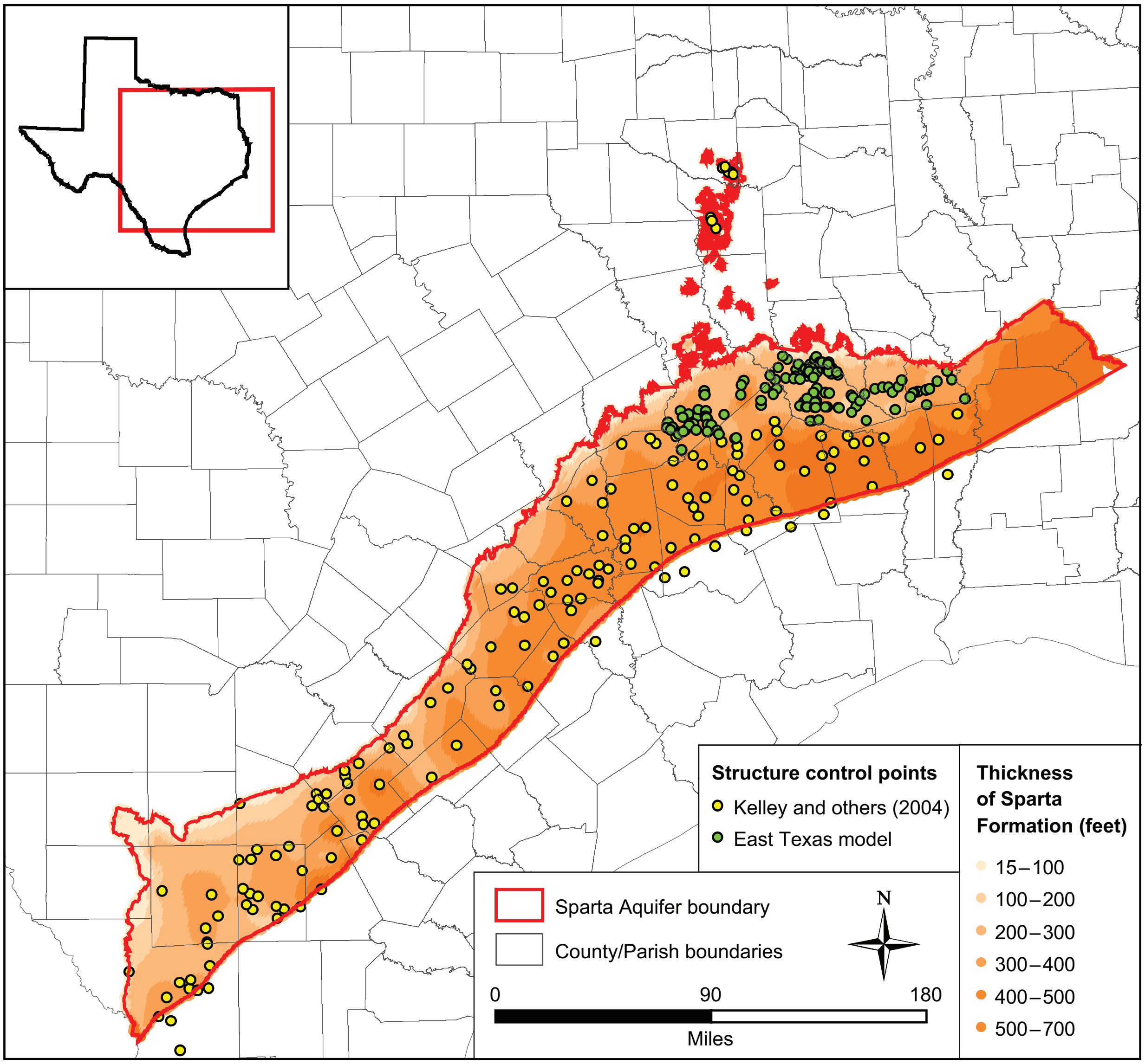

Figure 5-6. Thickness of the Sparta Aquifer.

Guevara (1972). Because of inadequate control, the Queen City Aquifer net sand isopach map (Figure 5-7) does not include areas within the outcrop, which are a significant portion of the East Texas Basin. For the same reasons, the Sparta net sand isopach map (Figure 5-8) does not include outcrop areas. Sand thicknesses decrease downdip moving away from sediment sources and from high-energy to low-energy depositional settings. The impact of the basement high of the San Marcos Arch is apparent in decreasing sand thickness of both the Queen City and Sparta formations. The Queen City Formation sand thickness in the updip subsurface varies from more than 250 feet in East Texas southwest of the Sabine Uplift to more than 1,000 feet in the Rio Grande Embayment.

The lobate complex shape of the contour lines, particularly in East and Central Texas, reflects the individual fluvial sand input centers. Slightly less lobate contour lines in South Texas suggest that the sediments were partially reworked and redistributed. The Sparta Formation sand thickness in the updip subsurface is

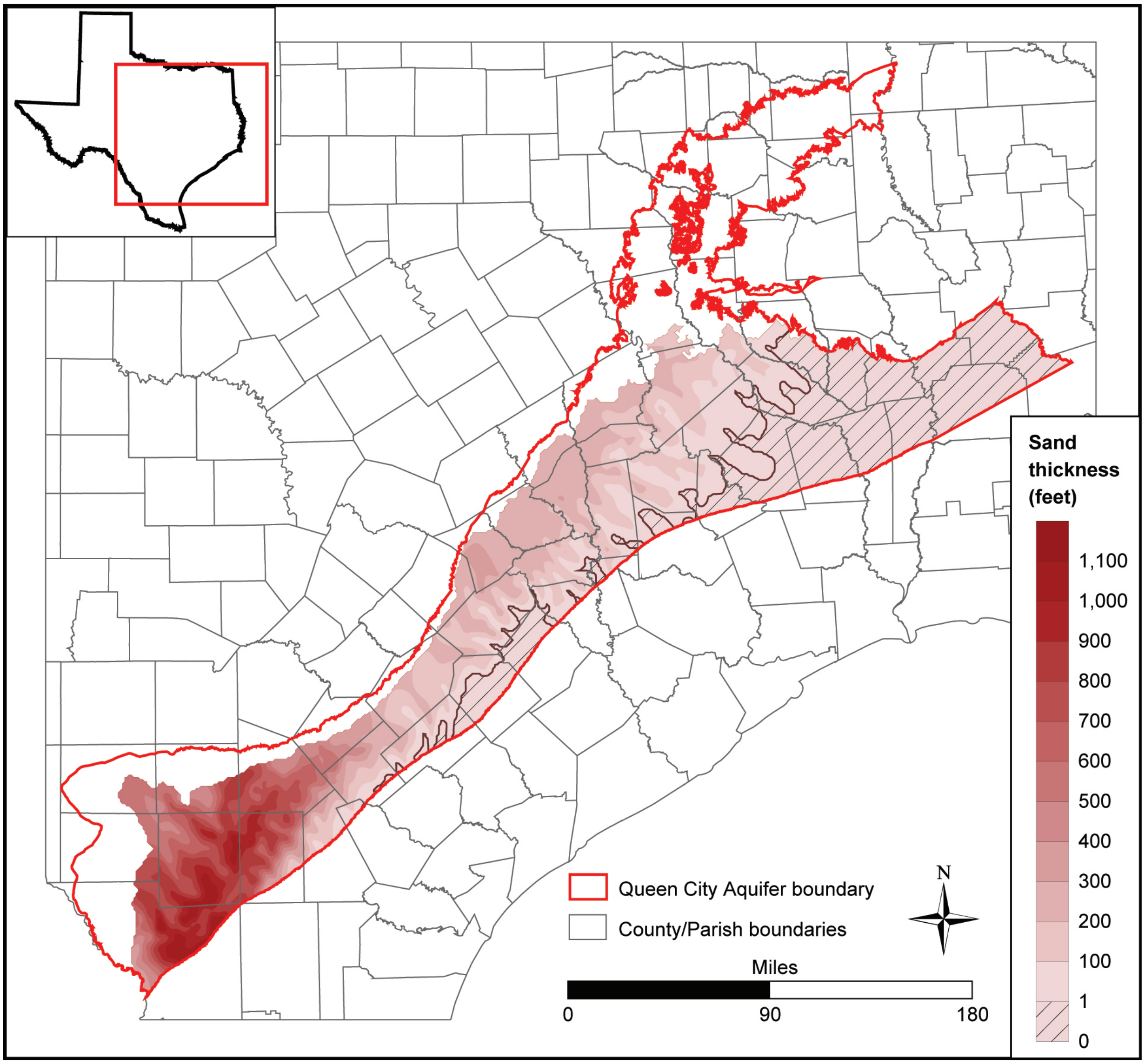

Figure 5-7. Queen City sand thickness (after Guevara and Garcia, 1972).

more constant throughout the study area at approximately 200 to 300 feet, with the influence of the San Marcos Arch in Wilson, Gonzales, and Fayette counties again manifested in a reduced sand thickness of about 100 feet. The contour lines show well-developed lobes on either side of the arch but are parallel to the formation strike at the arch location. This is explained by a lack of terrestrial sediment input during the time of the Sparta sedimentation on the San Marcos Arch and by lateral sediment transport along the coast of the ancestral Gulf of Mexico (Ricoy, 1976).

5.4
HYDRAULIC PROPERTIES

Relatively few aquifer pump tests have been performed in the Queen City and Sparta aquifers. Kelley and others (2004) performed a review of the available aquifer hydraulic properties for these aquifers. In support of the development of the TWDB groundwater availability model, specific capacity data

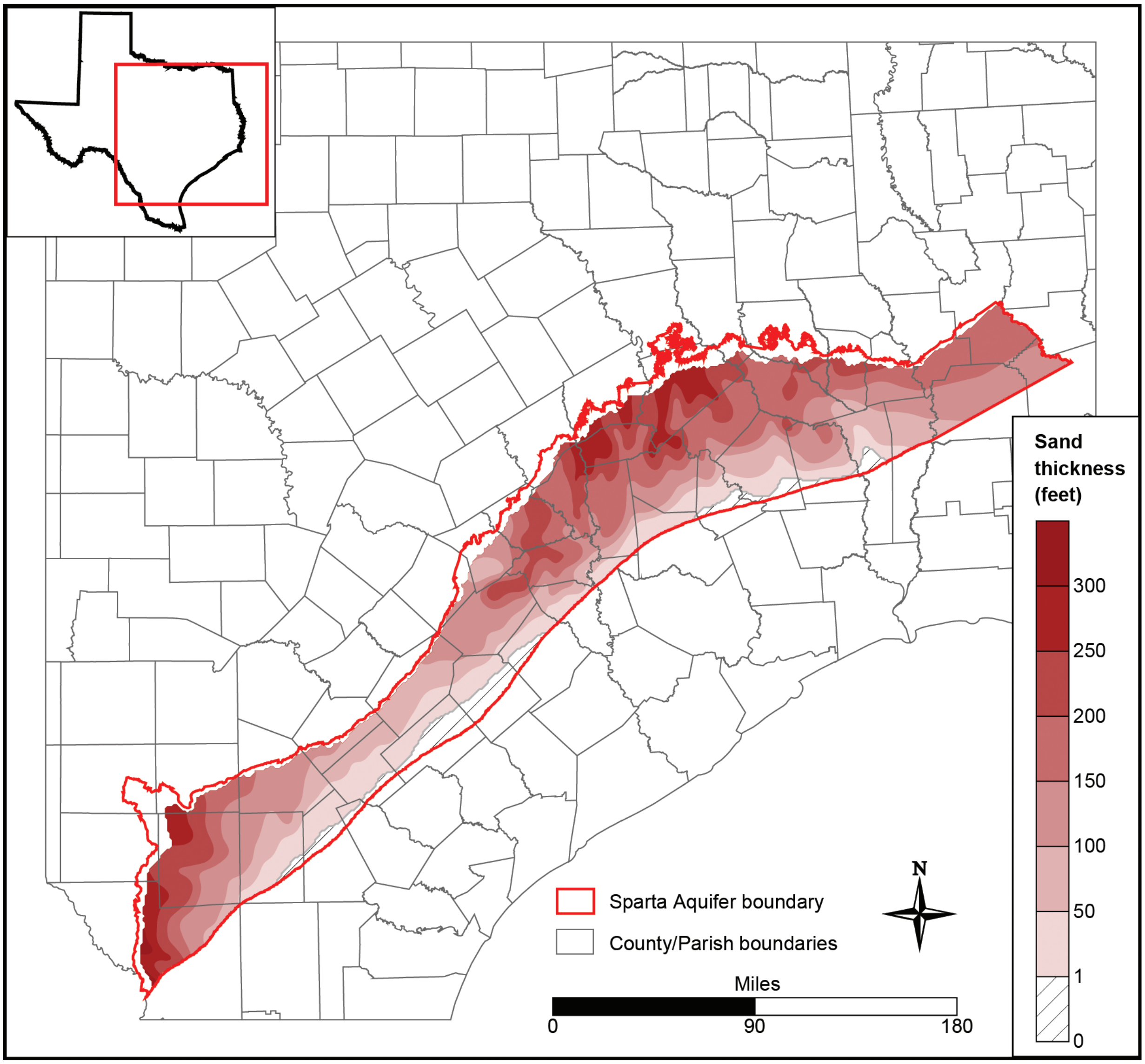

Figure 5-8. Sparta sand thickness (after Ricoy and Brown, 1977).

were compiled from the well records at the Texas Commission on Environmental Quality. A total of 617 unique tests were assigned to the Queen City Aquifer, but only 38 measurements were identified as Sparta Aquifer tests. In addition, direct hydraulic conductivity data for the Queen City Aquifer were extracted from a Bureau of Economic Geology report developed for TWDB documenting aquifer properties of the Carrizo-Wilcox Aquifers (Mace and others, 2002). Table 5-1 provides a summary of the hydraulic conductivity database developed in Kelley and others (2004) for the Queen City and Sparta aquifers.

Issues of bias surely affect the available measured hydraulic conductivities. Specifically, these measurements are representative of the more productive portions of the aquifers, which correspond to the sandier sections of the aquifers. Second, they are almost all restricted to shallow measurements. Payne (1968), Prudic (1991), and Young and Kelley (2006) have shown evidence for positive correlation between sand bed thickness

Table 5-1. Summary statistics for hydraulic conductivity.

Statistic	Queen City			Sparta
	TCEQ	Mace	Combined	
Number of samples	617	412	1,029	38
Arithmetic mean (ft/day)	9.8	17.0	12.7	18.3
Median (ft/day)	3.9	5.0	4.2	5.7
Geometric mean (ft/day)	3.8	5.7	4.5	5.8
Standard deviation K (ft/day)	18.0	52.7	36.3	30.0
Standard deviation Log10(K ft/day)	0.62	0.64	0.63	0.80

Source: Data after Kelley and others (2004)
TCEQ = Texas Commission on Environmental Quality; ft/day = feet per day

and hydraulic conductivity. Prudic (1991) also demonstrated in the Texas Gulf Coastal Plain aquifers that hydraulic conductivity decreases with depth, a concept explored in more detail from a theoretical basis in Young and Kelley (2006). Neither of these trends was discerned in the Queen City and Sparta hydraulic conductivity data analyzed by Kelley and others (2004).

Very few measurements of storativity and specific yield are published for the Queen City and Sparta aquifers. A literature review was performed for the aquifers in Texas and was documented in Kelley and others (2004). The literature review of values of storativity of the Queen City and Sparta aquifers provides a range in magnitude from 1.0×10^{-4} to 5.2×10^{-3}, with a geometric mean equal to 2.35×10^{-4}. Specific yield estimates were all from previously calibrated modeling studies and ranged from 0.01, which is unrealistically low for an unconsolidated clastic aquifer, to 0.25.

5.5
WATER LEVELS AND GROUNDWATER FLOW

Groundwater within the Queen City and Sparta aquifers occurs under water table conditions in the outcrop areas and artesian conditions downdip of the outcrops where the aquifers are confined. Groundwater flow within the outcrop areas is essentially controlled by local topography, flowing from the higher elevation areas and discharging in the lower elevation areas (streams and riparian corridors). Within the confined portions of the aquifer, groundwater flow is controlled by regional topography, flowing from the outcrop toward the subcrop and discharging by processes of cross-formational flow and flow to regional sinks (major streams and rivers). The relative amount of groundwater flow occurring within the unconfined portions of the aquifer is thought to greatly exceed the downdip groundwater flow occurring in the confined sections of the aquifer (see discussion of aquifer discharge below).

Over a large portion of East Texas, the Queen City Aquifer exists in outcrop (ground surface) within the East Texas Embayment and surrounding the Sabine Uplift. In this portion of Texas, the presence of ridges and valleys with significant elevation differences results in the development of localized groundwater basins within the aquifer and the absence of a regionally coherent flow system (Fogg and Kreitler, 1982). This implies that most flow paths in this region are locally controlled from topographic highs to topographic lows, with the great majority of recharge discharging locally.

In the outcrop belt of the Queen City and Sparta aquifers, groundwater recharges in the higher elevations along drainage divides and discharges in lower elevations in creeks and rivers. Some

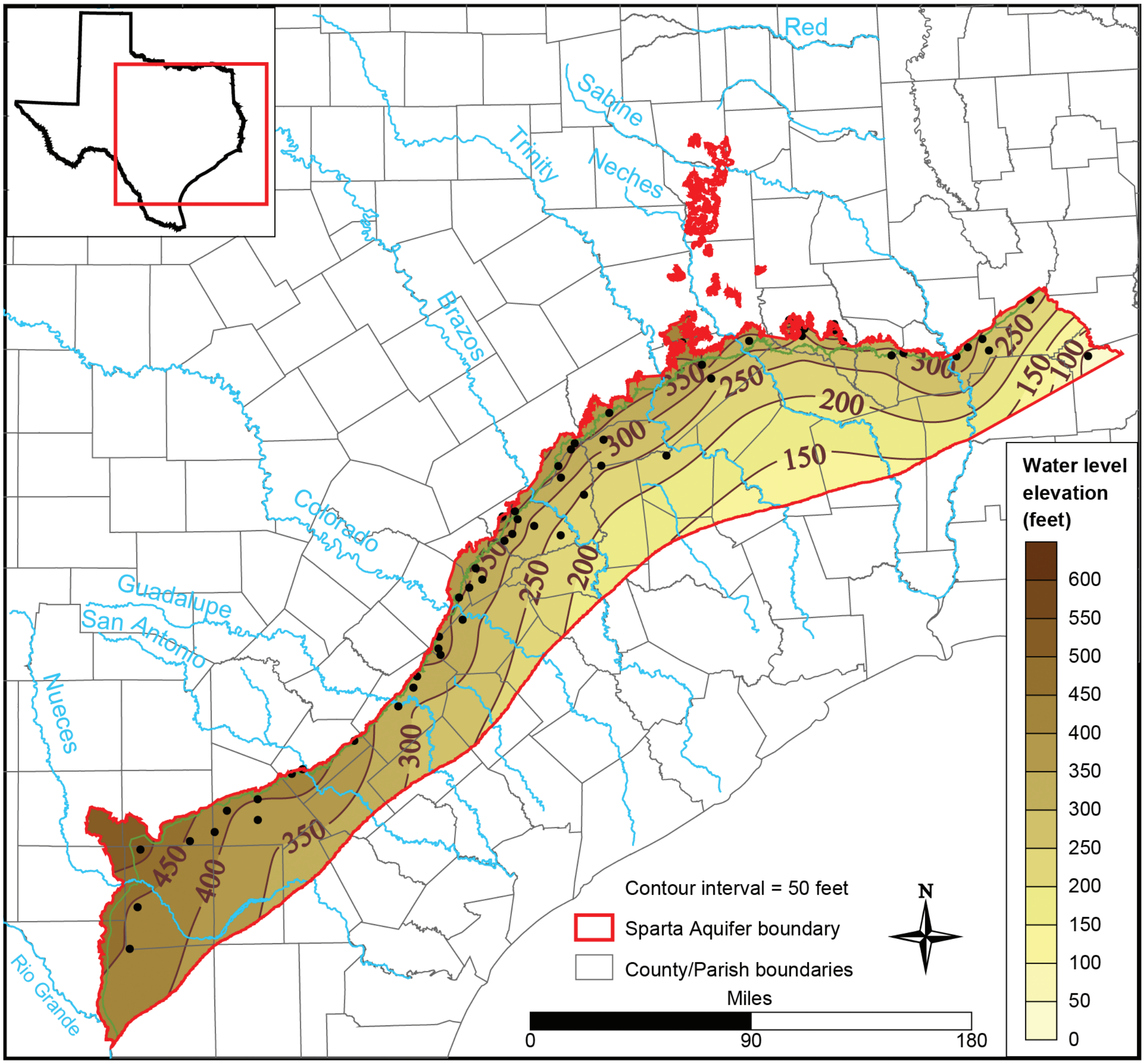

Figure 5-9. Estimated water level elevation contours for predevelopment conditions in the entire Sparta Aquifer.

portion of recharge at the outcrop flows into the confined portions of the aquifers, moving horizontally along the dip of the formations in response to regional elevation gradients and vertically through cross-formational flow. In general, the dip of the formations and land surface is toward the Gulf of Mexico, resulting in groundwater flow in southward and southwesterly directions in Nacogdoches, San Augustine, and Sabine counties and in the southeasterly direction in the counties from Houston County in the north to La Salle County in the south.

Predevelopment and historical water level surfaces were constructed for the Queen City and Sparta aquifers and are documented in Kelley and others (2004). Please see Kelley and others (2004) for details regarding assumptions and data supporting interpreted head surfaces. Figure 5-9 shows the estimated predevelopment head surface for the Sparta Aquifer. As expected, the heads are highest in the outcrop and lower in the confined downdip portions of the aquifer. Conceptually, this suggests that the aquifer system recharges at the outcrop in the highest elevations available to the aquifer system and flows out as streams, springs, and groundwater evapotranspiration in the outcrop and into the confined section of the aquifer, losing potential (head) along the flow path. Groundwater reaching the confined portions of the aquifer discharges upward under natural conditions to overlying units between the outcrop and the portions of the aquifer with poor water quality. A similar predevelopment map was developed for the Queen City Aquifer in southern and Central Texas. Head patterns were similar, with heads being generally higher, reflecting an updip outcrop elevation relative to the Sparta (higher ground elevation). A predevelopment head surface was not developed for the northern portions of the Queen City Aquifer because data were lacking over large portions of the region, and contouring could not replicate the subregional hill to valley flow systems seen in the few counties with significant data.

As a result of limited historical development, water levels in the Queen City and Sparta aquifers have generally been stable across the state, except for localized declines in areas of high pumping. Because pumping volumes are relatively small and these aquifers are less productive than many other Texas Coastal Plain aquifers, drawdown associated with pumping tends to be local, and regional reductions in head in the confined portions of these aquifers have not been observed. Water level declines in the Queen City tend to be more common in the central and southern parts of the aquifer where the aquifer is more likely to be confined or semi-confined and storativity is low. Water level declines in the Sparta are less common, with local declines reaching 40 to 60 feet in wells screened in the confined portions of the aquifer.

To better conceptualize vertical gradients and the potential for cross-formational flow between the Queen City and Sparta aquifers and between these aquifers and the underlying Carrizo-Wilcox Aquifer, Kelley and others (2004) conducted a pressure head versus screen-midpoint depth analysis similar to methods used in Fogg and Kreitler (1982). In summary, vertical pressure gradients are generally upward in areas of Central and South Texas and are generally downward in the northeast. There is evidence for a decrease in upward gradients in Central Texas from pre-1950 to post-1950 head measurements, suggesting decreasing heads in the Carrizo. There was a lack of measurements prior to 1950 in the southern portions of the aquifers from which to investigate temporal trends. However, the magnitude of the downward vertical gradient in northeast Texas showed evidence of an increasing trend over time, reflecting development and water level decline of the underlying Carrizo Aquifer.

5.6

RECHARGE AND DISCHARGE

Recharge can be defined as water that enters the saturated zone at the water table (Freeze, 1969). Recharge is a complex function of rate and volume of precipitation, soil type, water level, soil moisture, topography, and evapotranspiration (Freeze, 1969). Recharge is expected to vary seasonally. For example, winter and early spring is generally a high precipitation time. During this time, soil moisture would also be high while evapotranspiration rates would be low. These conditions combine to increase the potential for recharge. In the heat of the summer, precipitation events tend to be more isolated, soil moisture is lower, and evapotranspiration is highest. These conditions combine to decrease the potential for recharge. Potential sources for recharge to the water table include precipitation, stream or reservoir leakage, or irrigation return flow. In the Queen City and Sparta aquifers, recharge is conceptualized to occur both as diffuse recharge in the outcrop and as focused recharge in areas where streams are predominantly losing (South Texas). Similarly, the amount of recharge occurring as diffuse recharge is expected to decrease from the wet humid northeast portions of the state to the more arid southwest.

Recharge in the major aquifers of Texas has been studied by many investigators. These studies have been summarized by Scanlon and others (2002). However, few estimates of recharge are available for the Queen City and Sparta aquifers in Texas. Muller and Price (1979) estimated groundwater availability for the aquifers of Texas, which they typically equated to recharge estimates. The development of the Queen City and Sparta groundwater availability models (Kelley and others, 2004) also provides estimates of recharge. If Muller and Price (1979) availability estimates are considered equivalent to recharge, they can be compared to estimates developed by Kelley and others (2004). Table 5-2 summarizes this comparison, and shows that the recharge estimate from Kelley and others (2004) is similar to that by Muller and Price (1979) for the Sparta but is significantly reduced for the Queen City Aquifer.

Table 5-2. Recharge estimates for the Queen City and Sparta aquifers.

	Muller and Price (1979)		Kelley and others (2004)	
Aquifer	AFY	in/yr	AFY	in/yr
Queen City	682,100	1.3	364,522	0.7
Sparta	163,800	1.3	196,442	1.5

AFY = acre-feet per year; in/yr = inches per year

In the predevelopment long-term steady-state condition of an aquifer, recharge equals discharge. As a result, quantifying stream base flow and springflow can provide one of the few, if not the only, means of constraining regional aquifer recharge. A limitation of this approach is the inability to account for downdip flow to the confined section and groundwater evapotranspiration. Thus, this approach tends to underestimate recharge. The value of these estimates is that they provide a lower limit to regional aquifer recharge. Such studies have not been performed over the entirety of the Queen City and Sparta aquifers to date.

Estimates of stream-aquifer interaction and springflow have been made across various portions of the aquifers in Texas and are documented in Kelley and others (2004). This chapter summarizes those studies that apply most directly to the Queen City and Sparta aquifers. Table 5-3 summarizes the Queen City and Sparta stream-aquifer interaction studies. Stream-aquifer interaction can be quantified through several means, including low-flow studies, hydrograph separation studies, and modeling studies. Most studies germane to these aquifers were reported in a survey study performed by the U.S. Geological Survey (Slade and others, 2002). They documented 41 gain/loss studies that intersect the Queen City and/or Sparta outcrop. Most of these studies also intersected other aquifers in the study segments and are not included in Table 5-3. In addition to these studies documented by Slade and others (2002), three additional studies have become available since the U.S. Geological Survey study.

In support of the Lower Colorado River Authority-San Antonio Water System water supply project studies, the Lower Colorado River Authority performed a detailed low-flow study on the Colorado River below Austin to Bay City in Matagorda County (Saunders, 2006). The study period was carefully chosen to be a dry (low runoff) period from October 1, 1999, through March 31, 2000. In the reach from Bastrop to Smithville, which included the Queen City and Sparta aquifers, they observed an average gain of 59 cubic feet per second (47,741 acre-feet per year or 1,723 acre-feet per year per mile).

The U.S. Geological Survey performed base flow (1966 through 2005) and low-flow (2006) studies from McLennan County to Fort Bend County (Turco and others, 2007). They estimated a gain of 134 cubic feet per second (97,075 acre-feet per year or 4,221 acre-feet per year per mile) across the Queen City and Sparta outcrops. Recently, the U.S. Geological Survey published a gain and loss study on the Guadalupe River (Ockerman and Slattery, 2008). In the reach across the Queen City and Sparta aquifers in the Lower San Marcos River, they estimated a net gain of 293 cubic feet per second (212,261 acre-feet per year or 6,065 acre-feet per year per mile).

Although there is likely great uncertainty in the stream gain estimates provided in Table 5-3, it has been documented that streams gain in the order of 100 to 1,000 acre-feet per year per mile of stream for the major rivers crossing the outcrops of the Queen City and Sparta aquifers and the Carrizo-Wilcox Aquifer in areas of the state northeast of the Guadalupe. As a result, one can conclude that aquifer stream discharge in the Queen City and Sparta aquifers is probably in the order of 100,000s of acre-feet per year in the Queen City and Sparta aquifers in Texas.

Discharge also occurs in areas where the water table intersects the surface at springs or seeps. These springs usually occur in topographically low areas in river valleys or in areas of the outcrop where hydrogeologic conditions preferentially reject recharge. Kelley and others (2004) provide a complete review of the available information at that time. A summary of available springflow data for the Queen City and Sparta aquifers is available in Table 5-4. The available information is limited because the primary source for spring information (Brune, 1981) did not include spring surveys for counties from Angelina County southwest to Burleson County and from Gonzales County southwest to Atascosa County. In fact, only eight counties are represented in Table 5-4. Therefore, is likely that there

Table 5-3. Stream-aquifer interaction studies predominantly in the Queen City and Sparta outcrop.

River	River reach	Gain (cfs)	Gain (AFY)	Reach (mile)	AFY/ mile	Date of study	Reference
Guadalupe River	Lower San Marcos River	293	212,261	35	6,065	1987–2006	Ockerman and Slattery (2008)
Colorado River	Bastrop - Smithville	59	42,742	24.8	1,723	10/1999–3/31/2000	Saunders (2006)
Brazos River	Brazos - Valley Junction to SH-21 near Bryan	134	97,075	23	4,221	3/8/2006	Turco and others (2007)
Red River	Sugar Creek - FM 1403 to SH 154	0.15	109	0.8	136	6/10–11/1964	Slade and others (2002)
Trinity	Big Elkhart Creek - northwest of Grapeland to mouth	5.18	3,753	25.7	146	9/15–16/1965	Slade and others (2002)
Trinity	Little Elkhart Creek - south of Grapeland to mouth	-1.59	(1,152)	17.5	(66)	9/16/1965	Slade and others (2002)

cfs = cubic feet per second; AFY = acre-feet per year; SH = state highway; FM = farm to market are many more undocumented smaller springs and seeps, particularly in the northeastern part of the outcrop.

The available measured springflow rates range from 0.23 cubic feet per second (167 acre-feet per year) to a high of 3.4 cubic feet per second (2,463 acre-feet per year) measured at Elkhart Creek Springs and originating from the Sparta Sand (Brune, 1975). Springs in the Queen City and Sparta aquifers are limited to the outcrop and typically would be integrating flow from shallow subregional flow paths. Brune (1981) noted that throughout much of the region he studied, including select regions of the Queen City and Sparta outcrop area, springflows have shown a general decline over time.

In addition to stream and spring discharge, groundwater evapotranspiration is also expected to be a significant discharge mechanism for the aquifer. However, no quantitative estimates exist of this flux for these or any other aquifers in Texas other than model predictions. In 2005, the TWDB funded a study on groundwater evapotranspiration and its application to Texas groundwater availability models (Scanlon and others, 2005). The study did provide evidence to suggest that groundwater evapotranspiration is potentially a significant discharge mechanism. The limited riparian

Table 5-4. Documented springs in the Queen City and Sparta aquifers.

County	Spring	Formation	Flow rate (cfs)	Flow rate (AFY)	Date of measurement	Source
Burleson	Sour or Spring Lake Springs	Sparta	0.40	290	1936	Brune (1975)
Camp	Couch or Lee Springs	Queen City	0.27	196	1-21-78	Brune (1981)
Houston	Caney Creek Springs	Sparta	1.70	1,232	9-16-65	Brune (1975)
Houston	Elkhart Creek Springs	Sparta	3.40	2,463	9-15-65	Brune (1975)
Houston	Hays Branch Springs	Sparta	1.80	1,304	9-16-65	Brune (1975)
Nacogdoches	Waterworks Springs (1 of 2)	Sparta	0.46	333	1914	Brune (1981)
Nacogdoches	Waterworks Springs (2 of 2)	Sparta	0.46	333	2-13-78	Brune (1981)
Rusk	Spring	Queen City	0.51	369	11-17-78	TWDB well database
Smith	Spring Lake Springs	Queen City	1.27	920	10-31-79	Brune (1981)
Smith	Springs in Ray Creek	Sparta and Weches	0.81	587	10-30-79	Brune (1981)
Upshur	Hoover Springs and other nearby springs	Queen City	0.23	167	1-17-78	Brune (1981)
Upshur	Horn Springs	Queen City	0.49	355	1-20-78	Brune (1981)
Upshur	Valley Springs	Queen City	0.49	355	1-20-78	Brune (1981)
Van Zandt	Cherokee Springs	Queen City	0.26	188	9-26-79	Brune (1981)
Van Zandt	Red Hill Springs	Queen City	0.25	181	9-26-79	Brune (1981)
Wood	Big Woods Springs	Queen City	0.34	246	10-23-79	Brune (1981)
Wood	Gunstream Springs	Queen City	3.25	2,354	1978	Brune (1981)
Wood	Holly Springs and other nearby springs	Queen City	1.94	1,405	10-22-79	Brune (1981)

cfs = cubic feet per second; AFY = acre-feet per year studies where groundwater evapotranspiration has been estimated through field measurements have generally found that groundwater evapotranspiration rates range between 30 percent and 50 percent of potential evapotranspiration. Generally speaking, maximum groundwater evapotranspiration rates could vary from 19 to 66 inches per year (Scanlon and others, 2005). Unfortunately, there is a lack of riparian evapotranspiration measurements in Texas, leaving this discharge mechanism poorly constrained in regional groundwater availability modeling.

In addition to mechanisms of natural discharge, post-development groundwater pumping is a key aquifer discharge mechanism. Pumping of the Queen City Aquifer has historically been focused in the northeastern parts of the state in the outcrop areas of the aquifer where water quality is the best. Earliest reports of development of the aquifer in East Texas date back to the mid- to late-1800s, and the first water level measurements were made in Cherokee, Henderson, Freestone, Leon, Nacogdoches, and Rusk counties in 1936. Early water levels are also available from the 1940s for portions of Cass, Harrison, Upshur, and Wood counties. Pumpage from the Sparta Aquifer began in the late 1800s and the early 1900s across the state. The first recorded water level measurement available on the TWDB Web site was taken in 1900 in Fayette County. Significant numbers of water level measurements are not available until about 1936. In general, groundwater from the Sparta Aquifer is used predominantly for domestic and stock purposes, with two exceptions. The Sparta Aquifer has been used as a primary source of groundwater in Houston and Brazos counties. In Brazos County, wells tapping the Queen City and Sparta sands have provided groundwater for the city of Bryan since 1915 and for Texas A&M University and the city of College Station since 1951.

The most current estimates of pumping for the Queen City and Sparta aquifers are available on the TWDB Historical Water Use Web site for the year 2003. Table 5-5 provides a summary of the groundwater use by water user group for 2003. Kelley and others (2004) reported historical pumping through 1999 and projected pumping through 2050 for these aquifers. At that time projected pumping was expected to triple for the Sparta and double for the Queen City by 2050.

Comparing pumping volumes to aquifer recharge estimates (and by extension natural discharge estimates) reveals that pumping is a relatively small percent of recharge even if one considers the lower recharge estimates (Table 5-2).

5.7
WATER QUALITY

Water quality of the Queen City and Sparta aquifers has been described by many county assessments of groundwater resources. In Kelley and others (2004), Dr. Alan Dutton (now with the University of Texas, San Antonio) evaluated both hydrochemical facies and total dissolved solids of groundwater in these aquifers across the entire state. This section will review his maps of total dissolved solids and some of the relevant conclusions from his work.

Table 5-5. Reported water use in acre-feet per year for 2003.

Aquifer	Municipal	Manufacturing	Steam-electric	Irrigation	Mining	Livestock	Total
Queen City	7,844	0	0	901	1,741	5,527	16,013
Sparta	3,995	2,944	0	1,142	58	1,803	9,942

Source: TWDB Historical Water Use Web site, www.twdb.state.tx.us/wrpi/wus/summary.htm

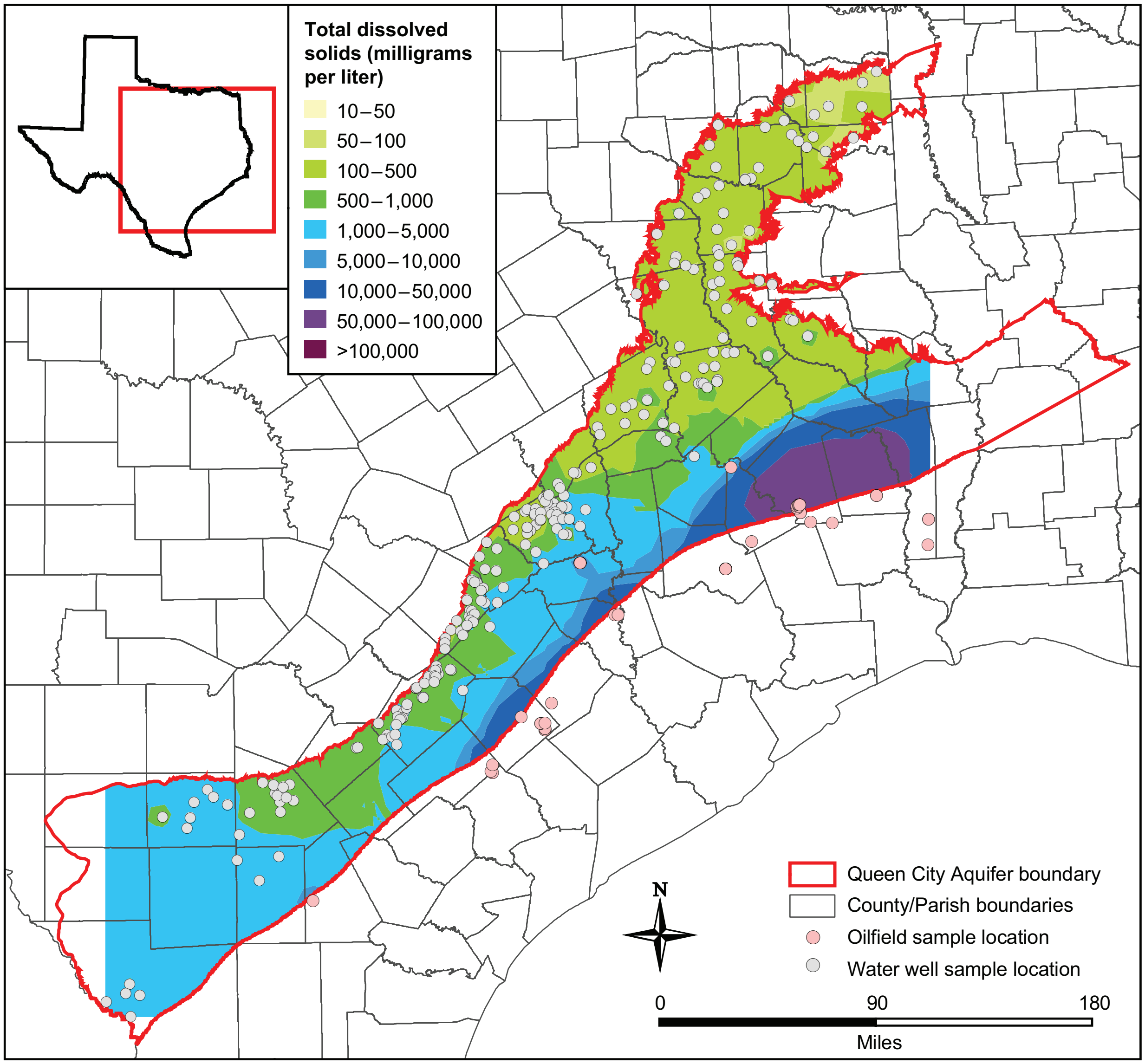

Figure 5-10. Map of total dissolved solids in the Queen City Aquifer and equivalent downdip section in Texas.

Water quality data were compiled from water supply wells taken from TWDB Internet files and were augmented with data from the U.S. Geological Survey Internet files on chemical composition of co-produced formation waters from oil or gas wells in the downdip section of the Claiborne Group. Figures 5-10 and 5-11 plot the total dissolved solids trends for both the Queen City and the Sparta aquifers, respectively. The aquifers were found to have similar chemical compositions, similar regional trends in water quality, and very similar average total dissolved solids values (516 milligrams per liter in the Queen City and 610 milligrams per liter in the Sparta). The groundwater total dissolved solids were generally higher in the confined portions of the aquifers as compared to the unconfined portions of the aquifer, and in general, total dissolved solids were greater in the southern portions of the aquifer than in the central and northern portions. In the Queen City Aquifer, this trend is at least in part driven by the large amount of outcrop in the northeastern half of the state.

Differences in average total dissolved solids and the proportion of

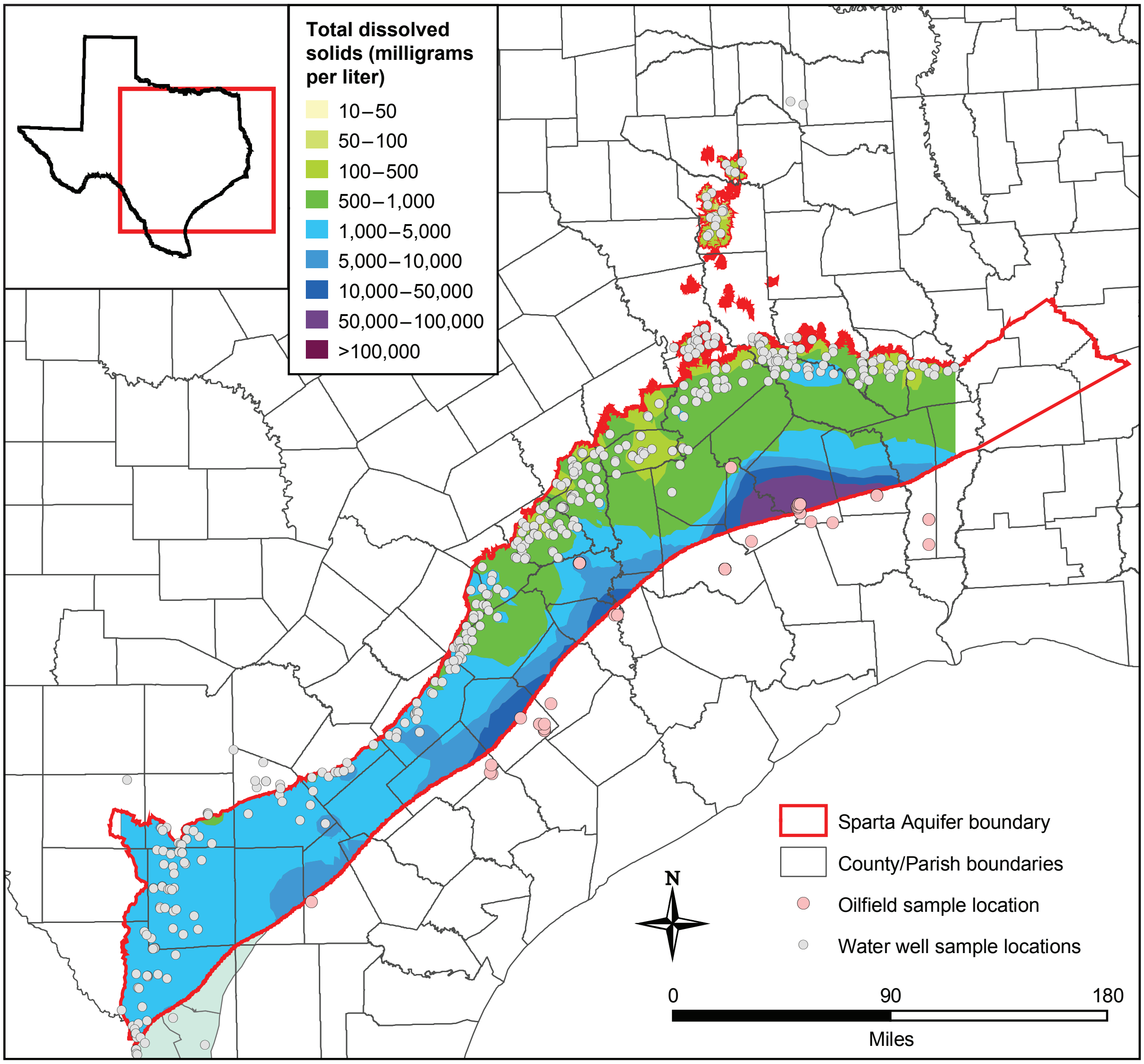

Figure 5-11. Map of total dissolved solids in the Sparta Aquifer and equivalent downdip section in Texas.

hydrochemical facies in the southern versus northern parts of the Queen City and Sparta aquifers have implications for the conceptual model of the movement of groundwater and recharge. Domenico and Robbins (1985) found that recharge rate, breadth of the recharge area, and aquifer transmissivity control the displacement of the connate water and the subsequent replacement with fresh water. The downdip increase in total dissolved solids along with sodium and chloride concentrations in both aquifers might reflect less displacement by meteoric water of connate water. The downdip extent of connate water displacement appears to be greater in the northern than in the southern parts of the aquifers. In the north, the Queen City Aquifer is shallow and unconfined across much of the East Texas Basin, which explains the observed lower total dissolved solids concentrations. Lower recharge rates, lower transmissivity, or both could account for less displacement of saline water and higher average total dissolved solids in the south than in the north. Depositional environments within the aquifers can be the factor controlling connectivity of sands from the outcrop areas to the deeper portions of the aquifer, thereby influencing displacement. Payne (1968) observed that in the south-central portions of the Sparta Aquifer in Texas, the distance to bad water is very close to the downdip extent of the outcrop as a result of limited downdip sand thickness due to the stand-plain depositional environment that tends to produce sand trends parallel to strike.

5.8

IMPACTS OF AQUIFER DEVELOPMENT WITH AN EMPHASIS ON AQUIFER DISCHARGE

The preceding discussion has focused on the general hydrogeology and groundwater flow within the Queen City and Sparta aquifers. Some discussion has focused on historical changes in water levels and vertical gradients that have resulted from groundwater pumping. In this section, we will focus on a more quantitative discussion with the aid of the results of the Queen City and Sparta groundwater availability models. This section will review the steady-state groundwater flow balances for these two aquifers on a regional basis.

In a natural aquifer system unaffected by pumping, the aquifer system is in a long-term dynamic equilibrium condition generally referred to as a steady-state condition (or predevelopment). In this predevelopment state, aquifer recharge is balanced by aquifer discharge resulting in no net change in groundwater storage. Recharge may include areal recharge from precipitation, cross-formational flow from adjacent water-bearing formations, and stream losses. Discharge may include stream base flow, springflow, evapotranspiration, and cross-formational flow. Human activities alter the dynamic equilibrium of the predevelopment flow system through pumping withdrawals, changes in recharge through development and irrigation, and changes in vegetation and land use. Generally, groundwater withdrawals due to pumping have the most significant impact on aquifer hydraulics. The water removed by pumping is supplied through some combination of decreased groundwater storage, reduced groundwater discharge, and increased recharge. If pumping remains relatively constant and natural discharge can decrease and/or recharge can increase, a new steady-state condition will be established. In this new post-development equilibrium, the source of the pumped water will be drawn from some combination of reduced discharge or increased recharge, again the latter of which is usually negligible. Bredehoeft (2002) terms these two volumes as capture. The sources of discharge, which are ultimately captured by pumping, include stream base flow, springflow, evapotranspiration, and cross-formational flow.

Bredehoeft (2002) defined sustainable yield (physically sustainable pumpage) as being equal to the rate of capture. In the situation of sustainable aquifer dynamics, the pumping rates in the basin are being matched by the capture in discharge with a net result of water levels becoming stable (albeit at a lower level than prior to development). It is important to note that a sustainable yield may not be a desirable future state of an aquifer and, therefore, may not represent an optimal yield. For example, a sustained yield could result in decreased discharge to streams (streamflow capture) that would prove to be undesirable. If a basin is continually pumped at a rate that is greater than the basin's discharge rate (potential capture), then water levels will continually decline and natural discharge will diminish. This condition was referred to as an unstable basin by Freeze (1969) and is inherently unstable.

Pumping from the Queen City and Sparta aquifers to date has been relatively low, as evidenced by relatively stable groundwater levels over time. Large portions of the Queen City and Sparta aquifers are minimally impacted by pumping relative to predevelopment. However, some portions of these aquifers have experienced significant drawdown. In these regions, stream base flow, springflow, evapotranspiration, and cross-formational flow are expected to have been, or will be, decreased (pumping capture).

A review of the steady-state water balance of the Queen City and Sparta aquifers taken from the groundwater availability model (Kelley and others, 2004) provides a quantitative tool for examining the issues of aquifer discharge (potential aquifer pumping capture) and the issue of sustainable yield (from an aquifer perspective). Table 5-6

Table 5-6. Steady-state flow balance—Queen City and Sparta groundwater availability models.

	Volume of flow (acre-feet per year)									
Region	Recharge	Total outflow	Streams/ Springs	Evapotranspiration	Upper boundary	Lower boundary	Lateral flow	Total outflow	Net cross-formation	Effective recharge
Sparta - South	23,721	-63,979	-6,938	-3,472	-53,570	40,113	201	-63,979	-13,456	13,311
Sparta - Central	49,461	-60,686	-21,411	-15,599	-23,676	10,917	20	-60,686	-12,759	12,451
Sparta - North	123,260	-123,266	-46,472	-55,721	-1,706	-19,068	-299	-123,266	-20,774	21,067
Total	196,442	-247,931	-74,822	-74,791	-78,951	31,962	-78	-247,931	-46,989	46,829
Queen City - South	66,590	-109,826	-65,236	-7,271	-37,319	42,283	1,022	-109,826	4,964	-5,916
Queen City - Central	49,278	-59,980	-31,772	-19,255	-8,857	10,163	-96	-59,980	1,306	-1,749
Queen City - North	248,653	-269,690	-121,206	-143,841	21,037	-3,983	-660	-269,690	17,054	-16,394
Total	364,522	-439,496	-218,213	-170,367	-25,139	48,463	267	-439,496	23,323	-24,058

	Percent of total outflow							Percent of recharge		
Region	Recharge	Total outflow	Streams/ Springs	Evapotranspiration	Upper boundary	Lower boundary	Lateral flow	Total outflow	Net cross-formation	Effective recharge
Sparta - South	37.1	-100.0	-10.8	-5.4	-83.7	62.7	0.3	-269.7	-56.7	56.1
Sparta - Central	81.5	-100.0	-35.3	-25.7	-39.0	18.0	0.0	-122.7	-25.8	25.2
Sparta - North	100.0	-100.0	-37.7	-45.2	-1.4	-15.5	-0.2	-100.0	-16.9	17.1
Average	72.9		-27.9	-25.4	-41.4	21.7	0.0	-164.1	-33.1	32.8
Queen City - South	60.6	-100.0	-59.4	-6.6	-34.0	38.5	0.9	-164.9	7.5	-8.9
Queen City - Central	82.2	-100.0	-53.0	-32.1	-14.8	16.9	-0.2	-121.7	2.7	-3.5
Queen City - North	92.2	-100.0	-44.9	-53.3	7.8	-1.5	-0.2	-108.5	6.9	-6.6
Average	78.3		-52.4	-30.7	-13.6	18.0	0.2	-131.7	5.7	-6.3

Note: positive numbers indicate inflows; negative numbers indicate outflows

Source: After Kelley and others, 2004

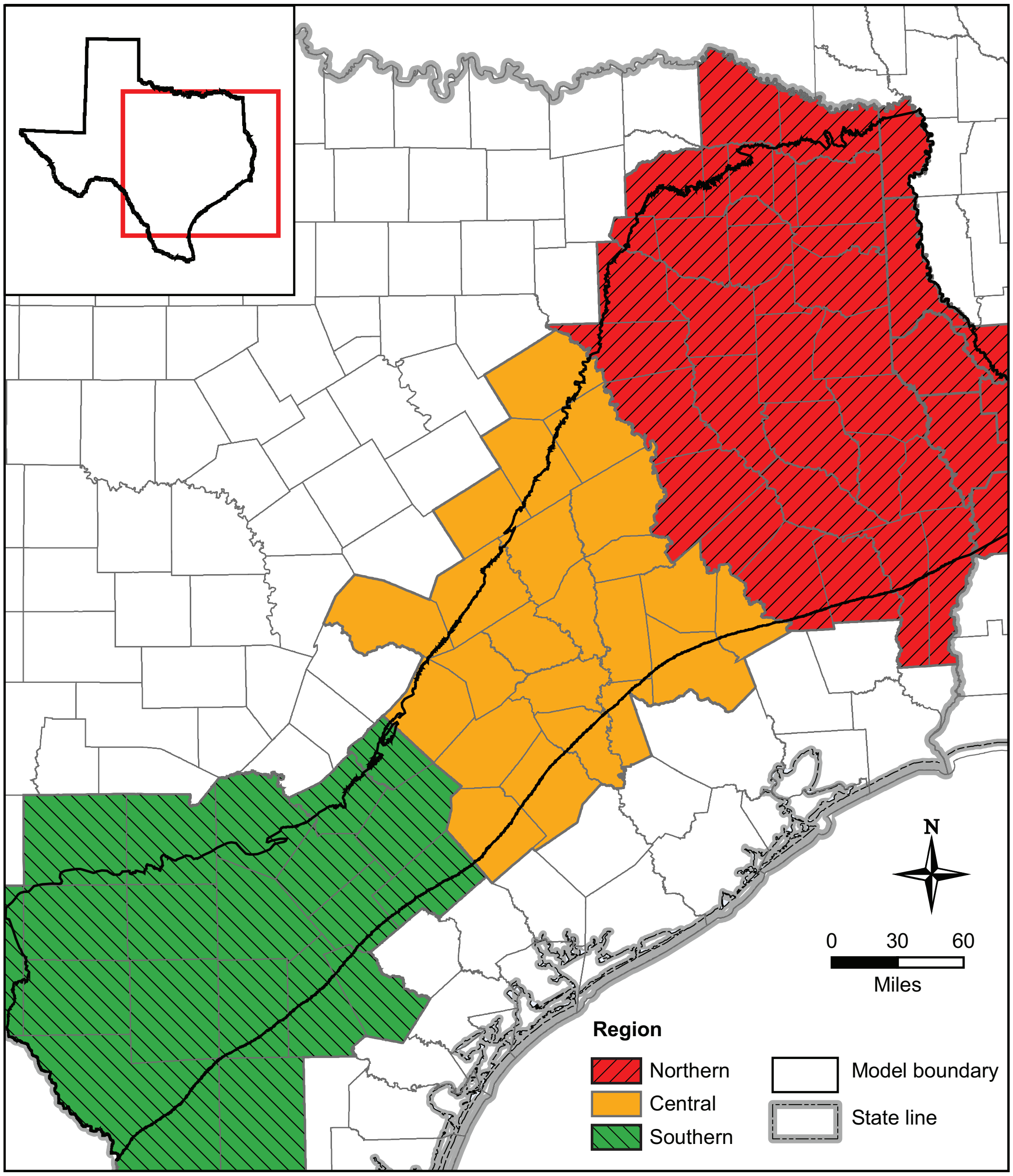

Figure 5-12. Aquifer subregions referenced in the water balance calculations.

summarizes the steady-state water balance for the Queen City and Sparta aquifers expressed in acre-feet per year and as a percent of total outflow from each aquifer or as a percent of outcrop recharge. Aquifer inflows are positive numbers and aquifer outflows are negative. The aquifers have been divided into a southern, central, and northern region for comparative purposes (see Figure 5-12 for delineation of these regions). Flow within the Weches confining unit between the Sparta and the Queen City aquifers is considered vertical and is not included in Table 5-6. Recall that these are steady-state flow terms; therefore, there is no change in storage and aquifer inflows and outflows are balanced.

To look at the regional sustainability of the aquifer systems, one can first look at total aquifer outflow, which theoretically equates to the available pumping capture existing for each aquifer. This represents a theoretical maximum development for the aquifer, which in reality is never achievable because local pumping may be focused to the degree that it cannot capture adequate volumes in a time frame commensurate with the pumping duration. This condition is seen in select areas of these aquifers.

For both aquifers in all three regions, except the northern Sparta region, there is more aquifer outflow from the aquifer than the amount of recharge occurring within the outcrop. This is the result of cross-formational flow. For example, the Sparta south outcrop recharge is approximately 23,721 acre-feet per year, but the aquifer received an additional 40,113 acre-feet per year of inflow along its lower boundary, dominantly in the aquifer subcrop. The net cross-formational flow from the aquifer (lower boundary minus upper boundary flows) is approximately -13,456 acre-feet per year, which is approximately equal to the aquifer downdip flow from the outcrop to the confined portion of the aquifer (some refer to this as effective recharge). The southern Sparta behaves like a classic coastal plain outcrop-confined aquifer system with some percent of recharge discharging to streams, springs, and evapotranspiration and some moving to the confined section and exiting through cross-formational flow. A review of the effective recharge expressed as a percent of recharge for the Sparta Aquifer shows that the percent of recharge flowing downdip into the confined sections of the aquifer decreases from south to north, whereas the volume increases. This is, in part, a product of the shallower water tables and perennial streams in northeastern Texas, which act as large sinks to the increased recharge that occurs in the more humid environment.

In the Sparta, like the Queen City, total outflow from the aquifer is greater than outcrop recharge in all cases, indicating that cross-formational flow is important. However, in contrast to the Sparta, the Queen City Aquifer outcrop regions are discharging more groundwater (to streams, springs, and evapotranspiration) than they are receiving through recharge. This excess outcrop discharge in the northern Queen City is the result of both flow from the overlying Sparta in Smith, Wood, and Upshur counties where the Sparta exists in outcrop and upward flow from the Carrizo Sand in river floodplains. Most of the upper boundary flow into the Queen City is occurring in Smith County from the overlying Sparta.

One of the many significant conclusions that must be drawn from this analysis is that cross-formational flow, though hard to conceptualize and effectively impossible to measure, is a significant source of flow for coastal plain aquifer systems. Therefore, when we model an aquitard underlying an aquifer as a no-flow boundary, in many instances this must significantly affect model results. Secondly, it shows that the coastal plain aquifers are connected and that production from one aquifer may be supported by flow from another aquifer.

Another important conclusion is that it is very important to properly characterize the major sources of aquifer discharge under predevelopment conditions because they are the portions of the aquifer flow balance eclipsed through development (pumping capture). Table 5-7 summarizes the recharge and total discharge volumes for the Queen City and Sparta aquifers and also includes the components of aquifer discharge as a percent of the aquifer total discharge. This table highlights the importance of each discharge mechanism, as currently modeled, for the aquifers. To accurately model the future state of an aquifer being developed, the natural discharge mechanisms must be accurately modeled in terms of location and volume.

Stream and spring discharge is an important discharge mechanism, representing approximately 28 percent and 52 percent of total aquifer discharge for the Sparta and Queen City Aquifers, respectively (Table 5-7). Groundwater evapotranspiration is modeled to be a significant discharge mechanism in the northern Queen City Aquifer. This would be expected because the Queen City exists in outcrop across the majority of the East Texas Basin where water tables are shallow because of significant rainfall. Cross-formational flow can only become a source of capture if there is a net outflow. In the coastal plain under predevelopment conditions, this will result when outcrop recharge enters the confined section of the aquifer and discharges through cross-formational flow. This condition is predicted to occur in the Sparta but generally not in the Queen City because the groundwater availability models predict that the Queen City outcrops discharge more groundwater than is recharging through precipitation. Cross-formational flow is occurring from the Carrizo to the Queen City within the Queen City outcrop. This is most pronounced in the northern Queen City Aquifer where the Queen City outcrops across the majority of the East Texas Basin, and, therefore, deeper aquifers must regionally discharge to major streams through the Queen City (see Fogg and Kreitler, 1982). Table 5-7 shows that under predevelopment conditions, there is little lateral flow across the boundaries chosen to divide the three aquifer regions. This, of course, could change significantly after development.

A review of heads within the Carrizo, Queen City, and Sparta aquifers provides some physical evidence of the cross-formational flow characteristics of these aquifers predicted by the groundwater availability models. As a result of pumping, vertical gradients within coastal plain layered aquifer systems such as the Carrizo-Wilcox, Queen City, and Sparta aquifers are altered from their predevelopment conditions. Figure 5-13 shows the head difference, measured in feet, between the combined Queen City and Sparta Aquifer head and the Carrizo-Wilcox Aquifer head. The head surfaces used to make this difference plot are representative of 1980 and were developed as part of the U.S. Geological Survey Regional Aquifer-System Analysis program (Garza and others, 1987). A gray dot represents a location where the vertical hydraulic head difference (gradient) is down from the Queen City and Sparta aquifers to the Carrizo-Wilcox Aquifer. A triangle represents a location where the vertical head difference (gradient) is upward from the Carrizo-Wilcox Aquifer to the Queen City and Sparta aquifers.

In predevelopment, one would expect dominantly downward gradients in the East Texas Basin and dominantly upward

Table 5-7. Aquifer discharge under predevelopment conditions as predicted by the Queen City and Sparta groundwater availability models.

Region	Recharge (AFY)	Total outflow (AFY)	Discharge flow component as a percent of total outflow			
			Stream/ Springs	Evapotrans-piration	Cross-formational	Lateral
Sparta - South	23,721	-63,979	-10.8%	-5.4%	-83.7%	0.0%
Sparta - Central	49,461	-60,686	-35.3%	-25.7%	-39.0%	0.0%
Sparta - North	123,260	-123,266	-37.7%	-45.2%	-16.9%	-0.2%
Total/Average	196,442	-247,931	-27.9%	-25.4%	-46.5%	0.0%
Queen City - South	66,590	-109,826	-59.4%	-6.6%	-34.0%	0.0%
Queen City - Central	49,278	-59,980	-53.0%	-32.1%	-14.8%	-0.2%
Queen City - North	248,653	-269,690	-44.9%	-53.3%	-1.5%	-0.2%
Total/Average	364,522	-439,496	-52.4%	-30.7%	-16.7%	-0.1%

AFY = acre-feet per year

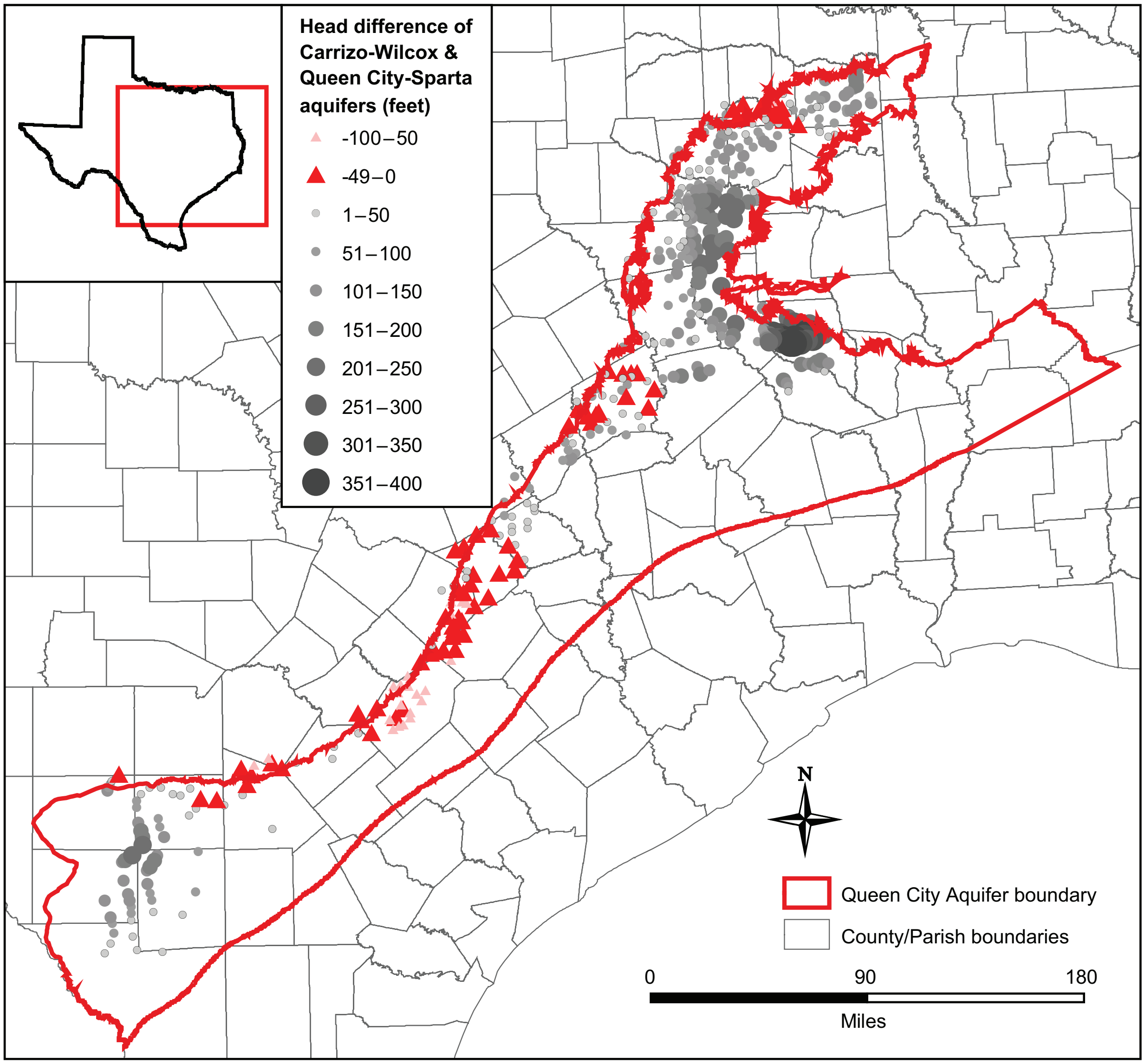

Figure 5-13. Vertical head differences between the Queen City and Sparta Aquifer system and the Carrizo-Wilcox Aquifer system in 1980 (after Garza and others, 1987) (positive values indicate flow from the Queen City and Sparta aquifers to the Carrizo-Wilcox Aquifer; negative values indicate flow from the Carrizo-Wilcox Aquifer to the Queen City and Sparta aquifers).

gradients in areas where the aquifers are dipping into the Gulf Coast Basin. Figure 5-13 is not representative of predevelopment conditions, as it represents heads in 1980. However, this figure shows that gradients tend to be downward in East Texas, which is consistent with the conceptual model and the fact that the Queen City and Sparta aquifers are unconfined in that region. It does appear that gradients are interpreted by Garza and others (1987) to be upward in the Cypress Creek valley, which is consistent with the groundwater availability model predictions of flow from the Carrizo-Wilcox across the Queen City to discharge to streams. Moving from East Texas to Central Texas, the gradients tend to become upward, consistent with an elevation-driven system. This trend is reversed in areas where the Carrizo-Wilcox Aquifer had been substantially developed by 1980, with significant head declines. Such a case can be observed around Brazos

County where the Carrizo heads have been significantly lowered. This head reversal becomes dominant in the Winter Garden region where Carrizo-Wilcox heads have significantly decreased as a result of development. In this area, vertical gradients have been reversed from predevelopment times, with flow directions now being downward from the Queen City and Sparta aquifers (and facies equivalents) to the Carrizo-Wilcox Aquifer. This is a situation where natural vertical flow from the Carrizo to the Queen City in the Winter Garden region has been reversed as a result of cross-formational discharge capture caused by heavy pumping from the Carrizo in the region. The head reversals between the Queen City and the Carrizo also affect groundwater flow within the Queen City and Sparta, impacting natural cross-formational flow within those aquifers. In the long term, development of the Carrizo-Wilcox Aquifer and the Queen City and Sparta aquifers is coupled by capture hydraulics, which can only be quantified by predictive models.

5.9

SUMMARY

The Queen City and Sparta aquifers are coastal plain aquifers that are classified as minor aquifers. These aquifers (and their facies equivalents) extend from the Rio Grande in South Texas to East Texas, with the Sparta Aquifer continuing into Louisiana and Arkansas. These aquifers provide sufficient productivity across their extent in Texas but development is sometimes limited by poor water quality.

Natural groundwater flow within these aquifers is from areas of recharge in the outcrops and downdip through cross-formational inflow to areas of discharge through groundwater flow to streams and springs, groundwater evapotranspiration, and cross-formational outflow. Although impacts from pumping can be observed locally, water levels have remained relatively stable regionally, indicative of relatively low pumping. In areas impacted by pumping, it is expected that in addition to decreased water levels (storage decline), stream base flow, springflow, evapotranspiration, and cross-formational flow have been decreased, and cross-formational inflow has increased as a result of pumping capture.

Through a review of the current Queen City and Sparta groundwater availability models, this chapter has shown that the dominant mechanisms of discharge within these aquifers are stream and spring discharge and groundwater evapotranspiration. Cross-formational flow is also a significant aquifer outflow mechanism, which has been estimated through regional modeling.

Because these components of aquifer discharge are the aquifer flows that are most impacted by pumping, characterization of them is important to ongoing management of the groundwater in these areas. Understanding the current and future impacts to the Queen City and Sparta aquifers as well as the other Texas Coastal Plain aquifers will require a continuation of aquifer monitoring and characterization, stream-aquifer interaction studies, and recharge studies. In addition, evapotranspiration and groundwater evapotranspiration studies are warranted in areas where this discharge mechanism is considered important.

Because of a lack of groundwater evapotranspiration measurements, uncertainty in this source of discharge could be the single greatest contributor to uncertainty in present and future predictions of sustainability of groundwater resources. Groundwater evapotranspiration is known to be a significant source of groundwater discharge in riparian areas and represents a significant source of pumping capture, especially in arid environments. However, groundwater evapotranspiration presents perhaps one of, if not the largest, hurdles for quantification, especially in humid environments where surface evaporation and vadose-zone evapotranspiration can be significant.

Managing Texas water resources will require a focus on understanding the mechanisms and scales of aquifer discharge. Future characterization and modeling studies should be focused on conceptualization and characterization of the aquifer water balance. Groundwater models provide the only means of integrating aquifer information and estimating the available discharge volumes and timing of discharge capture. From a review of the Queen City and Sparta aquifers and the associated groundwater availability models, we can see the importance of discharge as it relates to pumping capture and how many of our aquifer systems are regionally interrelated over the long term.

5.10
ACKNOWLEDGMENTS

Much of this paper is taken from the report documenting the Queen City and Sparta aquifer groundwater availability models. As such, we would like to acknowledge our co-authors on that study: Jean-Philippe Nicot and Seay Nance of the Bureau of Economic Geology and Alan Dutton currently at the University of Texas in San Antonio. We would also like to thank the Texas Water Development Board for funding much of the research provided herein.

5.11
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Chapter 6

Geology, Structure, and Depositional History of the Yegua-Jackson Aquifers

Paul Knox, P.G.[1], Neil E. Deeds, P.E.[2], Scott Hamlin, P.G.[3], and Van Kelley, P.G.[2]

The Texas Water Development Board (TWDB) designated the Eocene-age Yegua-Jackson interval as a minor aquifer in the 2002 State Water Plan (TWDB, 2002). This increase in status from “other aquifer” was a consequence of recognizing the large number of wells in the TWDB database completed in the Yegua-Jackson and the relatively large use of water from this interval (Preston, 2006). In the 2007 State Water Plan, it is reported that the existing groundwater supply in the aquifer is 7,285 acre-feet per year (assuming existing wells and infrastructure) with a total availability estimated at 25,000 acre-feet per year (TWDB, 2007). Domestic, livestock, irrigation, and some municipal uses occur from the Yegua-Jackson Aquifer. Several regions have developed water management strategies in the 2007 State Water plan that would further develop the aquifer, including drilling new wells and desalination. With the implementation of the proposed water management strategies, production from the aquifer is expected to exceed 15,000 acre-feet per year by 2040.

From a hydrogeologic perspective, there had been very little work done in the Yegua-Jackson Aquifer prior to 2006, especially at a scale larger than an individual county (Preston, 2006). As a result, TWDB sponsored a study over the last several years to determine the structure of the Yegua-Jackson Aquifer for the complete Texas section (results reported in Knox and others, 2007) and is currently funding the development of the Yegua-Jackson Aquifer groundwater availability model. This chapter will focus on the results of the recent structure development and will draw some inferences into how the results from this work can be of use for hydrogeologists interested in developing a groundwater availability model of the aquifer.

6.1
YEGUA-JACKSON AQUIFER SETTING

The Yegua-Jackson Aquifer exists predominantly in the outcrop or near-outcrop areas of the Yegua Formation and Jackson Group. In Texas, this outcrop area stretches in a thin band approximately parallel to the coastline, from Starr County in the Rio Grande Valley to Sabine County in East Texas, and is thus bracketed by the Rio Grande River to the south and the Toledo Bend Reservoir (along the Sabine River) to the east (Figure 6-1). The width of this outcrop varies from less than 10 miles in Gonzales County to almost 40 miles in La Salle County, with an area of approximately 11,000 square miles (Preston, 2006). Thirty-five counties intersect the Yegua-Jackson Aquifer as currently delineated (Preston, 2006).

The alternating sand- and clay-rich Yegua-Jackson interval includes the middle Eocene Upper Claiborne Group (Yegua and Cook Mountain formations) and the overlying upper Eocene to Oligocene Jackson Group (Caddell, Wellborn, Manning, and Whitsett formations), as shown in Figure 6-2. These units dip toward the modern coastline and are

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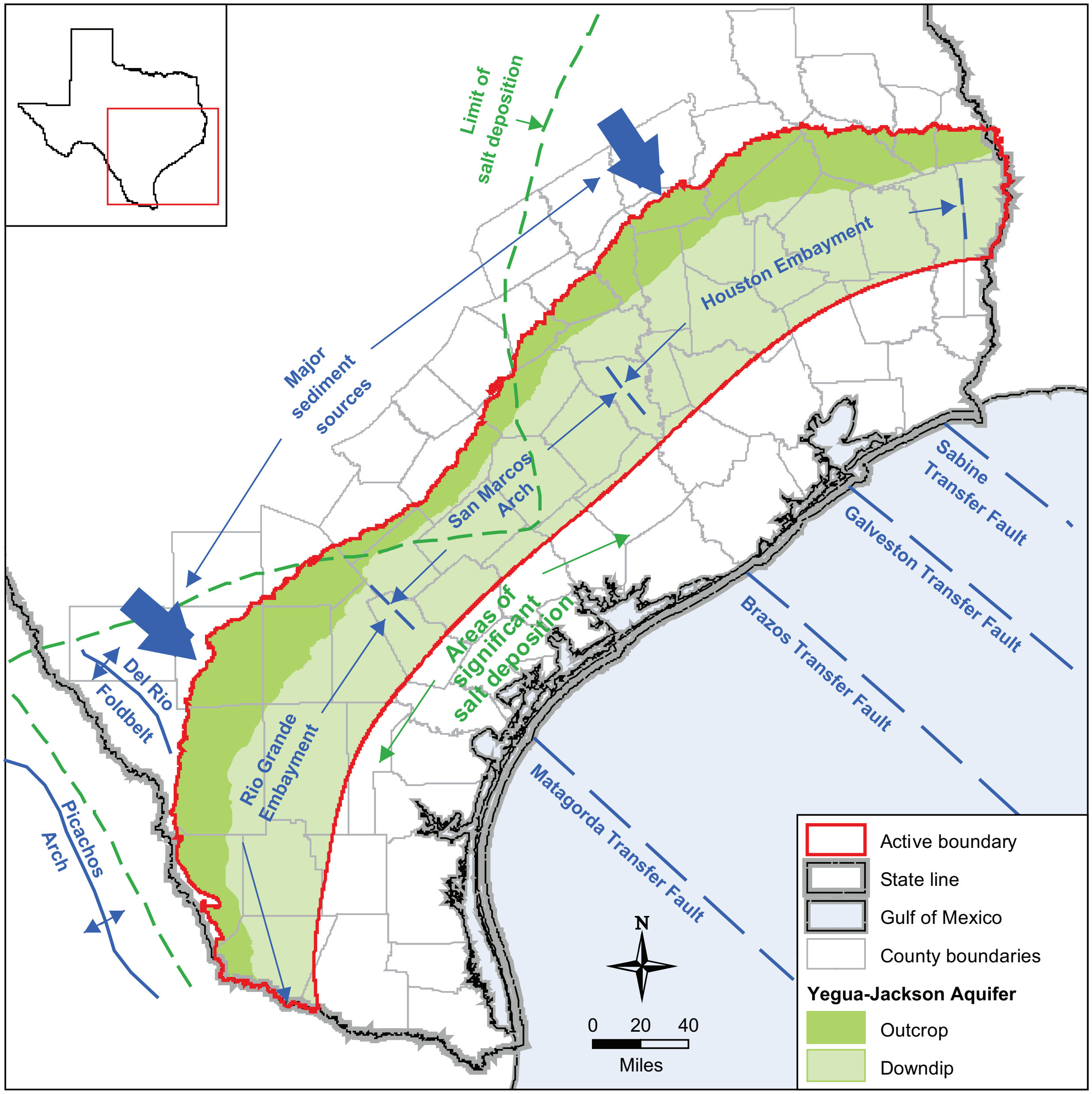

Figure 6-1. Yegua-Jackson structure development study area and major structural elements along the Texas Gulf Coast. Areas of significant salt deposition taken from Galloway and others (1983). Transfer faults from Huh and others (1996). Other features from Ewing (1991).

part of the progressive filling of the Gulf of Mexico Basin by sand, silt, and clay carried from the mountains of northern Mexico and the Rocky Mountains, as well as from other areas of Texas and the western part of the North American continental interior.

The generalized chronostratigraphy and lithostratigraphy for the Yegua-Jackson interval are shown in Figure 6-2 in relation to underlying and overlying units. The Yegua Formation was deposited during a strong influx of sediment, primarily in the Houston Embayment, during the time period from 38.2 to 37.8 mega-annum (Ma). The Jackson Group resulted from a much smaller sediment influx from 37.8 to 37.1 Ma and was deposited primarily on the shelf built by Yegua deposits.

6.2
PREVIOUS INVESTIGATIONS

An abundant body of previous work exists for the Yegua-Jackson interval because of its extensive resources of oil, gas, coal, and uranium. Geologic investigations extend from initial and broad stratigraphic investigations in the 19th century to modern-day detailed subsurface structural, chronostratigraphic, micropaleontologic, and depositional analyses. The hydrogeologic literature is more limited in quantity and scope than the stratigraphic literature and includes county water resource studies by both the U.S. Geological Survey and TWDB.

Early outcrop geology and stratigraphy were established by Renick (1926, 1936) and Sellards and others (1932). The economic importance of oil, gas, coal, and finally uranium resources spurred investigations from the early 1960s through about 1990 (for example, Fisher, 1963; Fisher and others, 1970; Eargle, 1972; Quick and others, 1977; Galloway and others, 1979; Kaiser and others, 1980; Jackson and Garner, 1982; Ewing, 1986; and Galloway and others, 1991). This work established, on the basis of outcrop and subsurface detailed investigations, the general structure, stratigraphy, depositional systems, and lithologic distribution of the Yegua-Jackson interval.

Period	**Epoch**	**Stratigraphic units**		**Age (in 10^6 years)**	**Paleontologic markers**
				32.0	
Oligocene	Lower	Vicksburg Formation			*Textularia warreni* *Globigerina ampliapertura* *Loxostoma delicata*
				33.9	
Eocene	Upper	Jackson Group	Whitsett Formation		*Marginulina cocoaensis, Massalina pratti*
			Manning Formation		*Textularia hockleyensis*
			Wellborn Formation		
			Caddell Formation		*Textularia dibollensis* *Camerina moodysbranchensis*
				37.1	*Nonionella cockfieldensis*
	Middle	Yegua Formation			*Discorbis yeguaensis*
				37.8	*Eponides yeguaensis*
					Anomalina umbonata, Nodosaria Mexicana
				38.2	*Ceratobulimina eximia*
		Cook Mountain Formation			*Operculinoides sabinensis* *Clavulinoides guaybalensis,* *Globorotalia spinulosa, Truncorotaloides topilensis*

Figure 6-2. Paleontologic markers and approximate ages for the Yegua-Jackson interval and adjacent formations. Markers and ages from Fang (2000), Harland and others (1990), and Galloway and others (1991).

Also during this period, the U.S. Geological Survey and TWDB carried out joint studies of the water resources of the Yegua-Jackson in many counties, especially those in southeast Texas (for example, Winslow, 1950; Dale, 1952; Anders and Baker, 1961; Tarver, 1966; Thompson, 1966; Rogers, 1967; Wesselman, 1967; Tarver, 1968; William F. Guyton and Associates, 1970; and Baker and others, 1974). These subsurface studies added important information regarding the distribution of fresh and slightly saline water in the aquifer and aquifer geochemistry.

Yegua-Jackson outcrop distribution was identified and compiled by the Bureau of Economic Geology at The University of Texas at a 1:250,000 scale during the 1970s, 1980s, and 1990s under the direction of Virgil Barnes (Barnes, 1968a, b; 1974a, b, c; 1975; 1976a; 1976b, c; and 1992). The Yegua and Cook Mountain/Laredo formations were mapped across the state. Over a large area of outcrop belt, the main formations of the Jackson Group (Caddell, Wellborn, Manning, and Whitsett) were mapped individually, including some local unit names such as the Yazoo Shale and the Nash Draw Sand.

Studies from the early 1990s to present have been prompted by the discovery of the downdip Yegua oil and gas trend and have employed the technologies of sequence stratigraphy, three dimensional seismic surveys, and organic geochemistry (for example, Sneider, 1992; Goings and Smosna, 1994; Ewing, 1994; Yuliantoro, 1995; Meckel and Galloway, 1996; Swenson, 1997; Ewing and Vincent, 1997; Thomas, 1999; Routh and others, 1999; Galloway and others, 2000; and Fang, 2000). This work has produced a refined chronostratigraphic understanding of the Yegua-Jackson interval that stands in some contrast to the lithostratigraphic-dominated understanding evident in outcrop mapping and in studies from the 1960s, 1970s, and 1980s.

6.3
STUDY APPROACH

The literature review was followed by gathering geophysical well logs and associated well data, chronostratigraphic analysis, digital lithologic analysis, mapping structure, sand distribution, and depositional systems. This analysis supported the subdivision of the Yegua-Jackson Aquifer into operable units that could be correlated across the state. From the top of the aquifer downward, these are the Upper Jackson, Lower Jackson, Upper Yegua, and Lower Yegua layers.

Data used to support the above analysis comprises three types: (1) stakeholder data, (2) borehole geophysical logs, and (3) literature data on Yegua-Jackson structure and on Yegua-Jackson lithology and depositional systems.

6.3.1
Data sources

Solicitation of stakeholders resulted in no electric log data that could be directly used in the project. The bulk of geophysical logs came from The University of Texas Bureau of Economic Geology, TWDB, and the Texas Commission on Environmental Quality Surface Casing Division:

- A grid of well logs and cross sections established by Dodge and Posey (1981) were used as a basis to develop a collection of geophysical logs. Where original logs were missing or inadequate for the study (did not cover the stratigraphic interval) and where wells were needed to create a more uniform grid, additional well logs were obtained from Bureau of Economic Geology files.
- Geophysical logs from two Yegua-Jackson wells in the TWDB library were gathered.
- About 30 logs were obtained from the files of the Texas Commission on Environmental Quality Surface Casing Division.

A total of 250 geophysical logs were selected (Figure 6-3), gathered, and scanned at 300 to 400 dots per inch resolution. Well locations were confirmed from Tobin base maps, and latitudes and longitudes were transferred to a geographic information system database with a resulting accuracy of approximately 1 mile. The spontaneous potential and resistivity curves from 150 logs were digitized for consistent, repeatable percent-sand calculations.

A number of faults that offset the Yegua and Jackson are known to exist within the study area (Quick and others, 1977; Dodge and Posey, 1981). These are predominantly downdip of the outcrop area, but throws on some faults reportedly exceed several hundred feet. These data were summarized in Knox and others (2007). Additionally, salt-related structures occur as localized features in the Rio Grande Embayment and downdip in the Houston Embayment (Ewing, 1986). Although these features may become important for fine-scale aquifer modeling, data spacing in this study was insufficient to yield well-supported detailed structure contour maps.

Data spacing also prevented highly detailed sand thickness mapping. To ensure that significant trends identified in other more detailed studies were not missed, information from Van Dalen (1981), Fisher (1969), and Fisher and others (1970) was compared to sand thickness trends identified in this study. Because Fisher and others (1970) studied the Jackson Group as a single interval, sand thickness contours were used only as very general trends in mapping the two (aquifer) layers of the Jackson that this study recognizes.

6.3.2
Methodology

To apply the chronostratigraphic concepts to the Yegua-Jackson interval, we (1) identified major flooding surfaces in well logs, (2) correlated these flooding surfaces to known paleontologic markers to ensure agreement with existing subsurface formation nomenclature, and (3) correlated the flooding surfaces updip to the point of outcrop and evaluated the correspondence with mapped outcrop formation boundaries. Because major lithologic differences are predominant in outcrop and age-specific flooding surfaces are more prominent in subsurface data, opportunities exist for disagreement between subsurface and outcrop formation boundaries.

From the distribution of the 250 wells used, a grid of 30 dip-oriented cross sections and 3 strike-oriented cross sections was created (Figure 6-3). Dip sections extend from the Yegua-Jackson outcrop area downdip (southeast) more than 50 miles and to depths exceeding 6,000 feet subsea to allow a more complete stratigraphic analysis. Strike sections extend from the Mexico to Louisiana borders. Two sections roughly parallel the outcrop and, depending on their location, show either mostly the Jackson interval (A-A') or mostly the Yegua interval (B-B'). A third strike section, C-C', was created from selected wells so that coverage of both intervals was optimized.

Previous interpretations of bounding surfaces for the base Yegua, top Yegua, top Jackson, base Vicksburg, and top Jackson/Vicksburg were taken directly from or correlated into the well grid from Dodge and Posey (1981), Coleman (1990), and various U.S. Geological Survey/TWDB county studies. Micropaleontologic markers on Dodge and Posey (1981) sections were correlated into the well grid and also taken directly from annotations on original copies of logs used in the grid. Because of the uncertainty of the source of the latter information, those data were used more as a rough check on correlations. Outcrop boundaries of the Jackson and Yegua intervals were projected onto cross sections, and surface elevations along section lines were taken from the U.S. Geological

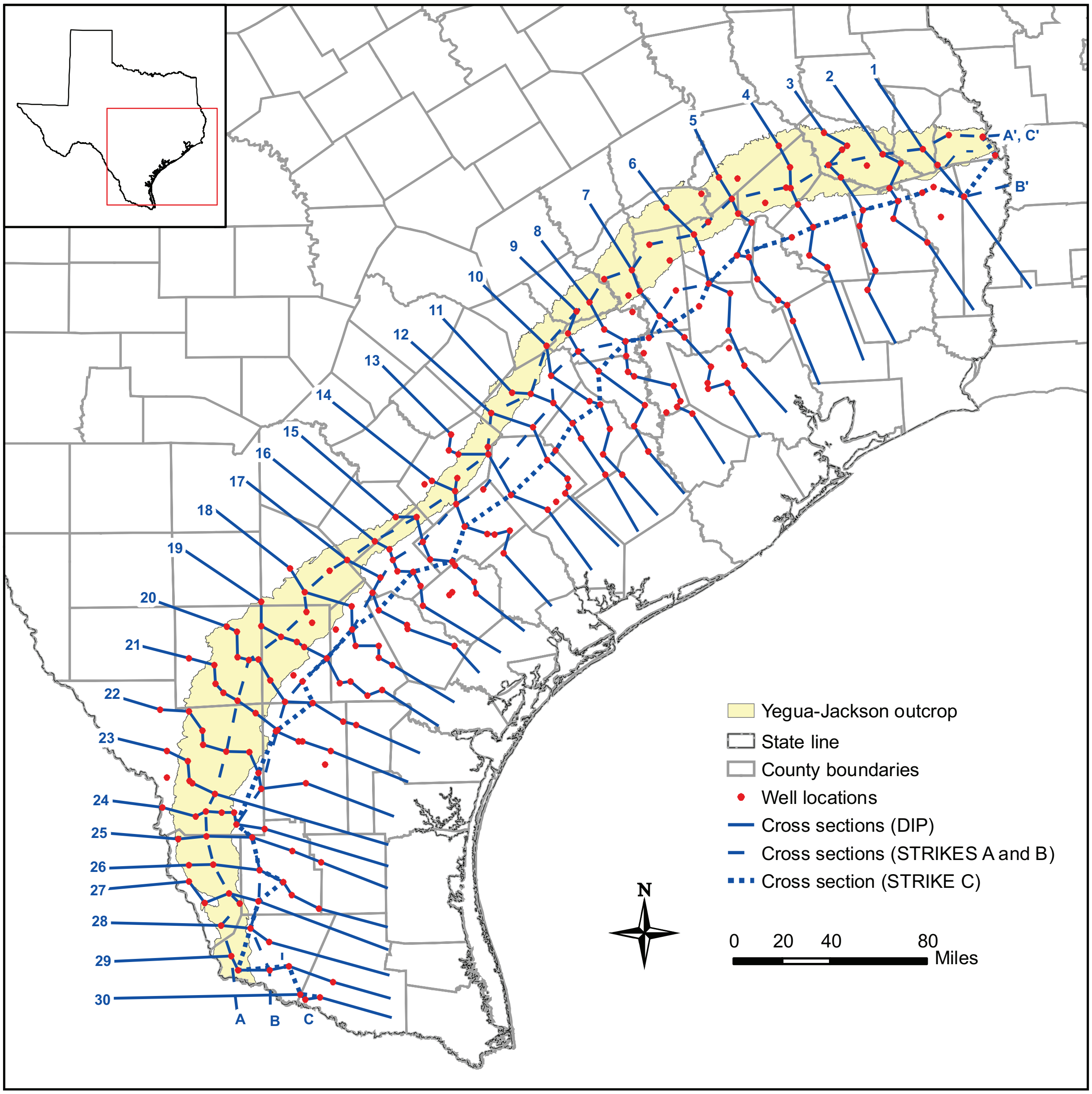

Figure 6-3. Stratigraphic correlation basemap with cross section lines.

Survey digital elevation model to place outcrop boundaries precisely on cross sections.

6.3.2.1
Structure mapping approach

- The structural elevation relative to sea level was mapped across the study area for five key surfaces:
- Top of the Jackson Group (top of Upper Jackson layer)
- Top of Lower Jackson layer
- Top of Yegua Formation (top of Upper Yegua layer)
- Top of Lower Yegua layer
- Base of Yegua-Jackson Aquifer

The first four surfaces are chronostratigraphic, meaning that they correspond to maximum flooding surfaces. The fifth surface, the base of the Yegua-Jackson Aquifer, is a lithostratigraphic surface. It does not follow a maximum flooding surface but instead generally corresponds to the base of significant sand bodies in the Yegua depositional cycle. A sixth surface, the chronostratigraphic base of the Yegua depositional cycle, was also interpreted, corresponding to the maximum flooding surface between the Sparta and Yegua depositional cycles.

6.3.2.2
Lithologic interpretation approach

Cumulative sand thickness in aquifer studies has been determined in the past using many different approaches, yielding results that are sometimes difficult for subsequent workers to reproduce. To overcome this issue, 150 well logs were selected, and spontaneous potential and resistivity curves digitized. Baseline values for shale and/or sand were established, and a cutoff value was used that produced results similar to geologist estimates. Because the study interval included freshwater, transitional, and saline water-bearing sediments, different algorithms and cutoffs were used for each interval. In freshwater zones, the resistivity curve was used to delineate lithology. In saline zones, spontaneous potential was used. And in transitional zones, either curve or a combination of curves was used, depending on mud resistivity and resulting spontaneous potential behavior.

A semi-automated approach was used to estimate the basic lithology, or the relative locations of sands and shales, from appropriate well logs. The automated approach was based on a simple set of rules that an analyst might use in interpreting a well log manually. Implemented in Perl programming language, it established lithology "baselines" for curves based upon the 5th and 95th percentiles of digital log data. A cutoff was applied at 50 percent between those two end members to discriminate sand from shale at the sample spacing of 0.5 foot. Values were summed over each layer to yield total sand thickness by layer. After calculated values were posted on base maps for each interval, each value was qualitatively compared to the original log by a geologist to confirm reasonable accuracy. When wells only partially penetrate a layer, sand thickness was considered a minimum value for the purpose of data contouring. In such cases, values were posted as '>' to visually indicate a minimum value and note the associated uncertainty.

Sand thickness values at wellbores were then divided by the isopach values at the wellbores to determine the layer sand percent, which was then gridded in ArcGIS 9.2 using the "topo to raster" function. Sand thickness grids were then created by multiplying the sand percent grids by the layer isopach grids. The final sand thickness maps contoured with "topo-to-raster" were then compared to sand thickness maps from previous workers such as Fisher and others (1970). In all cases, major features of published maps were captured adequately using the current distribution of study wells and unbiased computer contouring. Final maps were thus computer contoured, as opposed to hand contoured, because this process is simple and repeatable, and maps are easily updated as additional data become available.

6.3.2.3
Depositional systems mapping approach

For the four Yegua-Jackson layers, sand thickness trends from this study and other published studies were incorporated with interpretations of depositional setting based upon log curve shape and previous work. Regions of a layer dominated by similar depositional facies were outlined by hand, and hand-drawn boundaries were then digitized for incorporation as a geographic information system layer. In many cases, sand thickness values were used as proxies for determining position within a larger depositional system.

For example, deltaic settings in a Yegua layer containing less than 100 feet of sand were mapped as delta margins. The resulting facies-based regions of a layer can be used in modeling to constrain hydrologic parameters across a modeling layer.

6.4
AQUIFER STRUCTURE AND HYDROSTRATIGRAPHY

As discussed previously, the Yegua-Jackson Aquifer was subdivided into four layers on the basis of regionally correlatable shale-dominated horizons. Each of these layers is a separate hydrostratigraphic unit in which fluid flow is dominantly lateral and cross-layer flow is limited.

6.4.1
Yegua-Jackson Aquifer structure

This section will describe each of the four units of the Yegua-Jackson Aquifer and provide structure contour and isopach maps for each. Structure contours are generally smooth and follow the directional trends of the outcrop belt. Although down-to-the-coast growth faults, salt features, and even small, local up-to-the-coast faults exist, they were not accurately mappable, given the data spacing of this study. Future detailed studies should refer to Quick and others (1977), Dodge and Posey (1981), or Ewing (1986). In general, many faults exceeding 300 feet of throw for distances of 10 to 20 miles occur near the outcrop and in the shallow subsurface in South Texas from the San Marcos Arch southward (DeWitt, Karnes, Bee, Live Oak, Duval, Webb, Jim Hogg, and Starr counties). Fewer such faults are noted north and east of the San Marcos Arch, but studies of the detail of Quick and others (1977) that cover this area were not found during this study. Longer faults with throws exceeding 1,000 feet occur in the deeper subsurface of the Yegua-Jackson interval more than 30 miles downdip of the outcrop and roughly coincident with the Yegua-Jackson shelf edge.

Structural dips of Yegua-Jackson Aquifer layers are markedly steeper across the San Marcos Arch and flatter in the Houston and Rio Grande embayments (Figures 6-4 and 6-5). The Rio Grande Embayment has perhaps the gentlest dips, which occur in the LaSalle-McMullen County area. South Texas also has the steepest dips, occurring in southwestern Zapata and western Starr counties. Similarly, isopach maps (Figure 6-6) show that the thinnest areas are across the San Marcos Arch, with the Houston and Rio Grande embayments collecting the greatest sediment thicknesses. Cross sections and isopach maps (Figures 6-6, 6-7, and 6-8) of the interpreted structure (Knox and others, 2007) demonstrate that layers thicken very gradually in the downdip direction, resulting in subtle divergence of layer boundaries. Following is a discussion of regional thickness trends in each layer.

The Lower Yegua unit ranges in thickness from less than 500 feet near the updip limit of well control to more than 1,100 feet in middip to downdip parts of the study area. The Upper Yegua unit varies in thickness from less than 500 feet at the updip limit of well control up to more than 1,200 feet at the downdip study edge. The Lower Jackson unit ranges in thickness from less than 400 feet at the updip limit of well control to nearly 600 feet at the downdip edge of the study area. The Upper Jackson unit varies in thickness from less than 500 feet at the updip limit of well control to more than 1,000 feet at the downdip study edge.

6.4.2
Aquifer heterogeneity and character

Preceding discussions have addressed the logical subdivision of the Yegua-Jackson Aquifer into four layers and elucidated the structure and thickness of those layers. Each layer will likely be

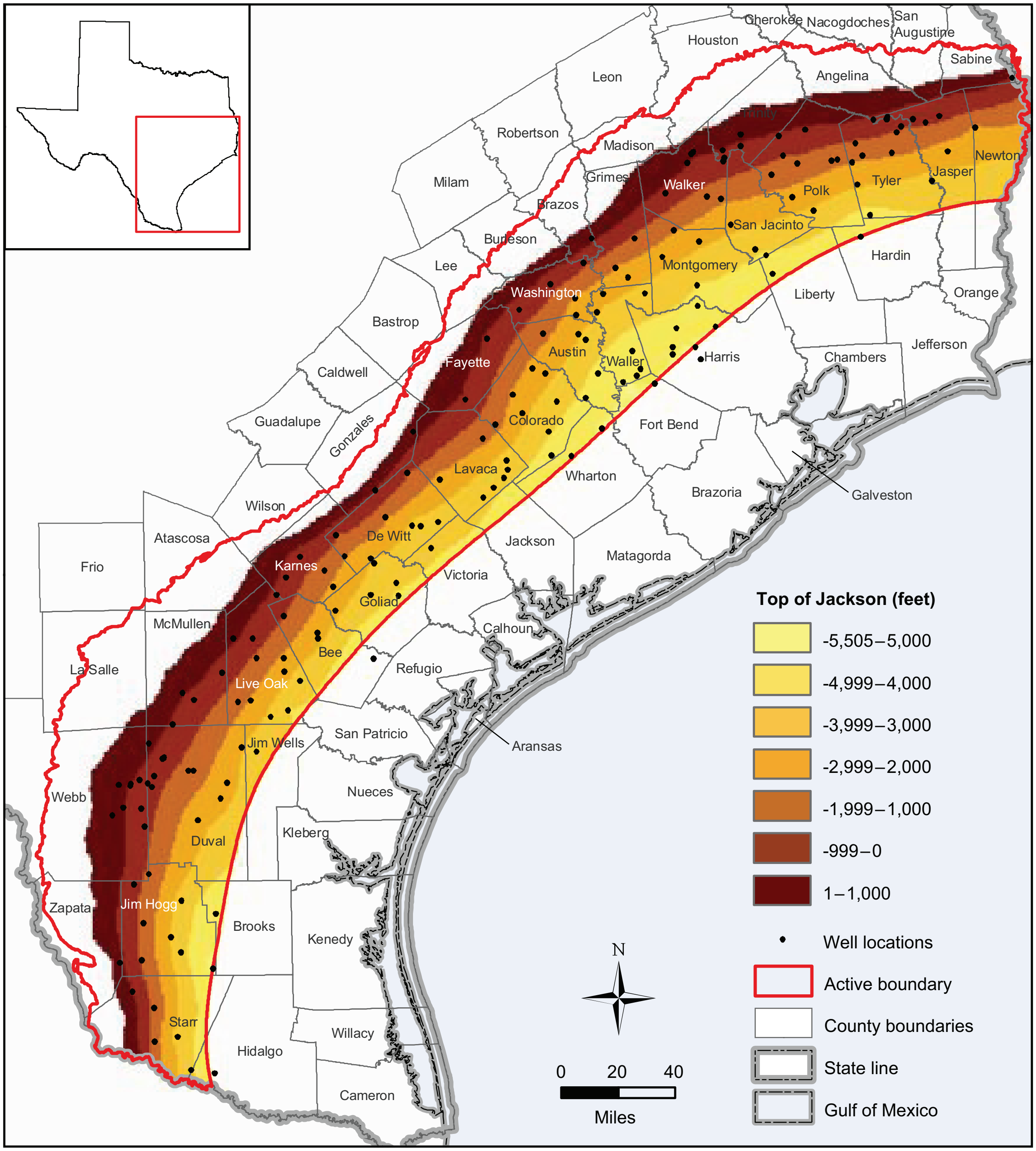

Figure 6-4. Top of Upper Jackson unit (Knox and others, 2007).

modeled as an individual unit. The lateral distribution of sand thickness within each layer and the depositional facies of those sands constitute the depositional heterogeneity of the aquifer. The quality and vertical and lateral connectedness of sands, along with any structural overprinting, govern the character of the aquifer. In this sense, character refers to the overall behavior of the aquifer and its response to inputs such as reduced recharge or increased pumping.

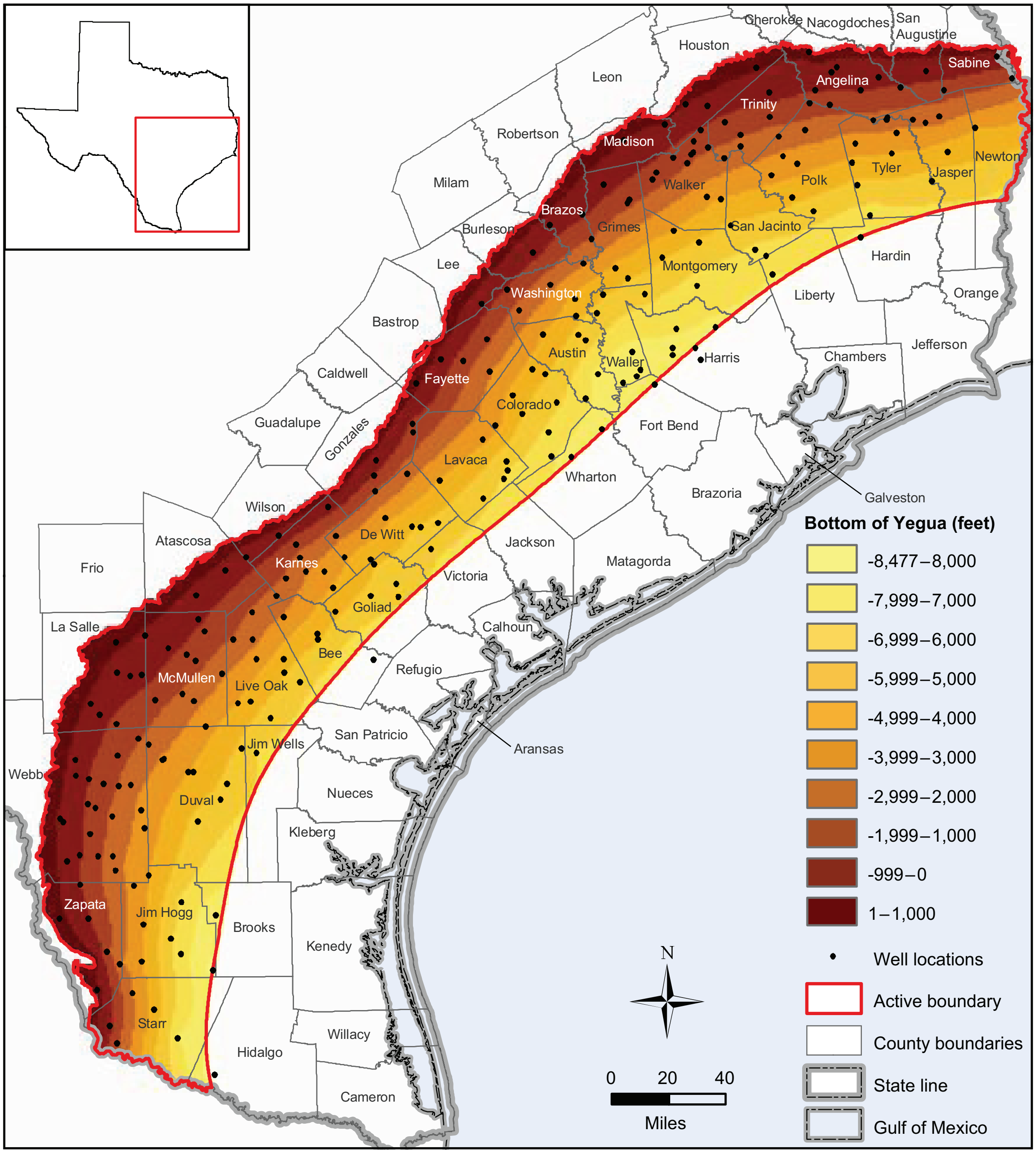

Figure 6-5. Base of Yegua-Jackson Aquifer (Knox and others, 2007).

General sand thickness, depositional facies, and character for each unit are discussed in the following sections, in the order in which they were deposited (Lower Yegua through Upper Jackson). For a complete discussion of the interpretive methods used, please refer to Knox and others (2007).

6.4.2.1

Lower Yegua unit

Net sand thickness of the Lower Yegua exceeds 400 feet in small areas and is greater than 100 feet across three-quarters of the study area. Sand thickness in the outcrop area is generally greater

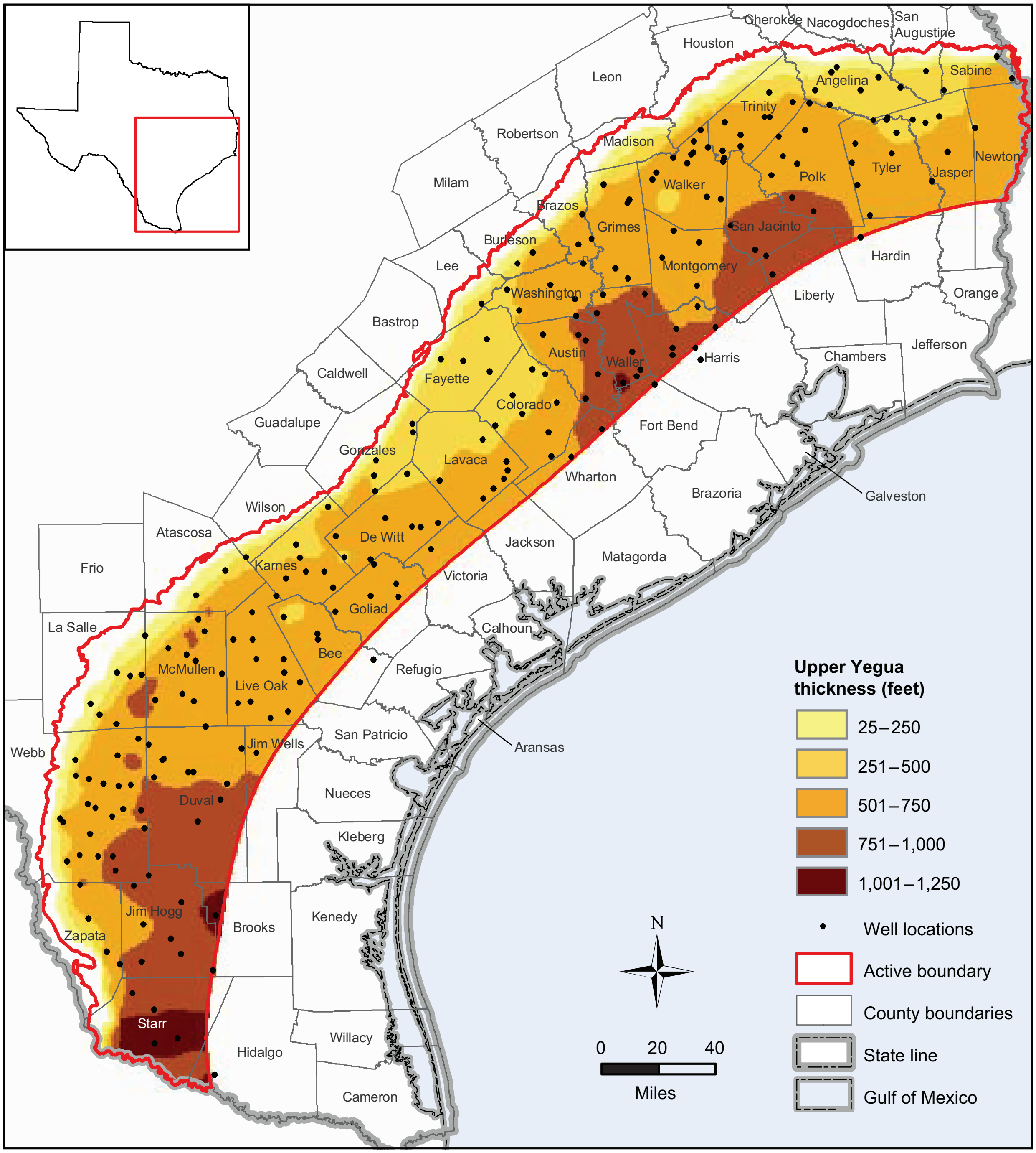

Figure 6-6. Thickness of Upper Yegua unit (Knox and others, 2007).

than 100 feet, except along the north and south flanks of the San Marcos Arch, and is commonly greater than 200 feet, reaching a maximum of more than 500 feet in far South Texas. In the subsurface, the Lower Yegua unit is thicker than 250 feet over large areas of the Houston Embayment and exceeds 400 feet across a broad area downdip of LaSalle and Webb counties in South Texas.

In the Lower Yegua unit, updip sand-rich intervals dominated by upward-fining sands are interpreted as dip-oriented fluvial deposits. Intervening areas of less than 100 feet of sand are marginal to these

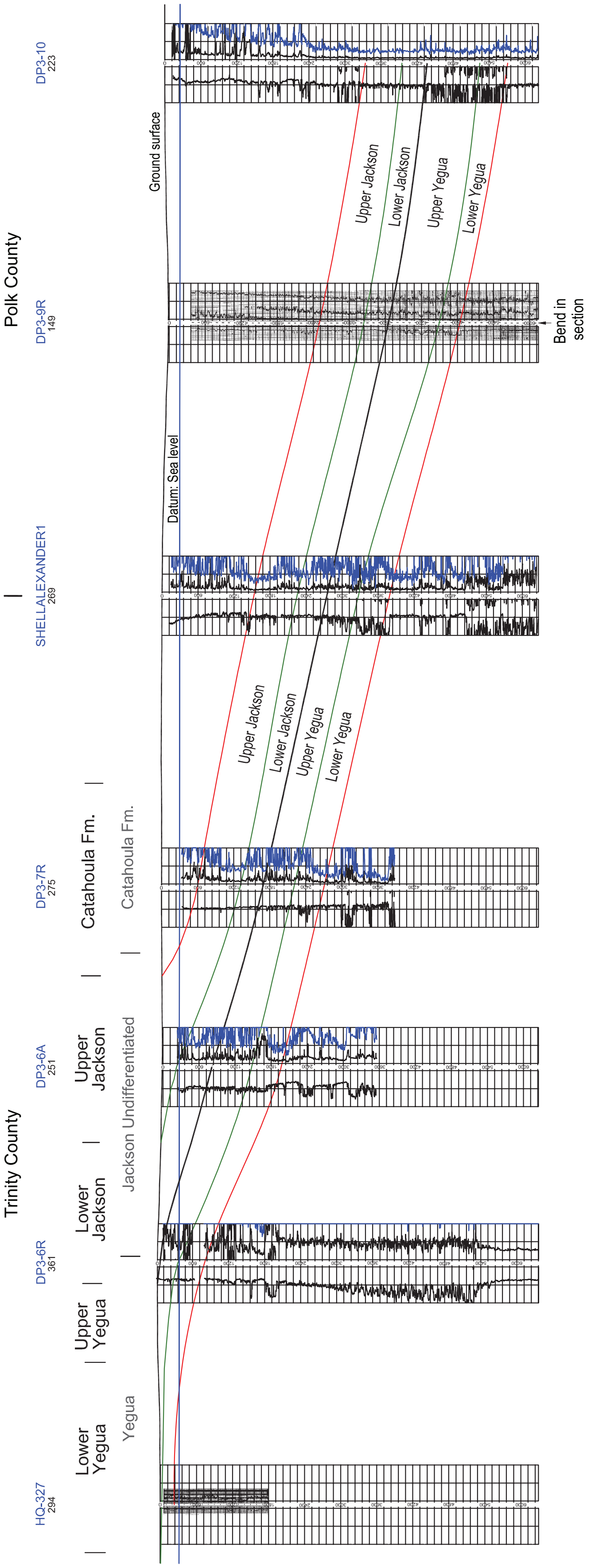

Figure 6-7. Modified dip section 4.

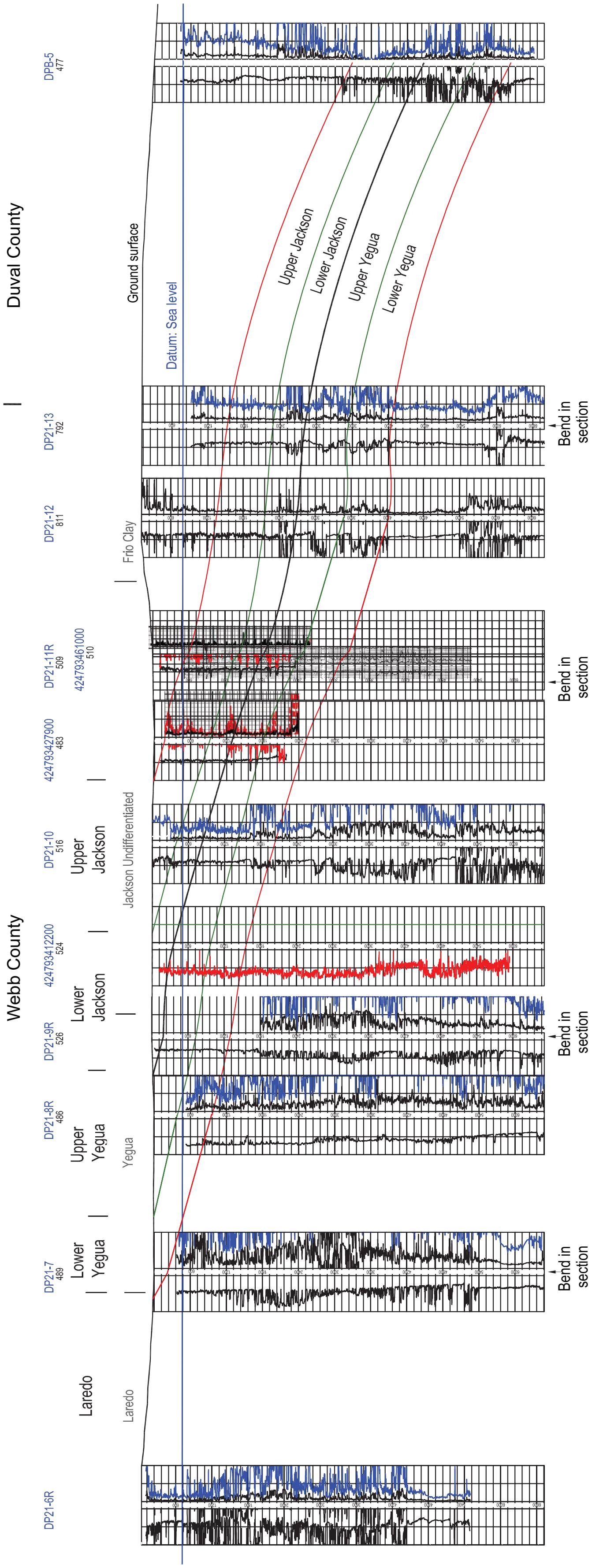

Figure 6-8. Modified dip section 22.

fluvial axes and are considered floodplain deposits, even though these areas may contain some individual upward-fining fluvial sand bodies. Sand-rich regions across the middle of the study area that are dominated by upward coarsening or blocky sand bodies are interpreted as deltaic facies fed by updip fluvial systems. In the northern and southern part of the study area, these deltas prograde out to the shelf-edge position as interpreted by Galloway and others (1983). Areas between the fluvial deposits and the shelf edge that contain less than 50 feet of net sand are interpreted as delta margin deposits. The area downdip of the shelf edge is dominated by shale, but a sandy interval in a well in South Texas exhibits an upward-fining sand body approximately 100 feet thick. This suggests that sandy sediment bypassed the delta and was carried by channels across the slope.

The predominance of fluvial facies in the outcrop area of the Lower Yegua unit would be expected to impart a strong dip-oriented bias in fluid flow, with only localized outcropping sand bodies to receive recharge. Deeper portions of the aquifer in the Houston Embayment will also probably have a dip-oriented grain, impressed upon it by the fluvially dominated deltaic facies and apparent dip-oriented incised channels on the shelf and slope. Communication with higher salinity areas of the aquifer and with basinal fluid might be expected to be significant, but downdip faulting may limit basinal driving pressures. Downdip deposits across the San Marcos Arch are limited and do not extend far downdip. In South Texas, the apparent dominance of wave-influenced deposition is expected to impart a more strike-oriented grain to fluid flow in the deeper subsurface. Progradation in far South Texas of deltas to and over the shelf edge have the possibility of increasing communication with deep basinal fluid regimes, especially because of locally steeper dips. However, the abundance of faults of more than 300 feet of throw for strike distances of 10 to 20 miles in the subsurface may act, especially locally, to impede such communication.

Fluvial sand bodies encountered in outcrop are expected to have high horizontal hydraulic conductivities and, internally, low to moderate vertical conductivities. Fluvial sand bodies in South Texas may have been influenced by a more arid climate, producing bed-load-dominated rivers, the deposits of which will be coarser grained and more internally heterogeneous. Such deposits would have very high lateral conductivity and moderate to good vertical conductivity. Fluvially dominated deltaic sands of the Houston Embayment will likely have slightly lower lateral conductivities and perhaps significantly lower effective vertical conductivity because of an increase in interbedded clay and mud. Distal deltaic and shelf facies can be expected to have progressively lower, respectively, lateral conductivity because of reduced grain size and reduced vertical conductivity because of increasingly laterally continuous mud and clay layers. Wave-modified or -dominated deltas from the San Marcos Arch southward would be expected to have finer grain size but better sorting and less interbedded mud and clay, resulting in moderate to high lateral conductivity and moderate to high vertical conductivity.

6.4.2.2
Upper Yegua unit

Sand thickness in the Upper Yegua unit outcrop area (Figure 6-9) generally exceeds 10 feet, except in the Rio Grande Embayment where sand is limited to very narrow dip-oriented bodies. Thicknesses of more than 200 feet are common in the outcrop area of the Houston Embayment, and across the San Marcos Arch, outcrop areas may contain as much as 400 feet of sand. In the subsurface, broad regions greater than 200 feet in thickness occur in

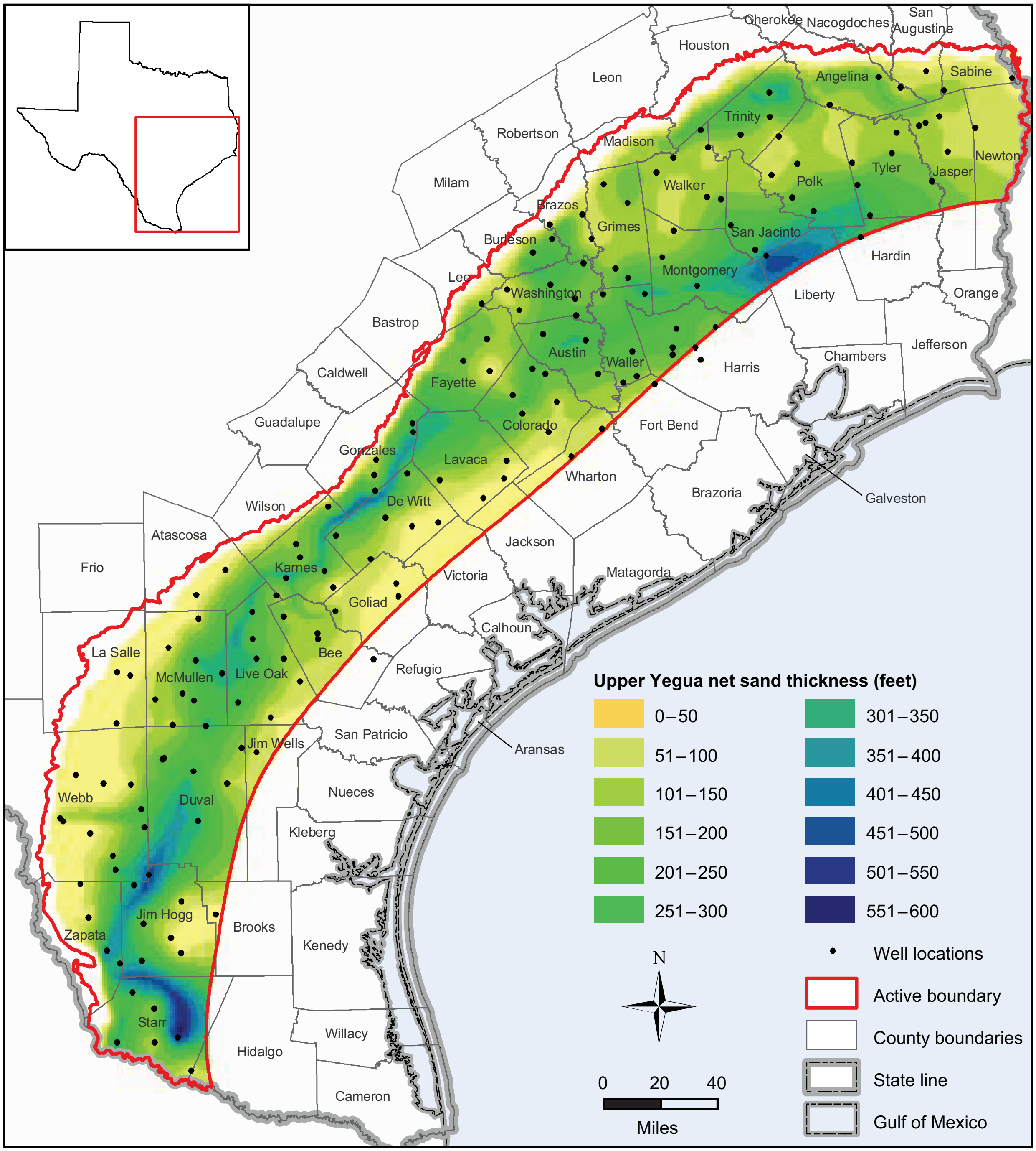

Figure 6-9. Net sand thickness of Upper Yegua unit (Knox and others, 2007).

the Houston Embayment, reaching a maximum of more than 400 feet near the junction of Liberty and San Jacinto counties. A strike-oriented sand exceeding 350 feet in thickness stretches from near the outcrop across the San Marcos Arch into the subsurface of the Rio Grande Embayment (Figure 6-9), emerging in outcrop in far South Texas. A maximum thickness of 575 feet was encountered in the subsurface of eastern Starr County. Shales in the updip area may contain thin (5 feet) to thick (50 feet) upward-fining sand interbeds, whereas downdip shales commonly occur in the upper part of the unit, may

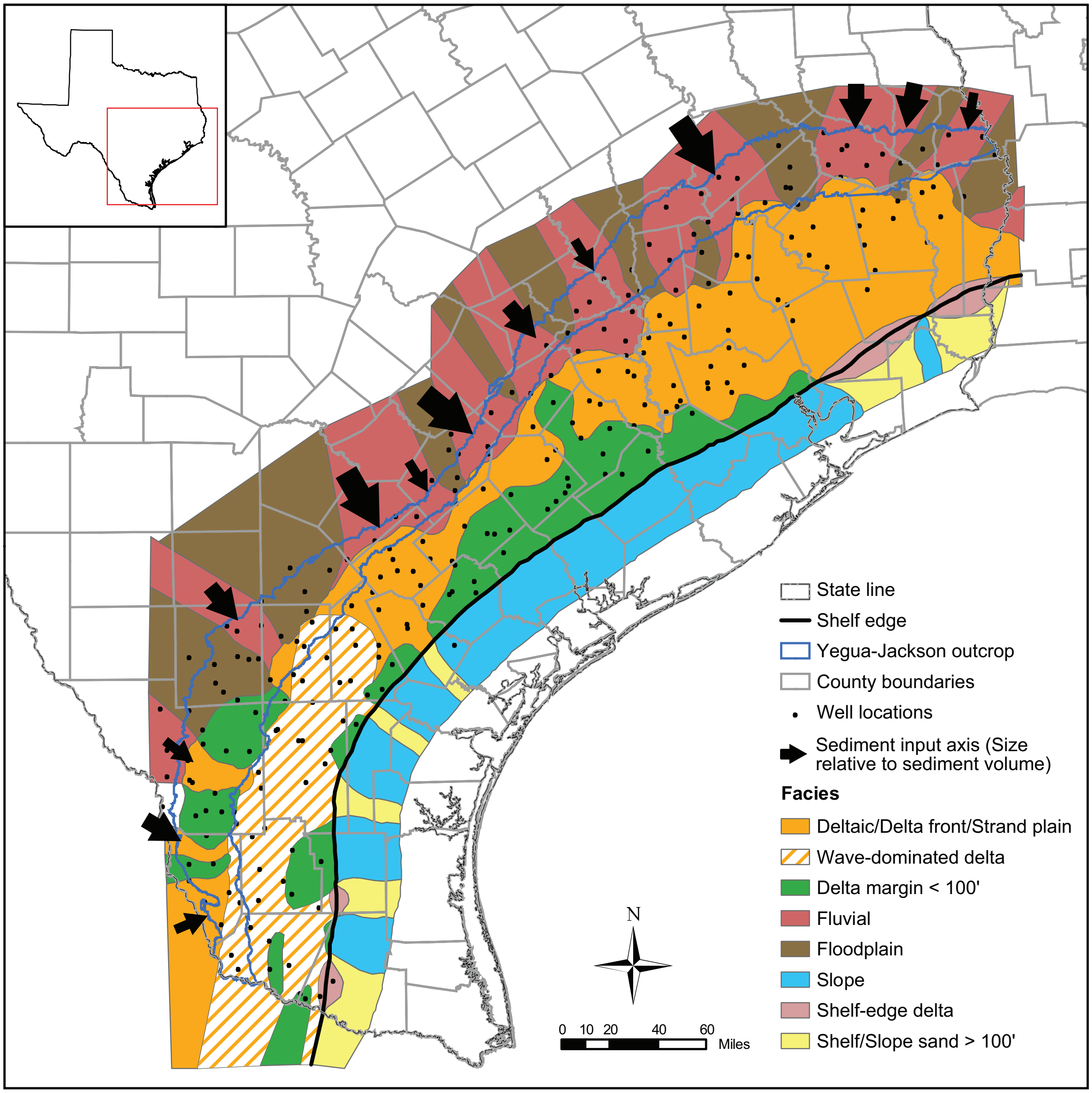

Figure 6-10. Upper Yegua depositional facies map (Knox and others, 2007).

be several hundred feet thick, and may contain thin (<10 feet) isolated sand interbeds.

The interpreted facies map for the Upper Yegua unit is shown in Figure 6-10. As in the Lower Yegua, updip regions are interpreted as fluvial axes separated by floodplain deposits (defined as having less than 100 feet of net sand). Sand-rich regions across the middle of the study area are interpreted as deltaic deposits fed by the updip fluvial systems. Deltaic centers in the southern part of the study area are likely more wave dominated as suggested by strike alignment and the dominance of blocky sand bodies. Thick sand accumulations at the shelf edge containing blocky sands or interbedded sand and shale are interpreted as shelf-edge deltas. These were constructed as deltas built to the shelf edge. Because of the rapidly deepening waters basinward of the shelf edge, sand deposits built vertically instead of continuing to prograde.

It is extremely likely, assuming the shelf-edge position is accurate, that abundant sand bypassed deltas near the shelf edge and was deposited on and carried across the slope.

As with the Lower Yegua unit, the predominance of fluvial facies in the outcrop area of the Upper Yegua unit in the Rio Grande Embayment would be expected to impart a strong dip-oriented bias in fluid flow, with only localized outcropping sand bodies receiving recharge. Outcrops as well as deeper portions of the aquifer in the Houston Embayment will also probably have a dip-oriented grain, impressed upon them by the fluvially dominated deltaic facies and apparent dip-oriented incised channels on the shelf and slope. Communication with higher salinity areas of the aquifer and with basinal fluid might be expected to be significant, but downdip faulting may limit basinal driving pressures. Sand deposits across the San Marcos Arch are significant near outcrop but do not extend far downdip. The linear strike-parallel nature of areas of thick sand suggest deposition in a wave-modified or -dominated deltaic or strand-plain setting, which is expected to impart a strike-oriented grain governing fluid flow. These trends continue into South Texas, where a similar strike-oriented bias would be expected. Progradation in far South Texas of deltas to and over the shelf edge have the possibility of increasing communication with deep basinal fluid regimes, especially because dips in the outcrop belt are markedly steeper. However, the abundance of faults of more than 300 feet of throw for strike distances of 10 to 20 miles in the subsurface may act, especially locally, to impede such communication.

Fluvial sand bodies encountered in the outcrops of South Texas are expected to have very high horizontal hydraulic conductivities and moderate to good vertical conductivities, for reasons cited above, whereas those in the Houston Embayment will likely have high horizontal and low to moderate vertical conductivities. Fluvially dominated deltaic sands of the Houston Embayment will likely have slightly lower lateral conductivities and perhaps significantly lower effective vertical conductivity because of decreased grain size compared with fluvial sands and an increase in interbedded clay and mud. Distal deltaic and shelf facies can be expected to have progressively lower, respectively, lateral conductivity because of reduced grain size and reduced vertical conductivity because of increasingly laterally continuous mud and clay layers. Wave-modified or -dominated deltas from the San Marcos Arch southward would be expected to have finer grain size but better sorting and less interbedded mud and clay, resulting in moderate to high lateral and vertical conductivity. Incised channels on the shelf and slope are expected to have moderate to high horizontal conductivity because of the coarser nature of sediments commonly delivered during sea level lowstands, the time at which such channels are most active. However, fill in these channels may be complex, so horizontal conductivity orthogonal to channel axes may be significantly reduced, as would be vertical conductivities.

6.4.2.3
Lower Jackson unit

Sand is a minority lithology in the Lower Jackson interval. Sand thicknesses in the outcrop exceed 100 feet only in the southern part of the Houston Embayment, the flanks of the San Marcos Arch, and far South Texas. Sand is broadly present in outcrops of the northern Houston Embayment but is generally thin, being less than 100 feet thick. In the main part of the Rio Grande Embayment, sand is present at outcrop only in narrow dip-oriented bodies. In the subsurface of the Houston Embayment, rounded sand regions 20 to 40 miles across occur where sand thickness exceeds 150 feet. These thick areas give way downdip to narrower (10–20 mile wide), dip-oriented regions approximately 100 feet thick. Areas between these rounded regions are narrow (5 miles) areas where sand may be less than 50 feet thick. From the south flank of the San Marcos Arch through the Rio Grande Embayment, a strike-parallel region approximately 30 miles wide exists where sand thickness often exceeds 100 feet and locally exceeds 200 feet. Downdip of this region, sand thickness tapers rapidly to zero. In far South Texas, an area where sand thickness exceeds 300 feet locally extends from the outcrop area in a dip direction to the downdip limit of control.

In the updip regions of the Lower Jackson unit, as in the Yegua, the depositional facies are interpreted as fluvial axes separated by floodplain deposits (defined as having less than 50 feet of net sand). Sand-rich regions across the middle of the study area are interpreted as deltaic deposits fed by the updip fluvial systems. Areas between fluvial and deltaic settings but containing less than 50 feet of net sand and dominated by thin upward-coarsening sands are interpreted as delta margins. Areas downdip of deltaic regions and containing between zero and 50 feet of net sand are interpreted as distal deltaic facies. Deltaic centers in the southern part of the study area have been interpreted by Fisher and others (1970) as being more wave-dominated deltas, or even strand-plain/barrier bar systems, as suggested by strike alignment and the dominance of blocky sand bodies. A similar interpretation is made here, and it is noted that more strike-aligned sand bodies result in a decrease of sand in the outcrop direction. Downdip shale-dominated intervals are more abundant in the Lower Jackson than in either of the Yegua units, indicating a significantly higher relative sea level, possibly related to decreased sediment supply. Thick sand accumulations at the shelf edge containing blocky sands or interbedded sand and shale are again interpreted as shelf-edge deltas, which feed sand down across the slope in narrow dip-oriented channels.

As with Yegua units, the predominance of fluvial facies in the outcrop area of the Lower Jackson unit in the Rio Grande Embayment and parts of the Houston Embayment would be expected to impart a strong dip-oriented bias in fluid flow. Fluvial axes in the Rio Grande Embayment are narrow, whereas those in the Houston Embayment are broad and common, with concomitant differences in recharge opportunity. Outcrops, as well as deeper portions of the aquifer in the Houston Embayment, will also probably have a dip-oriented grain, impressed upon them by the fluvially dominated deltaic facies and apparent dip-oriented incised channels on the shelf and slope. Communication with higher salinity areas of the aquifer and with basinal fluid might be expected to be significant, but downdip faulting of the few narrow shelf channels may strongly limit basinal driving pressures. Sand deposits across the San Marcos Arch are significant near outcrop but do not extend far downdip. The linear strike-parallel nature of areas of thick sand suggest deposition in a wave-modified or -dominated deltaic or strand-plain setting, which is expected to impart a strike-oriented grain governing fluid flow. These trends continue into South Texas, where a similar strike-oriented bias would be expected. Progradation in far South Texas of deltas to and over the shelf edge have the possibility of increasing communication with deep basinal fluid regimes, especially because dips in the outcrop belt are markedly steeper. However, the abundance of faults of more than 300 feet of throw for strike distances of 10 to 20 miles in the subsurface may act, especially locally, to impede such communication.

Fluvial sand bodies encountered in the outcrops of South Texas are expected to have very high horizontal hydraulic conductivities and moderate to good vertical conductivities, for reasons cited above, whereas those in the Houston

Embayment will likely have high horizontal and low to moderate vertical conductivities. Fluvially dominated deltaic sands of the Houston Embayment will likely have slightly lower lateral conductivities and perhaps significantly lower effective vertical conductivity because of decreased grain size compared with fluvial sands and an increase in interbedded clay and mud. Distal deltaic and shelf facies can be expected to have progressively lower, respectively, lateral conductivity because of reduced grain size and reduced vertical conductivity, which results from increasingly laterally continuous mud and clay layers. Wave-modified or -dominated deltas from the San Marcos Arch southward would be expected to have finer grain size but better sorting and less interbedded mud and clay, resulting in moderate to high lateral conductivity and moderate to high vertical conductivity. Incised channels on the shelf and slope are expected to have moderate to high horizontal conductivity because of the coarser nature of sediments commonly delivered during sea level lowstands, the time at which such channels are most active. However, fill in these channels may be complex, so horizontal conductivity orthogonal to channel axes may be significantly reduced, as would be vertical conductivities.

6.4.2.4
Upper Jackson unit

Shale dominates the Upper Jackson interval, with thin sands (most less than 30 feet thick) occurring in the middle or upper parts of the unit. More than 50 feet of sand is encountered in wide areas of the outcrop area, with the exception of the northernmost Houston Embayment and regions of the Rio Grande Embayment. Areas of unusually thick sand occur in the central Houston Embayment (Figure 6-11) where accumulations exceed 200 feet and far South Texas where they locally exceed 150 feet. A strike-oriented trend of thick sand extends from the central Houston Embayment where it can exceed 300 feet down across the San Marcos Arch and through the Rio Grande Embayment where it can reach more than 200 feet. This belt, which is approximately 30 miles wide and begins at the outcrop or just downdip (Figure 6-11), is locally interrupted by breaks 5 to 20 miles wide in which sand accumulation is less than 100 feet. In the southern Houston Embayment, dip-oriented fingers of 20 to 40 miles in width extend downdip to the limit of control. Across the San Marcos Arch and into the northern Rio Grande Embayment, broad regions where sand is absent lie downdip of the sand belt.

The interpreted facies map for the Upper Jackson unit is shown in Figure 6-12. As in the Yegua, updip regions are interpreted as fluvial axes separated by floodplain deposits (defined as having less than 50 feet of net sand). Sand-rich regions across the middle of the study area are interpreted as deltaic deposits fed by the updip fluvial systems. Areas between fluvial and deltaic settings but containing less than 50 feet of net sand and dominated by thin upward-coarsening sands are interpreted as delta margins. Areas downdip of deltaic regions and containing from less than 50 feet of net sand to zero sand are interpreted as distal deltaic facies. Areas updip of the shelf edge having no sand are mapped as “shelf” facies.

Deltaic centers in the southern part of the study area, as in the Lower Jackson layer, appear strongly wave influenced, especially compared to deltas in the northern part of the study area in which patterns of thick sands are more dip-oriented and are likely more fluvially dominated. Downdip shale-dominated intervals are less abundant in the Upper Jackson than in the Lower Jackson. This reinvigorated progradation (although still weaker than the Lower Yegua) indicates a lower relative sea level, possibly related to increased sediment supply. Thick

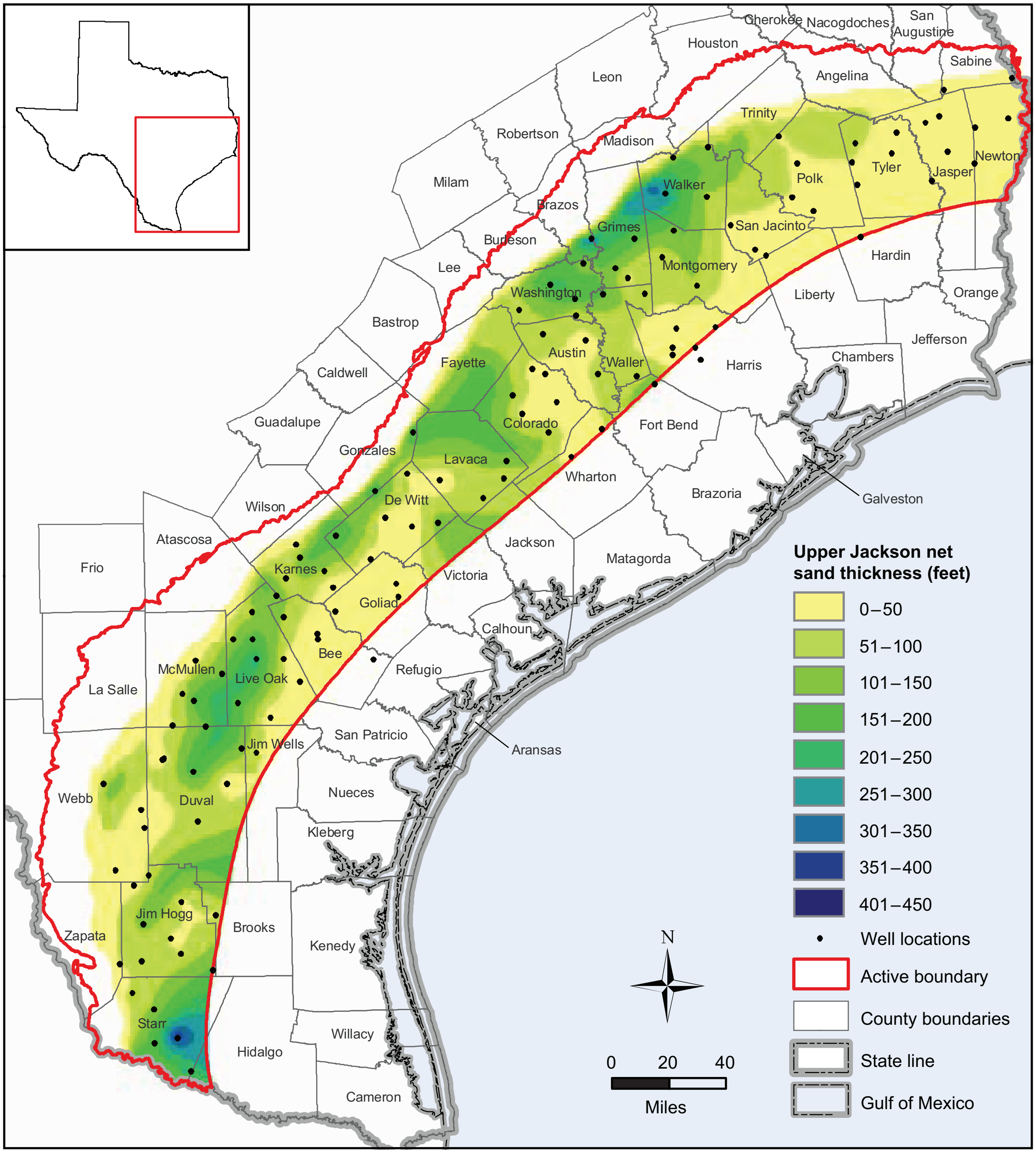

Figure 6-11. Net sand thickness of Upper Jackson unit (Knox and others, 2007).

sand accumulations at the shelf edge containing blocky sands or interbedded sand and shale are again interpreted as shelf-edge deltas, which feed sand down across the slope in narrow dip-oriented channels. However, in the Upper Jackson, the southern wave-dominated delta has built to, or past, the shelf edge, creating a strike-aligned shelf-edge sand body.

Fluvial facies in the southern half of the outcrop area of the Upper Jackson unit are expected to impart a strong dip-oriented bias in fluid flow, as would fluvial and fluvially dominated deltaic deposits

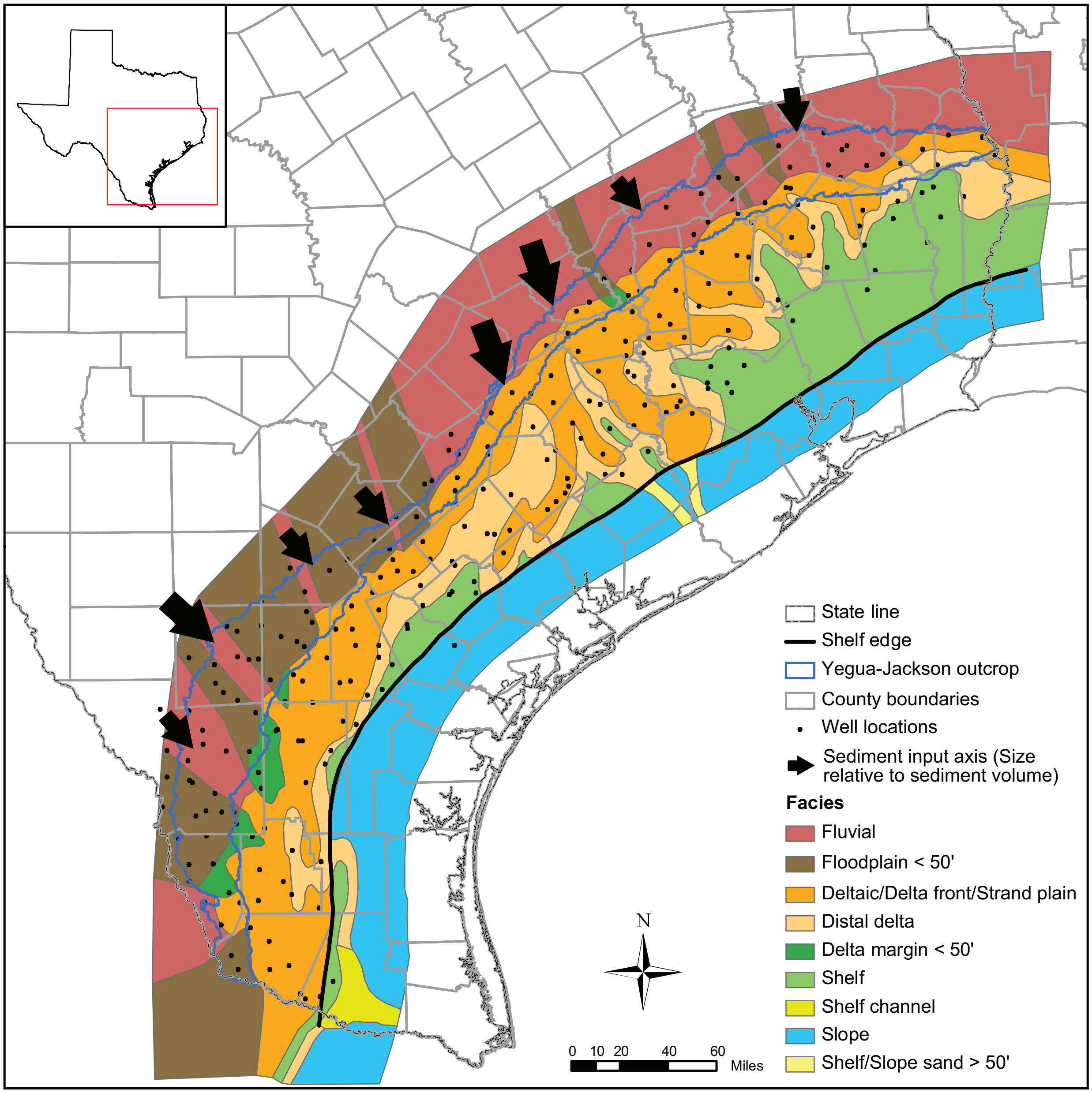

Figure 6-12. Upper Jackson depositional facies map (Knox and others, 2007).

in the northern half of the outcrop area. Such a bias would continue into the subsurface in the Houston Embayment, especially in the southern end of that area where thick sands reach the shelf edge. Communication with higher salinity areas of the aquifer and with basinal fluid might be expected to be significant, but downdip faulting of broad delta lobes and narrow incised channels may limit basinal driving pressures. Downdip of outcrops in the southern half of the study area, linear strike-parallel areas of wave-modified or -dominated deltaic or strand-plain sands are expected to impart a strike-oriented grain governing fluid flow. Because these deltas reach the shelf edge, there may be many narrow incised channels that cross the slope, in addition to the broad area mapped in Hidalgo County that does so. Communication with deep basinal fluid regimes would be expected, especially because of the steep dips in the outcrop area of far

South Texas. However, the abundance of faults of more than 300 feet of throw for strike distances of 10 to 20 miles in the subsurface may act, especially locally, to impede such communication.

Fluvial sand bodies encountered in the outcrops of South Texas are expected to have very high horizontal hydraulic conductivities and moderate to good vertical conductivities, for reasons cited above, whereas those in the Houston Embayment will likely have high horizontal and low to moderate vertical conductivities. Fluvially dominated deltaic sands of the Houston Embayment will likely have slightly lower lateral conductivities and perhaps significantly lower effective vertical conductivity because of decreased grain size compared with fluvial sands and an increase in interbedded clay and mud. Distal deltaic and shelf facies can be expected to have progressively lower, respectively, lateral conductivity because of reduced grain size and reduced vertical conductivity because of increasingly laterally continuous mud and clay layers. Wave-modified or -dominated deltas from the San Marcos Arch southward would be expected to have finer grain size but better sorting and less interbedded mud and clay, resulting in moderate to high lateral conductivity and moderate to high vertical conductivity. Incised channels on the shelf and slope are expected to have moderate to high horizontal conductivity because of the coarser nature of sediments commonly delivered during sea level lowstands, the time at which such channels are most active. However, fill in these channels may be complex, so horizontal conductivity orthogonal to channel axes may be significantly reduced, as would be vertical conductivities.

6.5
BENEFITS TO A CHRONOSTRATIGRAPHIC APPROACH

The stratigraphic approach used in this study is slightly different from that of previous aquifer studies. Emphasis is placed upon age-specific horizons bounding or within the aquifer that are regional in nature and prone to aquitard-like behavior. This methodology is known as chronostratigraphy. Research related to the cyclic nature of deposition over the past several decades (for example, Hays and others, 1976; Galloway, 1989; Mitchum and VanWagoner, 1991; and Tyler and Finley, 1991) has established the importance of this approach, especially in terms of evaluating fluid flow in the subsurface. The method is critical to understanding the structure and internal heterogeneity and, thus, the hydrologic behavior of the aquifer. This, in turn, leads to improved model accuracy and aquifer predictability.

Unlike lithostratigraphic correlation, which relies on lithologic changes to subdivide sedimentary intervals, chronostratigraphic correlation relies on recognition of depositional surfaces formed at critical times in a depositional cycle (Figure 6-13). During these relatively brief periods of time, broad areas of the coast are undergoing similar

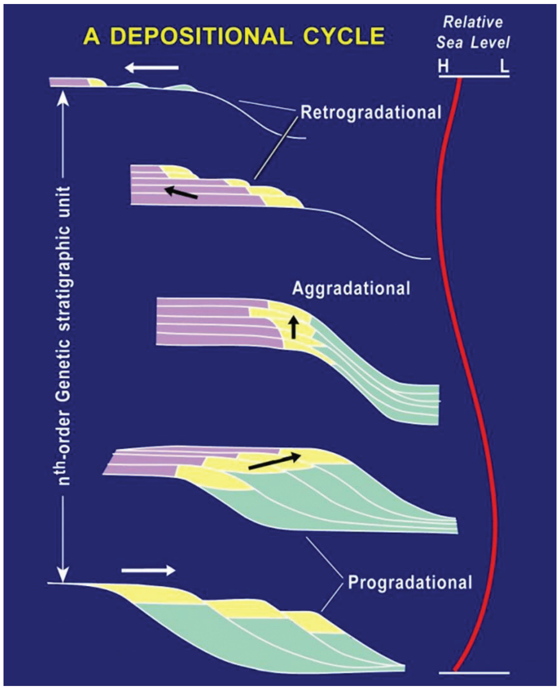

Figure 6-13. Depositional cycles (modified from Galloway, 1989).

depositional processes. It is now understood that global sea level has risen and fallen by as much as 450 feet over time spans of approximately 100,000 years. At sea level "highstand" times, deposition of fine-grained deposits (future aquitards) cover a large portion of the sand-rich sediments deposited during the last "lowstand" (future aquifer). Deposition at *maximum* highstand is idealized as a stratigraphic surface type known as a maximum flooding surface, and the associated fine-grained deposits are especially useful in defining aquifer framework in the subsurface because they often have a characteristic signature on geophysical logs. The Tertiary Gulf Coast interval is one of the areas in which these surfaces are expressed well in logs. Because the causative mechanism of high sea level is global in nature, these deposits can be traced across a regional extent. The intervals above and below these fine-grained deposits are sand-rich packages deposited under a common set of conditions, including positions of major sediment input. Predictive methods can then be applied to evaluating the geographic distribution of sand-rich areas within the package. These predictive methods are based on observations of modern depositional processes and systems such as rivers and deltas. The methods rely on the commonality of depositional conditions within the time frame of the package, and the location and style of sand-rich deposition will vary from package to package.

Beyond the issue of aquifer layering is the distribution of depositional systems *within* an aquifer layer because it provides information on lateral heterogeneity of the layer. This is governed not only by sand thickness distribution but by depositional facies distribution. Sand-rich sediments deposited in different settings will have different hydrologic properties because of differing grain size, sorting, sand body size and shape, and degree of interbedding of silts and muds. This affects sediment properties such as horizontal and vertical conductivity and storativity that might be measured at a wellbore. The internal architecture of an aquifer layer, governed by the characteristics of its depositional system setting, creates an overlay of fluid flow behavior on top of typical considerations such as head (fluid pressure) distribution. A lateral (along-strike) flow element to aquifer behavior may be impressed upon an aquifer because of deposition of large areas of highly conductive sands in a wave-dominated, shore-parallel delta. Conversely, dip-oriented sand-rich lowstand fluvial channels may provide a localized hydraulic conduit between saline-rich basinal sands and shallower freshwater sands.

6.6

CHALLENGES TO A CHRONOSTRATIGRAPHIC APPROACH

Outcrop mapping of geologic units is, by necessity, based on lithostratigraphy. The maximum flooding surfaces that are apparent in well logs cannot be readily identified in outcrop. Additionally, some stratigraphic relationships that are clear in the subsurface are more difficult to identify in outcrop, leading to discrepancies in the placement of major formational boundaries. This is significant because outcrop boundaries for the Yegua-Jackson Aquifer are used to define the aquifer extent, but maximum flooding surfaces were used to subdivide the aquifer in the subsurface.

Such issues did arise in the Yegua-Jackson Aquifer study. Outcrop studies identified the base of the Yegua as the first appearance, stratigraphically, of major sand beds. Subsurface correlation traced the maximum flooding surface within the shale below the Yegua. Thus, an additional surface had to be created for the subsurface that followed the convention of the outcrop: the first occurrence of major sand beds. Differences also occurred at the top of the Jackson Group. This boundary lies within a uniform-appearing sand-shale interval, and the boundary is difficult to follow in outcrop, especially where topography and vegetation limit the frequency of outcrops. Subsurface correlations were determined to be more accurate, and the recommendation has been made to change the aquifer boundaries slightly in some areas.

6.7
CONCLUSIONS

This paper summarizes the development of the structure and depositional framework for the Yegua-Jackson Aquifer in Texas. The aquifer exists predominantly in the outcrop or near-outcrop areas of the Yegua Formation and Jackson group. In Texas, this outcrop area stretches in a relatively thin band approximately parallel to the coastline from Starr County in the Rio Grande Valley to Sabine County in East Texas and is thus bracketed by the Rio Grande River to the south and the Toledo Bend Reservoir (along the Sabine River) to the east. The width of this outcrop varies from less than 10 miles in Gonzales County to almost 40 miles in La Salle County, with an area of approximately 11,000 square miles.

This paper describes the development of a chronostratigraphic framework for the Yegua-Jackson Aquifer that spans its entire extent in Texas. A chronostratigraphic approach to mapping provides a consistent depositional framework for the geologic intervals composing the aquifer. The dominant controls on aquifer framework in terms of fluid flow characteristics result from the distribution of sedimentary processes, both geographically and through geologic time. Estimating aquifer framework and heterogeneity on the basis of outcrop and limited subsurface data requires a predictive approach founded on an understanding of the activities that built the aquifer. The concepts of chronostratigraphy and depositional systems provide that predictive capability.

Unlike lithostratigraphic correlation, which relies on lithologic changes to subdivide sedimentary intervals, chronostratigraphic correlation relies on recognition of depositional surfaces formed at critical times in a depositional cycle. During these relatively brief periods of time, broad areas of the coast are undergoing similar depositional processes. At sea level highstand times, deposition of fine-grained deposits (an aquitard) cover a large portion of the sand-rich sediments deposited during the last lowstand (an aquifer). These highstand times are represented by maximum flooding surfaces, and their associated fine-grained deposits are especially useful in defining aquifer framework because they often have a characteristic signature on geophysical logs from wellbores. Thus, these deposits can be traced across a regional extent in the subsurface. The intervals above and below these fine-grained deposits are sand-rich packages deposited under a common set of conditions, including positions of major sediment input. Predictive methods for evaluating the geographic distribution of sand-rich areas within the package can then be applied. These predictive methods are based on observations of modern depositional processes and systems such as rivers and deltas. These methods rely on the commonality of depositional conditions within the time frame of the package, and the location and style of sand-rich deposition will vary from package to package.

Four major chronostratigraphic units (third-order genetic units) were defined for the Yegua-Jackson Aquifer. These include, from the bottom upward, the Lower Yegua, Upper Yegua, Lower Jackson, and Upper Jackson units, which each span one to two million years of deposition (third-order genetic units) and are of appropriate scale for regional groundwater availability modeling (generally 400 to 800 feet thick, thickening in the downdip direction). In addition to the development of the chronostratigraphic units, five types of maps were developed for the four chronostratigraphic units. These are a structure map, an isopach map, a sand thickness map, a sand percent map, and a depositional facies map. These maps provide the necessary framework for future hydrogeologic studies within the aquifers, studies that may include groundwater availability model development. The results of this research provide conceptual constraints on regional model parameterization and will have the depositional framework necessary to evaluate characterization data and to apply interpolation techniques during calibration.

As water resources in the state become more valuable and subject to greater use, it is expected that groundwater availability models will have to increase their accuracy, which implies an increase in understanding of the aquifer flow controls and dynamics. There are many valuable stratigraphic studies within the Texas Tertiary aquifers. However, many times these studies are at a subregional scale, and differences in nomenclature between studies make integration of these studies into a coherent whole difficult. Studies such as the one presented herein are recommended to be continued in the Texas Tertiary aquifers as they provide detailed structure, lithology, and depositional facies defined at the relevant aquifer scale. The resulting uniformity will prove critical to future groundwater resource management.

6.8

ACKNOWLEDGMENTS

The well logs critical to this investigation could not have been gathered without open access to resources at the Bureau of Economic Geology, the Texas Water Development Board, and the Texas Commission on Environmental Quality Surface Casing Division. Friendly and helpful guidance in these respective facilities was provided by Daniel Ortuño, Deborah Schultz, and Julia Harvey. We would like to acknowledge Scott Hamlin, the TWDB project manager, for his support and guidance through this structure development project. The skills and patience of Astrid Vreugdenhil, Sarah Pierson, and Michelle Tiemeier at INTERA, Incorporated, and Alex Sanders at Baer Engineering and Environmental Services, Incorporated, have transformed thoughts and ideas into geographic information system-based maps. Computer-aided, design-based cross section drawing was accomplished by Jorge Garza of INTERA, Incorporated, and we appreciate his patience. Funding for this study was provided by TWDB under contract 0604830617.

6.9
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Chapter 7

Hydrogeologic Framework and Geospatial Data Compilation for the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas

Sachin D. Shah[1], Natalie A. Houston[1], Christopher L. Braun[1]

The Brazos River Alluvium Aquifer lies under and adjacent to the Brazos River in Texas from Bosque County to Fort Bend County. One of 21 minor aquifers in the state (TWDB, 2007), the aquifer supplies water for irrigation, domestic, stock, and commercial uses. As demand for water increases statewide, the Brazos River Alluvium Aquifer likely will become more important in the future. A thorough understanding of the hydrogeology of the alluvium aquifer will be the foundation for future studies in the area. During October 2006–April 2007, the U.S. Geological Survey, in cooperation with the Texas Water Development Board (TWDB), conducted a study to delineate the altitude of the top, altitude of the base, and thickness of the Brazos River Alluvium Aquifer and to compile and summarize available hydraulic property data (specific capacity, transmissivity, and hydraulic conductivity). A digital elevation model was used to estimate the altitude of the top of the aquifer. The altitude of the base of the aquifer was estimated using data from wells (drillers' logs and borehole geophysical logs). The study area encompassed the Brazos River Alluvium Aquifer in parts of Bosque, Hill, McLennan, Falls, Robertson, Milam, Brazos, Burleson, Grimes, Washington, Waller, Austin, and Fort Bend counties (Figure 7-1) and a 1.5–mile-wide lateral buffer adjacent to the aquifer. The results of this study will be used by TWDB as part of the development of a groundwater availability model.

7.1
PREVIOUS STUDIES

Several studies involving all or parts of the Brazos River Alluvium Aquifer study area have been published. Cronin and Wilson (1967) completed the first comprehensive study of the Brazos River Alluvium Aquifer from Bosque County to Fort Bend County. That report describes the extent and thickness of the aquifer, provides estimates of the amounts and distribution of withdrawals and recharge, and provides estimates of the quantity and quality of groundwater available. It also includes descriptions of the hydrologic relations between the alluvium and the underlying bedrock and groundwater-surface water interaction in the Brazos River Alluvium Aquifer. As a part of the study, Cronin and Wilson (1967) obtained hydrogeologic data from test holes drilled.

From 1937 to 1943, nine reports were published documenting inventoried water wells in the following counties: Austin (May, 1938); Burleson (Clark, 1937a); Fort Bend (Elledge, 1937; Livingston and Turner, 1939); Grimes (Turner, 1939); Milam (Clark, 1937b); Robertson (Davis, 1942); Waller (Turner and Livingston, 1939); and Washington (Follett, 1943). Cronin and Follett (1963) published the first reconnaissance investigation of the groundwater resources of the entire Brazos River Basin in 69 counties from the New Mexico-Texas boundary to the Gulf Coast, including the 13 counties of this report. Additionally,

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[1] U.S. Geological Survey

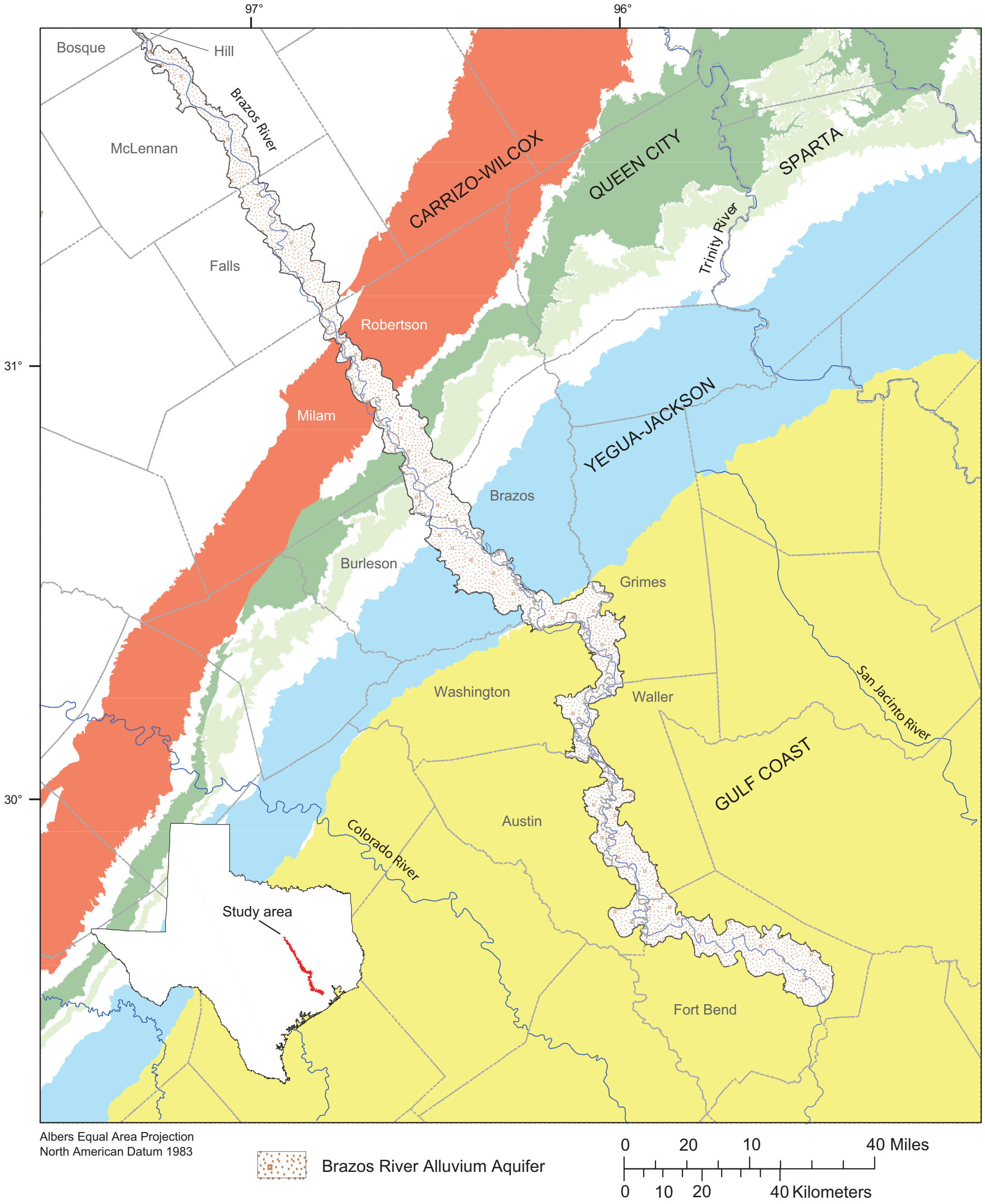

Figure 7-1. Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas, and underlying aquifers (outcrops only) (modified from TWDB, 2007).

Fluellen and Goines (1952) reported on the water resources of Waller County, and Hughes and Magee (1962) summarized the groundwater withdrawals of irrigation wells in the aquifer.

More recently, Naftel and others (1976) documented well drillers' logs, water level measurements, and chemical analyses of groundwater in Brazoria, Fort Bend, and Waller counties. Harlan (1990) assessed the hydrogeology of the Brazos River Alluvium Aquifer from Waco to Marlin, Texas. Wrobleski (1996) characterized the Brazos River Alluvium Aquifer at a hydrogeologic field site in Burleson County using aquifer test data to estimate hydraulic conductivity. HDR Engineering, Inc. (2001) developed a groundwater flow model for the Brazos River Alluvium Aquifer, combined with a conjunctive use analysis to quantify the amount of surface and groundwater along the Brazos River.

7.2
DESCRIPTION OF THE BRAZOS RIVER ALLUVIUM AQUIFER

The Brazos River Alluvium Aquifer extends along 350 river miles from southern Bosque County to eastern Fort Bend County, with a width of up to 7 miles (Ashworth and Hopkins, 1995, p. 35) (Figure 7-1). Alluvial sediments in the study area occur in floodplain and terrace deposits of the Brazos River (Cronin and Wilson, 1967). For this report, the Brazos River Alluvium Aquifer includes the floodplain alluvium that consists of fine to coarse sand, gravel, silt, and clay. The adjacent terrace alluvium is not an appreciable source of water and, thus, not considered part of the aquifer. Cronin and Wilson (1967) describe the composition of the floodplain alluvium as varying from place to place, with beds or lenses of sand and gravel that pinch out or grade laterally into vertically finer or coarser material. In general, the finer material is in the upper part of the aquifer, and the coarser material is in the lower part. The aquifer is generally under water table conditions and is used mainly for irrigation (HDR Engineering, Inc., 2001). The water table generally slopes toward the Brazos River, indicating that the river is a gaining stream in most places. Recharge to the aquifer occurs primarily from rainfall on the aquifer and subsequent downward leakage to the saturated zone, which (in the late 1960s) ranged from less than 10 to nearly 50 feet below land surface (Cronin and Wilson, 1967, p. 2). Discharge from the aquifer occurs primarily through evapotranspiration, discharge to the Brazos River, and withdrawals from wells. Some wells can yield as much as 1,000 gallons per minute, but the majority of wells yield from 250 to 500 gallons per minute (Ashworth and Hopkins, 1995, p. 35).

The Brazos River Alluvium Aquifer in the study area is underlain by geologic units that crop out in bands roughly parallel to the coast (Shah and Houston, 2007). Many of the geologic units, either individually or in groups, compose major and minor aquifers in the study area (Figure 7-1). Notable among the underlying aquifer units are the Carrizo-Wilcox Aquifer, the Queen City Aquifer, the Sparta Aquifer, the Yegua-Jackson Aquifer, and the Gulf Coast Aquifer. These aquifers dip gently from their outcrops toward the coast, with dip angles slightly greater than the land-surface gradient.

7.3
METHODS OF HYDROGEOLOGIC CHARACTERIZATION

For the hydrogeologic characterization in this report, information was compiled and synthesized from published reports generated by TWDB, the Texas Commission on Environmental Quality, various universities, and groundwater conservation districts, and then disseminated into the TWDB's Groundwater Availability Model Source Data Geodatabase schema (Shah and Houston, 2007).

7.3.1
Altitude of the top of the Brazos River Alluvium Aquifer

A U.S. Geological Survey 30-meter (98-foot) digital elevation model (DEM) resampled to 0.125 mile was used to estimate the top of the Brazos River Alluvium Aquifer for the study area. A DEM is a digital file consisting of terrain altitudes for land-surface positions at regularly spaced horizontal intervals, from which an accurate depiction of surface topography can be generated. The DEMs were obtained from the U.S. Geological Survey Seamless Data Distribution System (USGS, 2007). This portal provides DEMs with various resolutions for the United States. For this study a resolution of one arc-second (about 30 meters) was chosen. The models for each county then were merged to create a single DEM for the Brazos River Alluvium Aquifer study area.

7.3.2
Altitude of the base of the Brazos River Alluvium Aquifer

The contact between the alluvium and the underlying unit was estimated, or "picked," from drillers' or geophysical logs or published geologic sections based on lithology where no other determinations could be made. Many areas lacked sufficient log data (control points) to create a continuous surface for the altitude of the base. For these areas, the depths of wells known to be completed in the Brazos River Alluvium Aquifer without an associated driller's or geophysical log were used as control points. From the log and well-depth control points, a surface was estimated using the topo-to-raster method in the geographic information system (GIS) software ArcGIS 9.2 (ESRI, 2007). Topo to raster is a spline interpolation method specifically designed for creating altitude surfaces. The method honors the data without applying a smoothing algorithm and also accepts vectors as input data (ESRI, 2007).

Despite the use of well-depth control points to supplement the log control points, data gaps exist in parts of the study area. For example, drillers could not or did not distinguish the alluvium from the underlying unit for wells in some areas where both units were of similar lithology, which precluded identifying the base of the aquifer in places. Data gaps also occur in areas where the alluvium is too thin to yield adequate amounts of water, and, therefore, no wells exist in those areas.

After generating a preliminary raster surface for the base, contours were generated at 10-foot intervals using GIS software. The preliminary surface, contours generated from the surface, and the input control points were assessed to identify discrepancies, particularly in areas where both log and well-depth control points were used. For log control points, the base pick for each well was compared with picks for nearby wells. If the altitude was unrealistically high or low relative to altitudes from nearby wells, the log was re-examined to determine whether a pick more consistent with the nearby picks might be reasonable. In areas where there was a substantial difference in altitude between log control points and well-depth control points, altitudes from log picks were used preferentially over those from well depths; well-depth control points were discarded if there was a difference of more than 5 feet. After assessment and revision, the process was repeated several times. Contours generated from ArcMap (about 500 arcs) were then evaluated and modified manually where necessary. The final surface representing the altitude of the base was generated using both points and contours concurrently and the topo-to-raster interpolator. For the final map, a total of 1,364 control points were used: 386 from drillers' logs, 13 from geophysical logs, 955 from well depths, and 10 from geologic sections.

7.3.3
Thickness of the Brazos River Alluvium Aquifer

The thickness of the Brazos River Alluvium Aquifer was estimated by subtracting the raster surface of the base of the aquifer from the raster surface of the top of the aquifer, using the raster calculator in Spatial Analyst in ArcGIS 9.2 (ESRI, 2007). Subtracting the raster surfaces in GIS can provide an objective and unbiased rendition of differences between the two surfaces. Thicknesses in areas where the number of control points for one surface differ substantially from the other surface should be used with caution.

7.3.4

Hydraulic properties

Two hundred fifty-six of 358 specific capacity values (Shah and Houston, 2007) were obtained from specific capacity or aquifer tests performed by the U.S. Geological Survey in 1963 and 1964. The other 102 values were obtained from the online TWDB groundwater database Well-Site Remarks Table (TWDB, 2006).

Two hundred fifty-eight of 371 transmissivity values (Shah and Houston, 2007) were obtained from the U.S. Geological Survey specific capacity or aquifer tests from 1963 and 1964; four were obtained from published reports; and seven were computed from hydraulic conductivity values (Wrobleski, 1996). One hundred two transmissivity values were computed from the TWDB specific capacity values noted above, using an empirical equation for unconfined aquifers developed from the modified nonequilibrium (Jacob) equation (Driscoll, 1986, p. 1,021).

The modified nonequilibrium equation is

$$Q/s = T/264(\log[0.3Tt/r^2S]), \qquad (1)$$

where Q is the yield of the well in gallons per minute, s is the drawdown in the well in feet, T is the transmissivity of the aquifer in feet squared per day, t is time, and S is the storage coefficient of the aquifer.

The empirical equation is

$$Q/s = T/1500. \qquad (2)$$

This equation is derived by assuming "typical" values for the variables in the modified nonequilibrium equation. T is assumed to be 30,000 feet squared per day, t is assumed to be 1 day, r is assumed to be 0.5 foot, and S is assumed to be 0.075. The empirical equation was used because few wells with specific capacity data had values for all of the variables necessary to apply the modified nonequilibrium equation.

Seven hydraulic conductivity values (Shah and Houston, 2007) were compiled for closely adjacent sites in Burleson County from the Texas A&M University Brazos River Hydrologic Field Site (Wrobleski, 1996). Transmissivity values were not computed from these hydraulic conductivity values because saturated thickness at the sites was unknown.

7.4

HYDROGEOLOGIC CHARACTERIZATION

7.4.1

Altitude of the top of the Brazos River Alluvium Aquifer

Altitudes of the top of the Brazos River Alluvium Aquifer (land surface) (Figure 7-2) range from about 580 feet above North American Vertical Datum of 1988 (NAVD 88) at the northwestern end in Bosque County to about 17 feet above NAVD 88 at the southeastern end in Fort Bend County. The top of the aquifer slopes from northwest to southeast at a fairly consistent rate of about 2.5–3 feet per mile.

7.4.2

Altitude of the base of the Brazos River Alluvium Aquifer

The altitude of the base of the Brazos River Alluvium Aquifer (Figure 7-3) ranges from about 480 feet above NAVD 88 at the northwestern end in Bosque County to about 18 feet below NAVD 88 at the southeastern end in Fort Bend County. The altitude of the base is an uneven or undulating surface that, like the altitude of the top, decreases from northwest to southeast but not as consistently as the altitude of the top. There are small areas, for example in Brazos County, where the altitude of the base increases or decreases about 10 feet over short (tens of feet) distances. The largest change in base altitude occurs

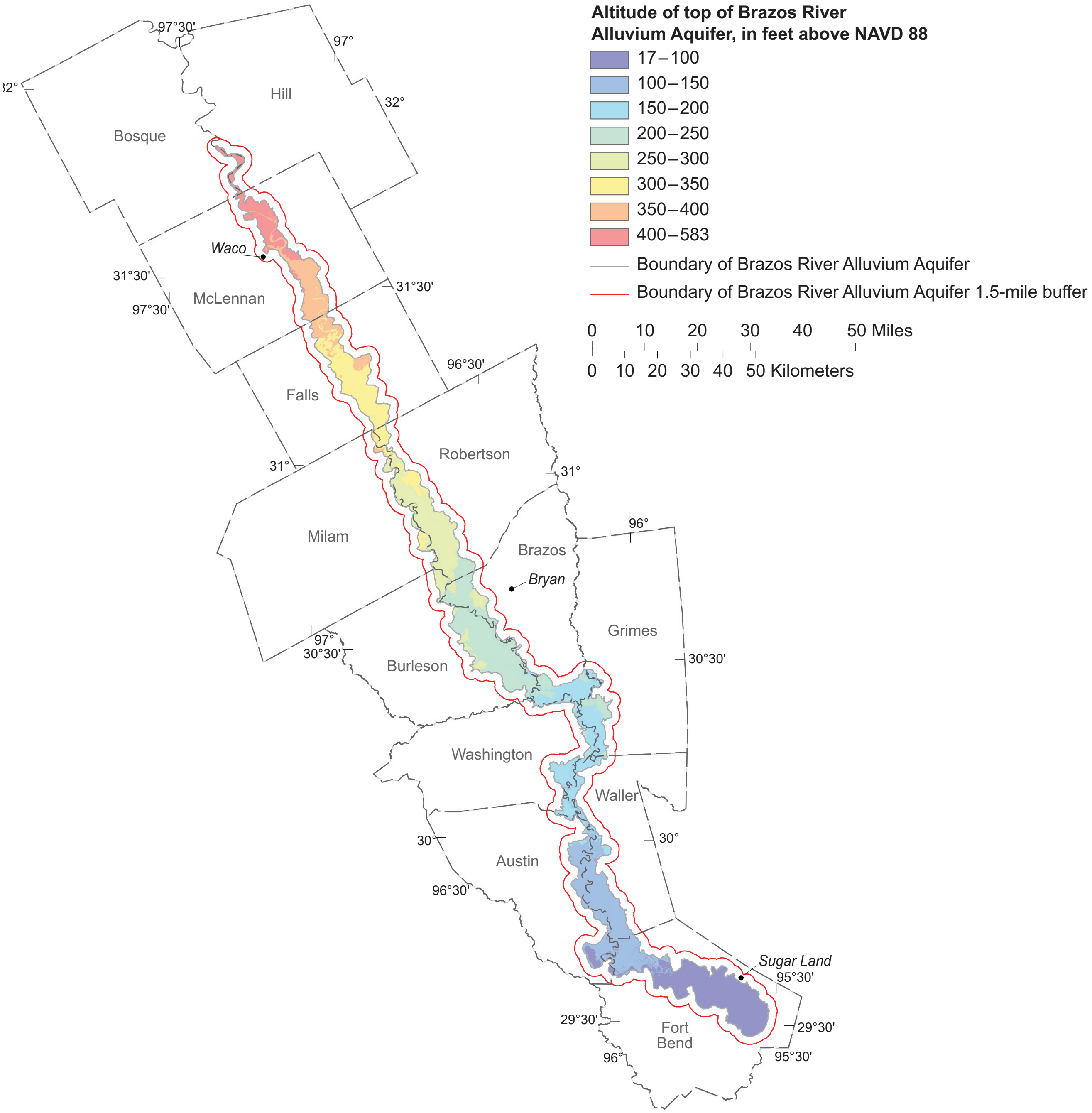

Figure 7-2. Altitude of the top of the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas. NAVD=North American Vertical Datum 1988

in Fort Bend County where the altitude decreases about 40 feet, although the altitude of the base is potentially less reliable in this county than other areas. There, drillers' logs do not always clearly differentiate the sand and gravel of the alluvium aquifer from that of the underlying Gulf Coast aquifer (Chicot, Evangeline, or Jasper aquifers locally, not shown in Figure 7-1). Because the lithology of the alluvium and the Gulf Coast Aquifer is so similar, a distinct pick is not easy to make. The control points used in Fort Bend County are those for which base picks could be made with reasonable confidence.

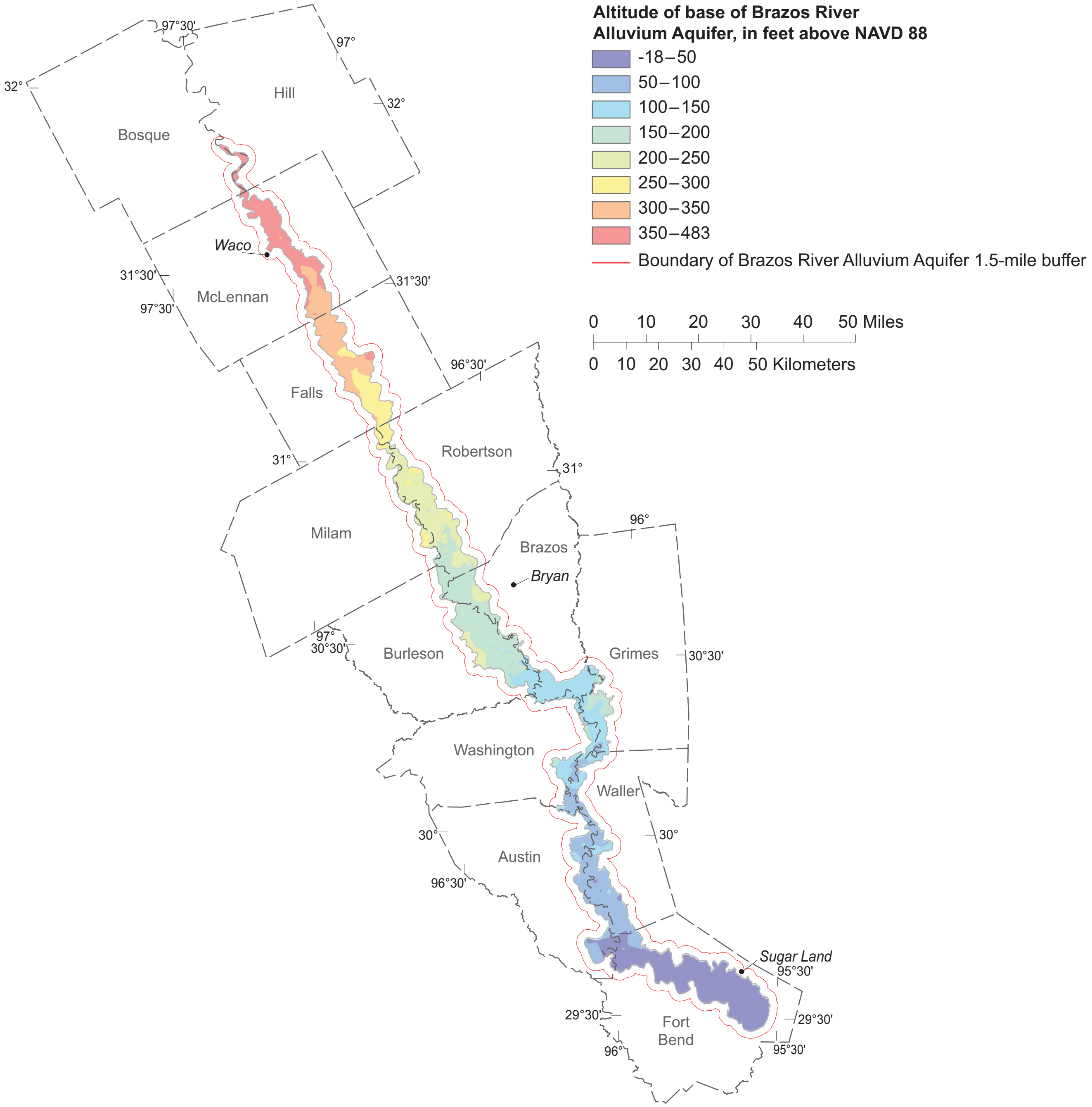

Figure 7-3. Altitude of the base of the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas. NAVD=North American Vertical Datum 1988

7.4.3

Thickness of the base of the Brazos River Alluvium Aquifer

The thickness of the Brazos River Alluvium Aquifer (Figure 7-4) ranges from negligible to 168 feet. Mapped thicknesses are less reliable in areas where few or no control points exist, such as near the aquifer boundary. Such areas occur west of the Brazos River in northwest Milam County, west of the Brazos River in northwest Burleson County, east of the Brazos River in Brazos County, east of the Brazos River in Grimes County, and east of the Brazos River in Waller

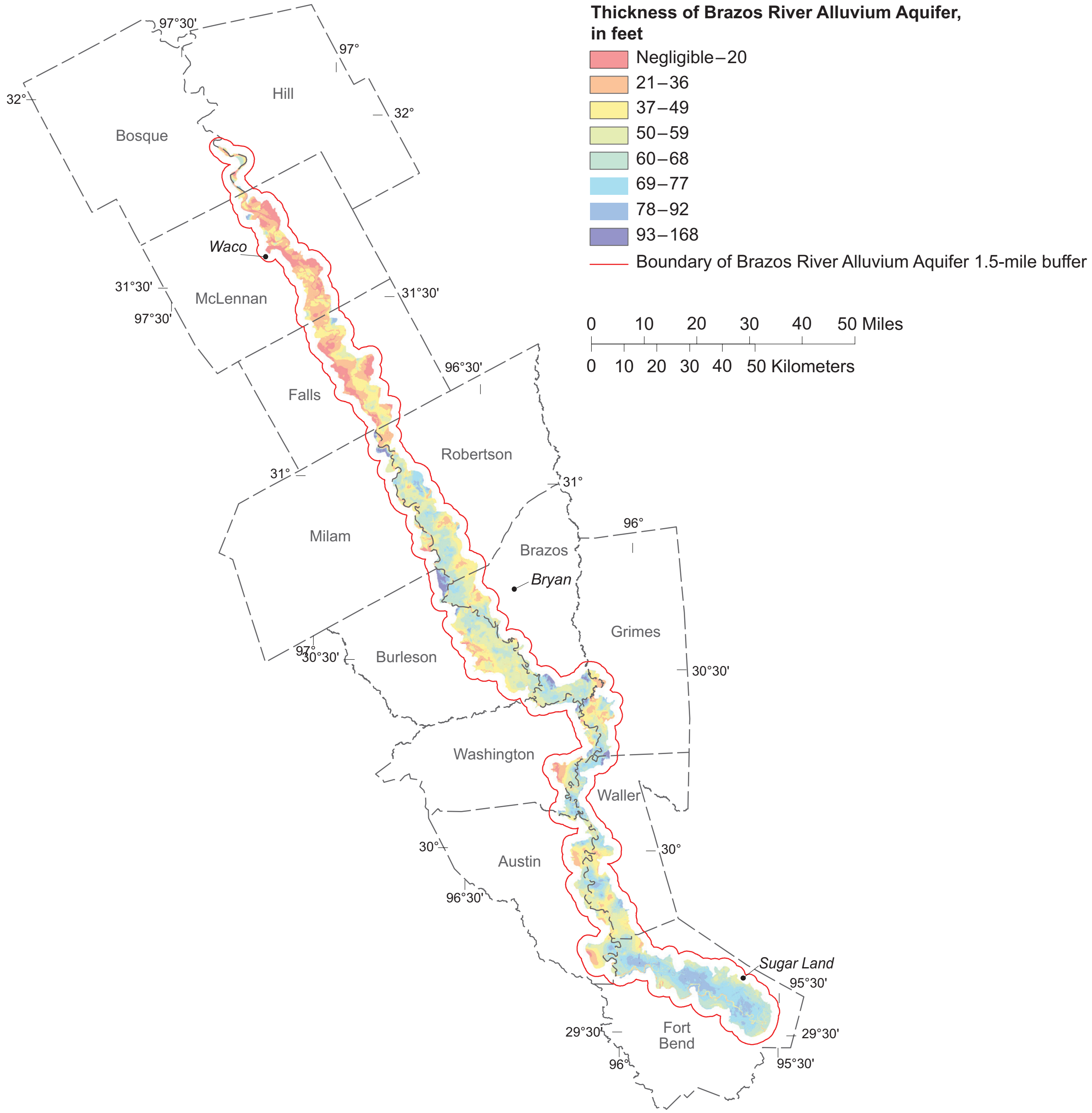

Figure 7-4. Thickness of the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas.

County. In areas of few or no control points, such as near the aquifer boundary, thicknesses greater than about 100 feet might be anomalous. As described in the previous section, another area where thicknesses potentially are less reliable is Fort Bend County because of the difficulty in identifying the base of the aquifer from logs.

7.4.4
Distribution of hydraulic properties

The areal distribution of hydraulic properties in the Brazos River Alluvium Aquifer (Figure 7-5) shows that most of the data are concentrated in the central part of the aquifer (Milam, Robertson, Burleson, and Brazos counties); few data exist for the northwestern and

Figure 7-5. Areal distribution of hydraulic properties of the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas. Outlined area denotes area in Burleson County where hydraulic conductivity values were taken.

southeastern parts of the aquifer. The largest and smallest specific capacities, respectively, are 134 gallons per minute per foot (Burleson County) and 1.44 gallons per minute per foot (Falls County); the median is 23.5 gallons per minute per foot (Table 7-1). A histogram of specific capacity values (Figure 7-6) shows that the most frequent range (about 82 percent of the values) is 0 to 40 gallons per minute per foot.

The largest and smallest transmissivity values, respectively, are about 28,000 feet squared per day (Brazos County)

Table 7-1. Summary statistics of hydraulic properties, Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas.

Hydraulic property	Number of wells	Minimum	First quartile	Median	Mean	Third quartile	Maximum
Specific capacity ([gal/min]/ft)	358	1.44	15.9	23.5	28.4	33.9	134
Transmissivity (ft^2/d)	371	289	2,980	4,550	5,590	6,800	27,800
Hydraulic conductivity (ft/d)	7	179	—	217	241	—	447

Note: All values rounded to three significant figures.
(gal/min)/ft = gallons per minute per foot; ft^2/d = feet squared per day; ft/d = feet per day

and about 300 feet squared per day (Falls County); the median is 4,550 feet squared per day (Table 7-1). A histogram of transmissivity values (Figure 7-7) shows that the most frequent range (42 percent of the values) is 0–4,000 feet squared per day. Among the 7 hydraulic conductivity values in Burleson County, the largest and smallest are 447 and 179 feet per day, respectively (Table 7-1).

7.5
SUMMARY

As the Brazos River Alluvium Aquifer becomes more important in the future and the demand for water increases statewide, a thorough understanding of the hydrogeology in the area is essential. The U.S. Geological Survey, in cooperation with TWDB, conducted a study to characterize and delineate the altitude of the top, altitude of the base, and thickness of the Brazos River Alluvium Aquifer and to compile and summarize available hydraulic property data. The study area encompasses the aquifer in parts of Bosque, Hill, McLennan, Falls, Robertson, Milam, Brazos, Burleson, Grimes, Washington, Waller, Austin, and Fort Bend Counties. A 1.5-mile-wide lateral buffer adjacent to the aquifer was used to ensure a complete characterization of the aquifer. A digital elevation model was used as the altitude of the top of the aquifer. The altitude of the base of the aquifer was generated using data from wells from various sources. The results of this study will be used by TWDB for input into a groundwater availability model.

7.6
ACKNOWLEDGMENTS

The authors would like to thank the Texas Water Development Board for providing the funding for this effort. In addition, we appreciate Joe Yelderman of Baylor University and Clyde Munster of Texas A&M University for their assistance in providing hydrologic data for areas in McLennan and Brazos counties.

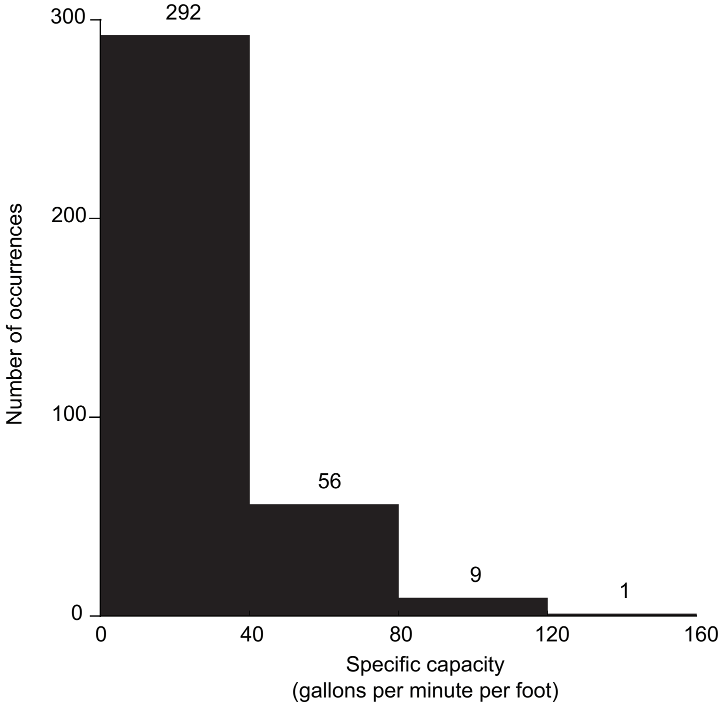

Figure 7-6. Histogram of specific capacity, Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas.

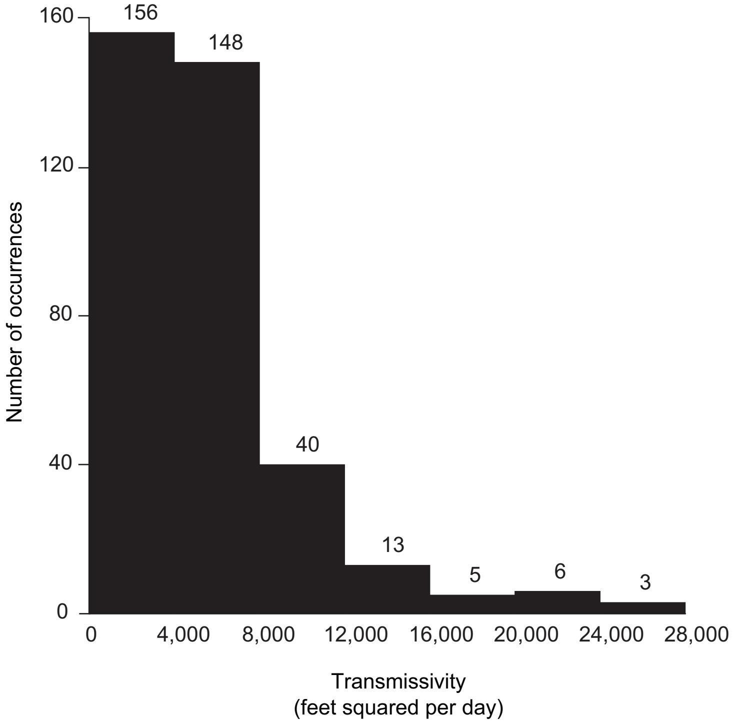

Figure 7-7. Histogram of transmissivity, Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas.

7.7
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Chapter 8

Low-Flow Gain-Loss Study of the Colorado River in Bastrop County, Texas

Geoffrey P. Saunders, P.G., C.G.W.P.[1]

A field investigation was conducted in November 2008 as a follow-up to previous gain-loss studies of the lower Colorado River in Texas. Previous studies conducted by the Lower Colorado River Authority (LCRA) of groundwater-surface water interaction between the Carrizo-Wilcox Aquifer and the Colorado River provided valuable information, but the results were inconclusive. The 2008 LCRA study was a more detailed investigation of gains and losses in river flow upstream and downstream from the outcrops of two productive aquifer units: the Simsboro Sand and Carrizo Sand.

8.1
STUDY AREA

The lower Colorado River flows through Bastrop County, Texas, in a meandering channel within a broad alluvial floodplain (Figure 8-1). Outcrops of the Simsboro Sand and Carrizo Sand are exposed along the banks of the river and underneath the alluvium associated with the river. The Simsboro Sand is exposed in a 70-foot cliff at Powell Bend upstream from the town of Bastrop (Figure 8-2). The Carrizo Sand underlies the Colorado River between Bastrop and the Colovista Country Club measurement site shown on Figure 8-1. At some locations, small seeps and springs may be found along the banks of the river, but most groundwater-surface water interaction occurs through the river alluvium.

8.2
PREVIOUS STUDIES

Earlier low-flow investigations by the U.S. Geological Survey in 1918 found that the Colorado River gained about 36 cubic feet per second across the outcrop of the Carrizo-Wilcox Aquifer (TBWE, 1960). A study conducted by LCRA of streamflow hydrographs during low-flow conditions in 1999 found data suggesting a possible gain in river flow of 59 cubic feet per second between gaging stations at Bastrop and Smithville, based upon the U.S. Geological Survey streamgage readings (Saunders, 2005). A field investigation conducted by LCRA in November 2005 also produced data suggesting a possible net gain in river flow from Utley to Smithville of 50 cubic feet per second (Saunders, 2006).

8.3
METHODS

This study was conducted according to the methods for low-flow investigations and gain-loss studies recommended by the U.S. Geological Survey (Riggs, 1972; Slade and others, 2002). Conditions of steady river flow, dry weather, and minimal tributary inflows, discharges, and withdrawals were ideal for a low-flow investigation during an ongoing dry period in late November 2008. The field investigation was conducted November 24 – 25, 2008. Although river flow is continuously monitored at gaging stations at Bastrop and Smithville, flow measurements for this study were taken at four mainstem locations, as well as on any tributaries between Utley and Smithville in which flow was present. Streamflow was measured using acoustic Doppler velocity meters and portable cut-throat flumes. Best efforts

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[1] Lower Colorado River Authority

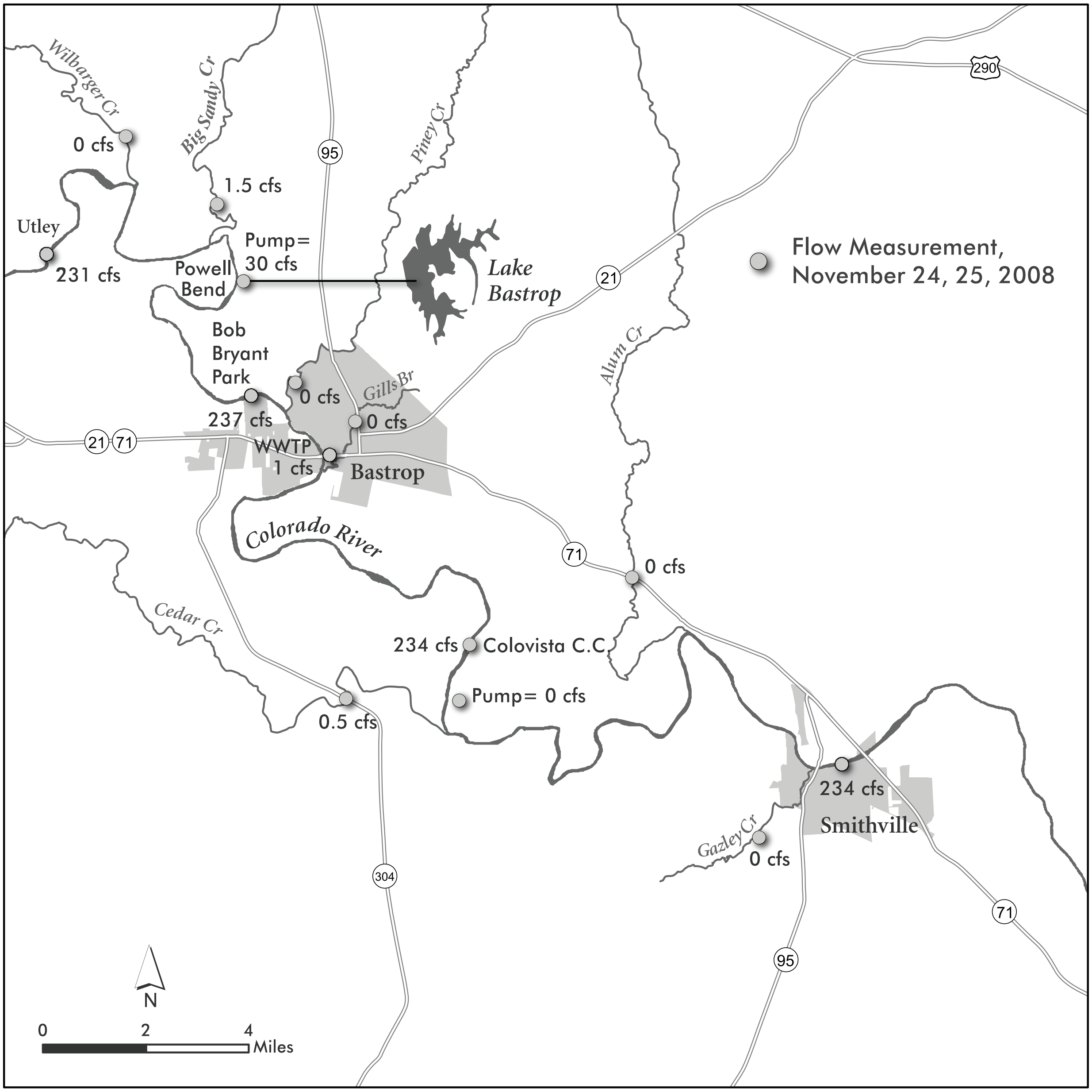

Figure 8-1. Low-flow measurements in the reach of the Colorado River from Utley to Smithville, Bastrop County, Texas, November 24–25, 2008 (LCRA graphic).
cfs = cubic feet per second

were made to maximize the accuracy of streamflow measurements; however, the estimated error associated with this type of measurement is 5 percent or better (Rantz, 1982). Furthermore, although flow measurements were not taken continuously for the two-day period of this study, the river was considered to be in a near-steady flow condition so that estimates of gains and losses could be estimated. In order to complete the estimates, all known discharges and withdrawals were verified by observation and by checking with the plant operators.

8.4
RESULTS

Results of data collection are shown in Table 8-1. The data are arranged in

Figure 8-2. Outcrop of the Simsboro Sand Formation along the Colorado River at Powell Bend, Bastrop County, Texas (LCRA photo).

order from upstream to downstream to indicate gain-loss relationships.

River flow measurements at Utley, Bob Bryant Park upstream from Bastrop, Colovista Country Club downstream from Bastrop, and Smithville were remarkably consistent, ranging between 231 and 237 cubic feet per second. There was a relatively large withdrawal of water at Powell Bend to supplement Lake Bastrop (30 cubic feet per second) during the field investigation. Tributary inflows were negligible at Wilbarger Creek (0 cubic feet per second); Big Sandy Creek (1.5 cubic feet per second); Piney Creek (0 cubic feet per second); Gills Branch (0 cubic feet per second); Alum Creek (0 cubic feet per second); Cedar Creek (0.5 cubic feet per second); and Gazley Creek (0 cubic feet per second). The City of Bastrop wastewater treatment plant was discharging (1 cubic foot per second) during the field investigation.

Although there was no significant increase in river flow between the mainstem measurement sites, the relatively large withdrawal of water at Powell Bend for Lake Bastrop (30 cubic feet per second) factors into the analysis. Considering differences in measured river flow, tributary inflows, and the withdrawal at Powell Bend, the data suggests a net gain between Utley and Bastrop of 30 cubic feet per second. Such a gain would most likely be attributable to groundwater contribution from the Simsboro Sand to the Colorado River.

Downstream from Bastrop, the data indicate no increase in river flow nor any significant withdrawals or discharges. Therefore, there was no apparent gain in river flow attributable to the Carrizo Sand during the field investigation.

Table 8-1. Results of data collection, November 24–25, 2008.

Mainsteam	Off-channel	Type	Flow (cfs)	Inflow (-) or outflow (+) (cfs)	Net gain-loss (cfs)
Colorado River at Utley		River flow	231		
	Wilbarger Creek	Tributary		0	
	Big Sandy Creek	Tributary		-1.5	
	Sim Gideon pumping station	Withdrawal		+30	
Colorado River at Bob Bryant Park		River flow	237		(237–231) -1.5 + 30 = 34.5
	Piney Creek	Tributary		0	
	City of Bastrop WWTP	Discharge		-1	
	Gills Branch	Tributary		0	
Colorado River at Colovista Country Club		River flow	234		(234–237) -1 = -4
	Colovista Country Club pump	Withdrawal		0	
	Cedar Creek	Tributary		-0.5	
	Alum Creek	Tributary		0	
	Gazley Creek	Tributary		0	
Colorado River at Smithville		River flow	234		(234–234) - 0.5 = -.5
				Net gain	+30

cfs = cubic feet per second; WWTP = wastewater treatment plant

8.5
CONCLUSIONS

As shown in Table 8-1, the total net gain to the Colorado River from the Carrizo-Wilcox Aquifer in Bastrop County was estimated to be 30 cubic feet per second during the November 2008 low-flow event. This compares to the U.S. Geological Survey 1918 estimate of 36 cubic feet per second and the LCRA estimate of 50 cubic feet per second in November 2005.

Thus, the potential groundwater contribution of flow to the Colorado River from the Carrizo-Wilcox Aquifer may be significant, particularly when compared to more well-known sources such as Barton Springs in Austin, which was flowing at 19 cubic feet per second during the field investigation in November 2008. Contributions to the base flow from these sources can be important during critical low-flow conditions.

Although groundwater flow in sand aquifers is generally considered to be slow and steady, it is possible that groundwater contributions to the lower Colorado River may be variable from one time period to another. However, a study of groundwater-surface water interaction prepared as part of development of the central Carrizo-Wilcox groundwater availability model indicated that base flow rates of rivers crossing the aquifer outcrop have not decreased over time, and seasonal variability in base flow for perennial streams may not fluctuate significantly (Dutton and others, 2003). In addition, flow from bedrock aquifers through the alluvium to the river is a complicated system and requires further data and analysis. As demands on groundwater resources increase with future growth in Central Texas, groundwater-surface water interactions may need to be periodically monitored to assess water availability in the decades to come.

8.6
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Chapter 9

Evaluation of the Brackish Groundwater Resources of the Wilcox Aquifer in the San Antonio, Texas, Area

Charles W. Kreitler[1], Kevin H. Morrison[2]

San Antonio Water System (SAWS) and LBG-Guyton Associates have evaluated the feasibility of the long-term production of brackish groundwater for desalination from the Wilcox Aquifer in southern Bexar and northern Atascosa counties. Desalination of brackish groundwater is an important component of SAWS' 2009 50-Year Water Management Plan. The results of this study indicate that the production of 10–25 million gallons per day of brackish groundwater is technically feasible. The Wilcox Formation in southern Bexar and northern Atascosa counties is brackish, with total dissolved solids values that range from about 1,200 milligrams per liter to 1,700 milligrams per liter. The Lower Wilcox contains thick sands that appear laterally continuous. A thick aquitard composed mostly of shale separates the brackish Wilcox sands from the overlying fresh water Carrizo Aquifer. Test wells at three locations were pumped at rates of about 1,000 gallons per minute for time periods extending up to two weeks. Based on the Texas Water Development Board's (TWDB) southern Queen City-Sparta groundwater availability model for the region, production of 20 million gallons per day for 25 years will cause water levels at the well field to decline about 250 feet. Current users of the Wilcox groundwater are located far updip from the proposed well field and, therefore, brackish pumping would have minimal impact to these users. Modeling suggests water levels in the overlying Carrizo may decline about 4 feet as a result of 50 years of continuously pumping 25 million gallons per day from the brackish Wilcox. Current groundwater users of the Carrizo experience seasonal water level variations far greater than the modeled impacts. Carrizo groundwater users are not expected to be impacted by Wilcox pumping.

These conclusions are based on 1) a regional evaluation that selected sites for detailed testing; 2) construction and hydrologic and hydrochemical testing of wells at three sites, two in Bexar County and one in Atascosa County; and 3) computer modeling of estimated water level declines from long-term production from three potential fields at the test locations. This paper summarizes the technical information for this groundwater study.

9.1
REGIONAL EVALUATION OF BRACKISH WILCOX AQUIFER

The regional extent of brackish groundwater was evaluated for the Wilcox Aquifer in southern Bexar, northern Atascosa, and western Wilson counties. Available electric log, water chemistry, pumping test, and water level data were reviewed. Approximately 170 electric logs were used. Lithologically, the Wilcox was subdivided into two units, an Upper Wilcox and a Lower Wilcox. The Upper Wilcox was characteristically shaley, whereas the Lower Wilcox contained thick sands. Figure 9-1 is an electric log from Test Well 3 (Atascosa County) that shows the presence of the

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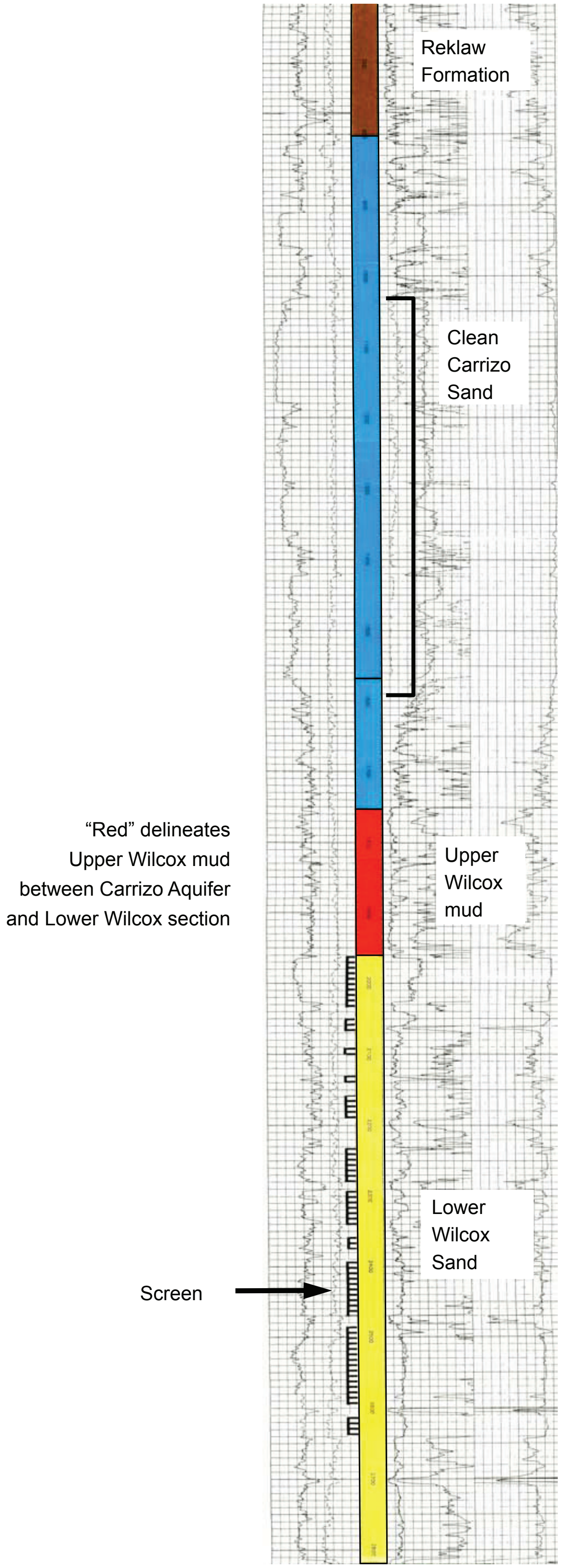
[1] LBG-Guyton Associates
[2] San Antonio Water System



“Red” delineates Upper Wilcox mud between Carrizo Aquifer and Lower Wilcox section

Figure 9-1. Geophysical log (resistivity and SP) for Test Well 3 Site, Atascosa County. Log shows Carrizo, Upper Wilcox shale section, Lower Wilcox Sand section, and Upper Midway.

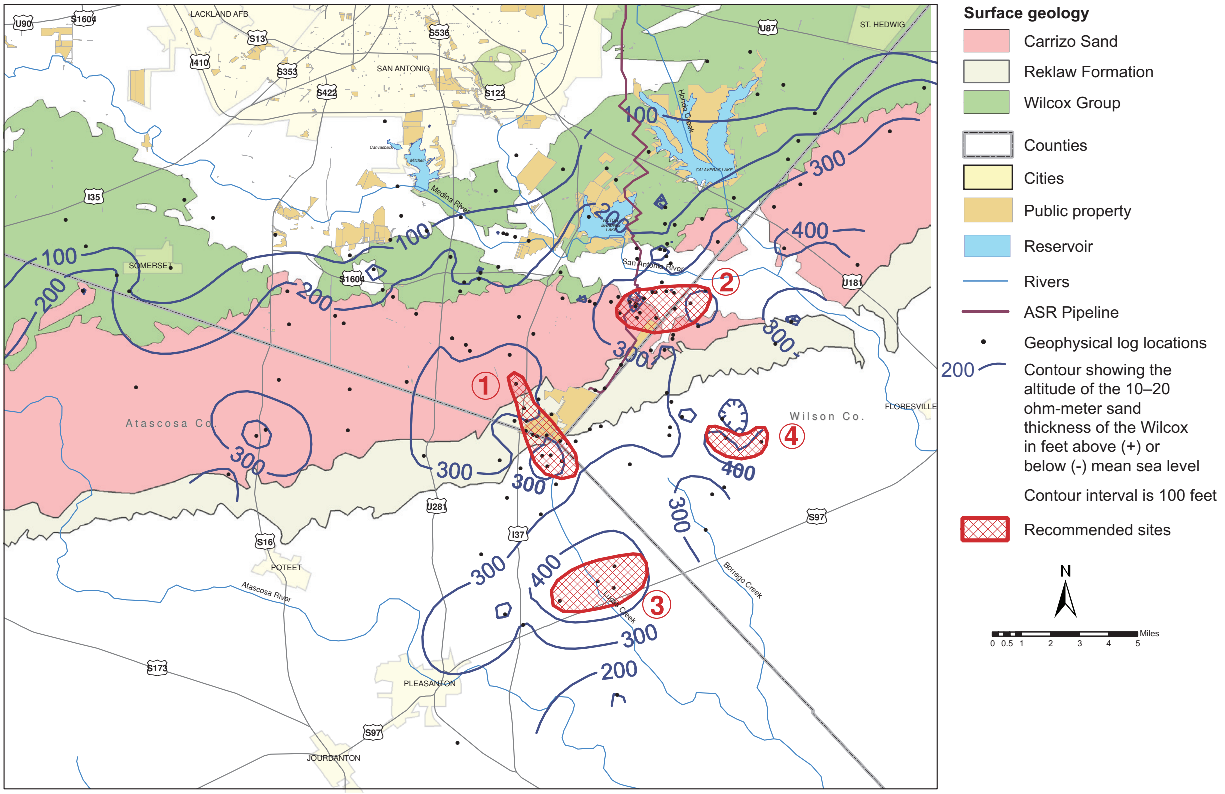


Figure 9-2. Isopach of sand thickness in Wilcox Aquifer in southern Bexar, western Wilson, and Atascosa counties.

Upper Wilcox shaley section and the Lower Wilcox sandy section. Several cross sections were prepared (LBG-Guyton, 2006), and structure maps were prepared for the top and base of the Wilcox. Individual sands along with their estimated salinities for all the logs were determined. From the electric log database, a brackish (1,000–3,000 milligrams per liter) sand thickness map for the Lower Wilcox was then constructed (Figure 9-2). The Lower Wilcox contains some thick sands. Four thick sand fairways were identified as favorable areas for additional testing and exploration. A thick sand fairway was considered to have at least 300 feet of sand that contained brackish groundwater. Four sites for potential testing were identified: 1) the southeast corner of Bexar County (Site 1); 2) south of the San Antonio River along the Bexar/Wilson county line (Site 2); 3) northern Atascosa County (Site 3); and 4) western Wilson County (Site 4). Of the four fairways identified, SAWS selected three sites (Sites 1, 2, and 3) for well construction and testing (Figure 9-2).

Review of the geophysical logs also indicated a laterally extensive shaley Upper Wilcox with thicknesses up to 400 feet (LBG-Guyton, 2008c). An Upper Wilcox aquitard isopach map was constructed (Figure 9-3). This shale section is present in the eastern half of Atascosa, southern Bexar, Wilson, and Gonzales counties.

9.2
SITE-SPECIFIC HYDROLOGIC AND GEOLOGIC DATA FROM THREE TEST SITES

Water wells and paired monitoring wells were constructed at Sites 1 and 2. Only a production well was constructed at Site 3 (Figure 9-2 and Table 9-1). The following testing was conducted at all three sites: 1) geophysical logging; 2) lithologic (grain size) analysis; 3) water chemistry analysis; and 4) long-term aquifer testing. Aquifer test data from Sites 1, 2, and 3 indicate that groundwater from the Wilcox Aquifer can be pumped at rates of at least 850 to 1,000 gallons per minute. The chemistry of the water indicates the groundwater is brackish with a total dissolved solids range of about 1,200 to 1,700 milligrams per liter (LBG-Guyton, 2008a).

9.2.1
Site 1

At Site 1 (Figure 9-2), a test/production well and a monitoring well were constructed to a total depth of about 1,800 feet (Table 9-1). Test Well 1 had 364 feet of brackish sand screened. In an earlier part of this study, a regional assessment estimated 300 feet. Sand collected from the screened intervals during drilling was analyzed to determine gravel pack and screen slot size.

Two aquifer tests were conducted. For the second test, the well was pumped at a rate of about 1,000 gallons per minute for 15 days with 185 feet of drawdown. The well had a 2-hour specific capacity of 8 gallons per minute per foot and a transmissivity of about 9,000 gallons per day per foot. Storativity was about 4 x 10^{-4} (Table 9-1).

9.2.2
Site 2

At Site 2 (Figure 9-2), a test/production well and a monitoring well were constructed to a total depth of 1,250 feet. This well site is stratigraphically updip from Site 1 and, therefore, is screened at shallower depths. Test Well 2 had

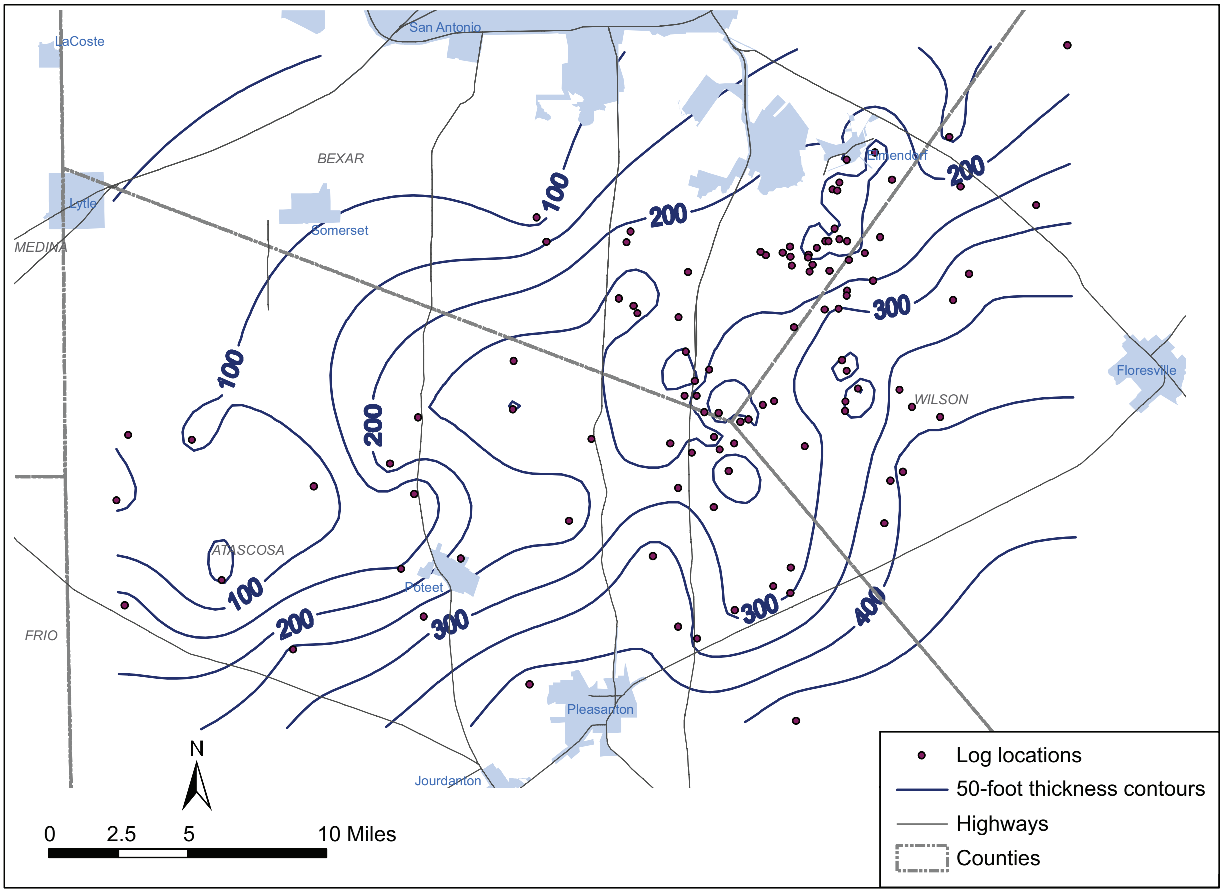


Figure 9-3. Upper Wilcox aquitard thickness map for Atascosa, Wilson, and Bexar counties.

Table 9-1. Summary of pumping tests performed on Wilcox brackish wells.

Tested well	Total screen footage	Observation well	Date test started	Average pumping rate (gpm)	Total minutes pumped	Total drawdown (feet)	2-Hour specific capacity (gpm/ ft)	Calculated transmissivity (gpd/ft)	Calculated transmissivity (gpd/ft) from observation well	Storage coefficient (unitless)
MW-1	176	—	11/14/06	194	970	82.6	2.4	6,460	—	—
TW-1	364	MW-1	4/18/07	1,074	3,600	177.4	8.0	9,150	9,840	3.7 x 10-4
TW-1	364	MW-1	3/4/08	986	21,791	184.5	8.0	8,980	8,290	3.7 x 10-4
MW-2	172	—	12/28/06	244	479	93.8	2.7	7,000	—	—
TW-2	254	MW-2	4/11/07	853	2,880	203.2	5.2	9,200	9,050	2.5 x 10-4
TW-3	431	—	2/12/08	986	2,880	143.4	9.7	9,970	—	—

Note: Test Well 1 step tests on 4/14/07 at 804 gallons per minute, 1,130 gallons per minute, and 1,332 gallons per minute
Test Well 2 step tests on 4/10/07 at 608 gallons per minute, 899 gallons per minute, and 1,148 gallons per minute
Test Well 3 step tests on 2/08/08 at 800 gallons per minute, 1,000 gallons per minute and 1,000 gallons per minute estimated from orifice weir

Source: LBG-Guyton Associates, 2008a

MW = monitoring/observation well; TW = test well; gpm = gallon per minute; gpd = gallons per day)

254 feet of brackish sand screened. The regional assessment had estimated about 300 feet. Sand collected during drilling of the screened intervals was analyzed to determine gravel pack and screen slot size. The well was pumped at a rate of 850 gallons per minute for 48 hours with 203 feet of drawdown. The well had a 2-hour specific capacity of 5.2 gallons per minute per foot and a

Table 9-2. Hydrochemistry of brackish Wilcox test well sites—Test wells 1, 2, and 3.

		Field parameters				Lab parameters												
Well ID	Sample date	pH (s.u.)	Temp (deg C)	Conductance (umhos/cm)	Lab	TDS (mg/L)	Turbidity NTU	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Total Iron (mg/L)	Total Alk (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Fluoride (mg/L)	Silica (mg/L)
MW-1																		
	11/14/06	7.7	31.0	2,160	LCRA	1,410	NP	44.8	22.8	424	9.38	0.647	207	207	274	508	NP	NP
					ELI	1,240	1.0	43.7	22.5	415	8.90	0.667	243	296	100	545	1.26	15.6
TW-1																		
	4/20/07	7.5	33.0	1,970	LCRA	1,360	NP	42.8	23.4	389	8.64	0.324	236	233	230	508	NP	19.1
					ELI	1,324	<0.1	43.2	23.0	391	8.60	0.300	248	303	285	508	1.36	17.6
	3/4/08	7.6	33.0	2,040	LCRA	1,390	1.5	44.2	22.4	386	7.91	0.306	233	233	238	526	NP	21.1
	3/12/08	7.6	33.5	2,040	LCRA	1,380	1.6	43.2	22.4	384	8.38	0.241	232	232	239	513	NP	20.9
	3/18/08	7.5	33.0	2,060	LCRA	1,380	1.1	42.7	21.9	381	7.78	0.238	232	232	230	506	NP	21.8
	3/26/08	7.5 [a]	33.0 [a]	1,900 [a]	ELI	1,427	1.4	44.6	24.5	406	9.20	0.265	256	312	242	498	0.28	12.7
MW-2																		
	12/28/06	7.7	29.0	2,070	LCRA	1,380	NP	14.8	7.4	497	5.84	NP	247	246	263	491	NP	NP
					ELI	1,188	4.0	12.9	7.1	455	5.60	1.970	263	320	240	511	0.84	15.7
TW-2																		
	4/13/07	7.9	29.5	1,980	LCRA	1,310	NP	15.7	7.6	442	5.20	0.133	236	236	245	464	NP	15.1
					ELI	1,437	1.0	15.5	7.4	433	5.00	0.167	230	281	260	492	2.22	14.4
TW-3																		
	6/13/07 [b]	8.3	38.5	3,040	LCRA	1,700	3.8	5.1	1.6	633	4.27	0.201	456	443	615	204	0.50	27.4
	8/24/07	8.4 [c]	-	2,580 [c]	LCRA	1,520	22.8	6.1	2.0	567	4.33	NP	422	404	427	144	0.75	NP
	1/8/08	8.0	38.5	2,480	LCRA	1,520	0.7	5.8	1.7	581	4.04	ND	407	373	496	180	0.53	19.7
	2/14/08	8.1	38.0	2,290	LCRA	1,380	0.2	5.0	1.5	508	3.75	ND	418	398	432	134	NP	19.4
					ELI	1,680	0.2	5.4	1.6	510	4.10	0.153	462	564	506	152	2.16	15.8
TCEQ Secondary Standard																		
		≥ 7	NS	NS		1,000	1.0 [d]	NS	NS	NS	NS	0.3	NS	NS	300	300	2.00	NS

Source: LBG-Guyton Associates, 2008a

TDS = total dissolved solids; Total Alk = Total alkalinity; ND = non detect; NP = not performed; NS = no secondary standard for this constituent; s.u. = standard units; umhos/cm = micromohs per centimeter; NTU = standard turbidity unit; mg/L = milligrams per liter

[a] Measured in field by Carollo
[b] Sample was retrieved from temporary well screened from 2,520 to 2,550 feet depth
[c] Measured at lab
[d] Standard for treated water

transmissivity of 9,200 gallons per day per foot. Storativity was 2.5 x 10^{-4} (LBG-Guyton, 2008a) (Table 9-1).

9.2.3

Site 3

Test Well 3 (Figure 9-2) is located farther downdip in the brackish Wilcox Aquifer in northern Atascosa County. At Site 3, a test/production well was constructed to a total depth of 2,660 feet. Test Well 3 had 431 feet of brackish sand screened. The regional assessment estimated more than 400 feet. Sand collected during drilling of the screened intervals was analyzed to determine gravel pack and screen slot size. The well was tested at about 1,000 gallons per minute for 48 hours with 143 feet of drawdown. The well had a 2-hour specific capacity of 9.7 and transmissivity of about 10,000 gallons per day per foot (LBG-Guyton, 2008a) (Table 9-1).

9.3

WATER CHEMISTRY DATA FROM THREE TEST SITES

The chemical composition of the groundwater from sites 1, 2, and 3 indicates the presence of brackish groundwater (total dissolved solids range from 1,000 milligrams per liter to 3,000 milligrams per liter) (Table 9-2). They are sodium chloride (Na-Cl) type waters, some of which also contain high concentrations of sulfate ($SO_{4)}$ and bicarbonate (HCO_3). At Test Well 1, the total dissolved solids were about 1,380 milligrams per liter. On a molar basis, the cations are dominated by Na and for the anions, Cl, SO_4, and HCO_3 have almost equal molar concentrations. The water is chemically classified as a Na-Cl-SO_4-HCO_3 type water. At Test Well 2, the total dissolved solids were about 1,300 milligrams per liter. On a molar basis, the cations are dominated by Na, and for the anions, the Cl is greater than the SO_4, which is greater than the HCO_3. The water is chemically classified as a Na-Cl-SO_4 type water. Total dissolved solids at Test Well 3 were about 1,600 milligrams per liter. On a molar basis, the cations are dominated by Na; the anions are dominated by Cl; the concentrations of SO_4 are lower than in Test Well 1; and the HCO_3 concentrations are higher than in Test Well 1. The water is chemically classified as a Na-Cl type (LBG-Guyton, 2008c). The presence of dissolved iron in the water from the wells indicates a reducing environment in the aquifer. Computer chemical thermodynamic modeling of the waters from the three wells indicates that the waters are under-saturated with respect to amorphous silica, at about saturation with respect to calcite, and over-saturated with respect to ferric hydroxide (Southwest Groundwater Consulting, 2008).

Water chemistry consistency is an important consideration in designing a desalination plant, especially the pretreatment requirements, and the longevity of reverse-osmosis membranes. The salinity of the brackish Wilcox Aquifer is similar across the study area in southern Bexar and northern Atascosa counties. Produced groundwater from potential well fields is not expected to vary chemically during long-term production. This is based on three lines of evidence:

Water chemistry consistency is an important consideration in designing a desalination plant, especially the pretreatment requirements, and the longevity of reverse-osmosis membranes. The salinity of the brackish Wilcox Aquifer is similar across the study area in southern Bexar and northern Atascosa counties. Produced groundwater from potential well fields is not expected to vary chemically during long-term production. This is based on three lines of evidence:

(1) The geophysical logs used in the construction of the regional cross section and brackish Wilcox sand thickness map indicate that the salinities calculated from the resistivity curves are consistently

within a range of 1,000–3,000 total dissolved solids across the area of investigation and do not show evidence of any source of highly saline water in the aquifer.

(2) The total dissolved solids between the three test wells are within a range considered acceptable by project engineers. There is a total dissolved solids range of 400 milligrams per liter. Downdip, concentrations of Na, Cl, and HCO_3 increase, and the concentration of SO_4 decreases (Table 9-2). As groundwater flows downdip from the outcrop, dissolved sulfate may be reduced, and organic material in the Wilcox sediments may be oxidized. This would explain the inverse relationship in concentrations of HCO_3 and SO_4.

(3) Significant chemical changes in the brackish groundwater are not anticipated during the long-term pumping of future well fields. Significant water chemistry changes were not observed during the sampling of individual test wells at different times. Water chemistry at Test Well 1 did not change from initial sampling in May 2007 to March 2008 (almost one year later). Nor were changes in water chemistry observed for water samples collected over time from the 15-day pump test at Test Well 1. The sample collected on March 4, 2008, had a very similar chemical composition to the sample collected 14 days later on March 18, 2008, after continuously pumping at a rate of about 1,000 gallons per minute (LBG-Guyton, 2008a) (Table 9-2). Long-term monitoring is needed to confirm these observations.

Major water chemistry changes are not expected for an individual well or well field over the life of the project. The electric logs indicate that salinity values are regionally consistent. There are no localized areas with significantly different resistivities. Conversely, the capture area for an individual pumping well is small in comparison to the regional extent of the brackish Wilcox Aquifer. Because of the very large volume of groundwater in a porous aquifer such as the Wilcox, the radial distance from which a pumping well pulls water is very limited. For example, after 50 years of hypothetically pumping of Test Well 3 at 1,000 gallons per minute, a water molecule would have moved to the well from a maximum distance of about 3,500 feet away. In other words, after 50 years of pumping, the source of water at Test Well 3 will come from a "cylinder" in the Wilcox with a radius of only about 3,500 feet.

9.4
GROUNDWATER MODELING

The amount of water level decline from brackish Wilcox production was evaluated for different pumping rates and different time periods (LBG-Guyton, 2008b). Water level changes were simulated with the TWDB Queen City-Sparta groundwater availability model, which supercedes the Carrizo-Wilcox (southern part) groundwater availability model (Kelly and others, 2004). With the Queen City-Sparta model, water level declines in the Carrizo and Wilcox aquifers can be simulated. A comparison of field data (for example, transmissivity) from the three test wells to hydraulic parameters in the model show they are similar; therefore, the official TWDB groundwater availability model was used without modification. A well field was located in the general area of each of the three test sites, and production was distributed between three well fields. The simulated production came primarily from the Lower Wilcox layer of the model. Total pumping rates were varied from 10 to 12.5 million gallons per day to 20 million gallons per day to 25 million gallons per day. The

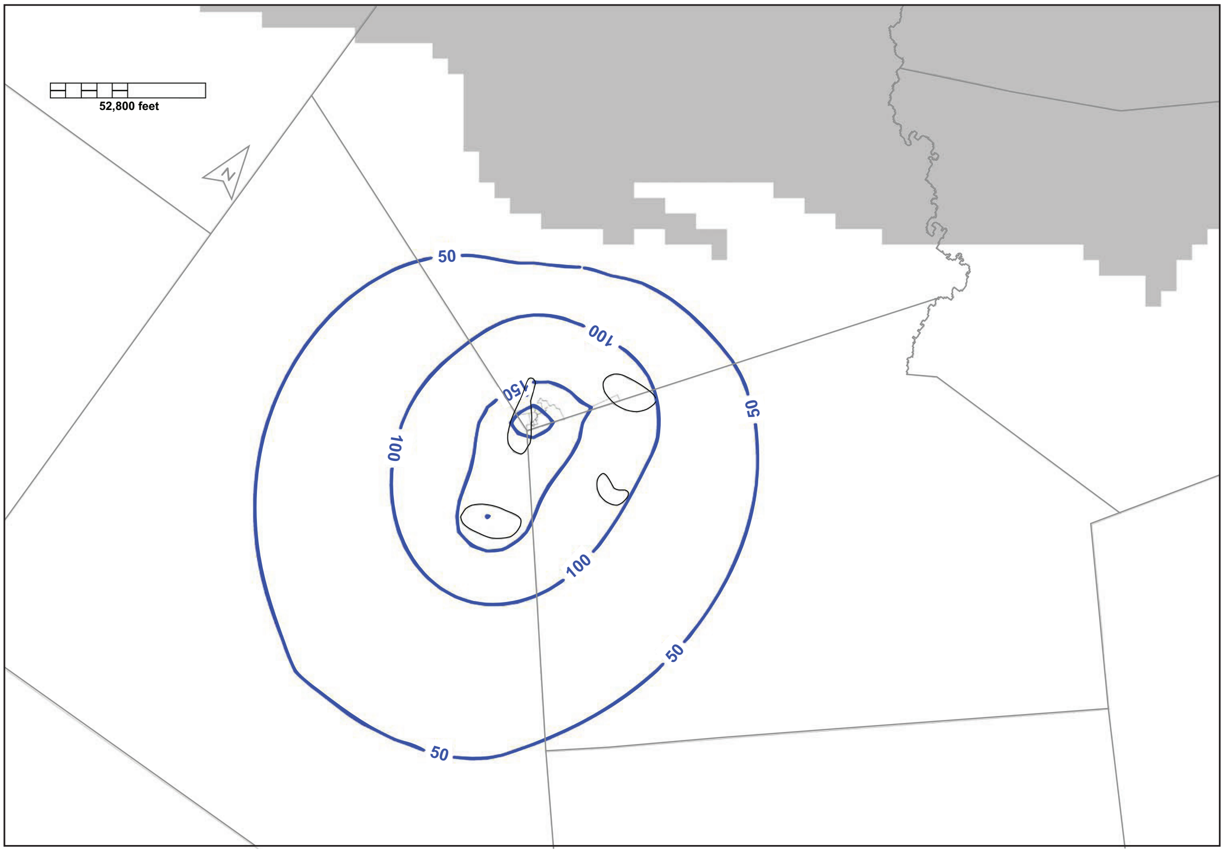


Figure 9-4. Simulated water level decline map, Lower Wilcox Aquifer, for a pumping rate of 20 million gallons per day after 25 years. Simulation made with the TWDB Queen City-Sparta groundwater availability model.

time periods for pumping were 5, 10, 25, and 53 years. The time period of 53 years (ending in 2060) was included since it represents the maximum water planning period being considered in the State of Texas regional water planning process. The Queen City-Sparta groundwater availability model divides the Carrizo-Wilcox Aquifer into Carrizo, Upper Wilcox, Middle Wilcox, and Lower Wilcox layers. Water level declines within the Lower Wilcox, Middle Wilcox, Upper Wilcox, and Carrizo were simulated.

With a production rate of 20 million gallons per day for 25 years, water levels declined nearly 250 feet in the Lower Wilcox in southeast Bexar County (Figure 9-4). Maximum simulated water level decline in the overlying Carrizo for the same pumping rate and duration (20 million gallons per day in the Lower Wilcox for 25 years) was about 4 feet (Figure 9-5). This is far less than is seasonally observed in the historic record of Carrizo water levels (Figure 9-6), which has varied on the order of about 60 feet. Only minor simulated water level declines occur in the Carrizo because the overlying Upper Wilcox muddy aquitard restricts flow between the Carrizo and the deep production zone in the Lower Wilcox (LBG-Guyton, 2008b).

The model predicts that most of the water level declines in the Wilcox will occur early, within the first five years of production; later (from 5 to 50 years), water level declines will slow and stabilize (equilibrate). This permits an early evaluation of the expected drawdown in the well field and whether the model has accurately predicted future conditions in the brackish Wilcox and Carrizo aquifers.

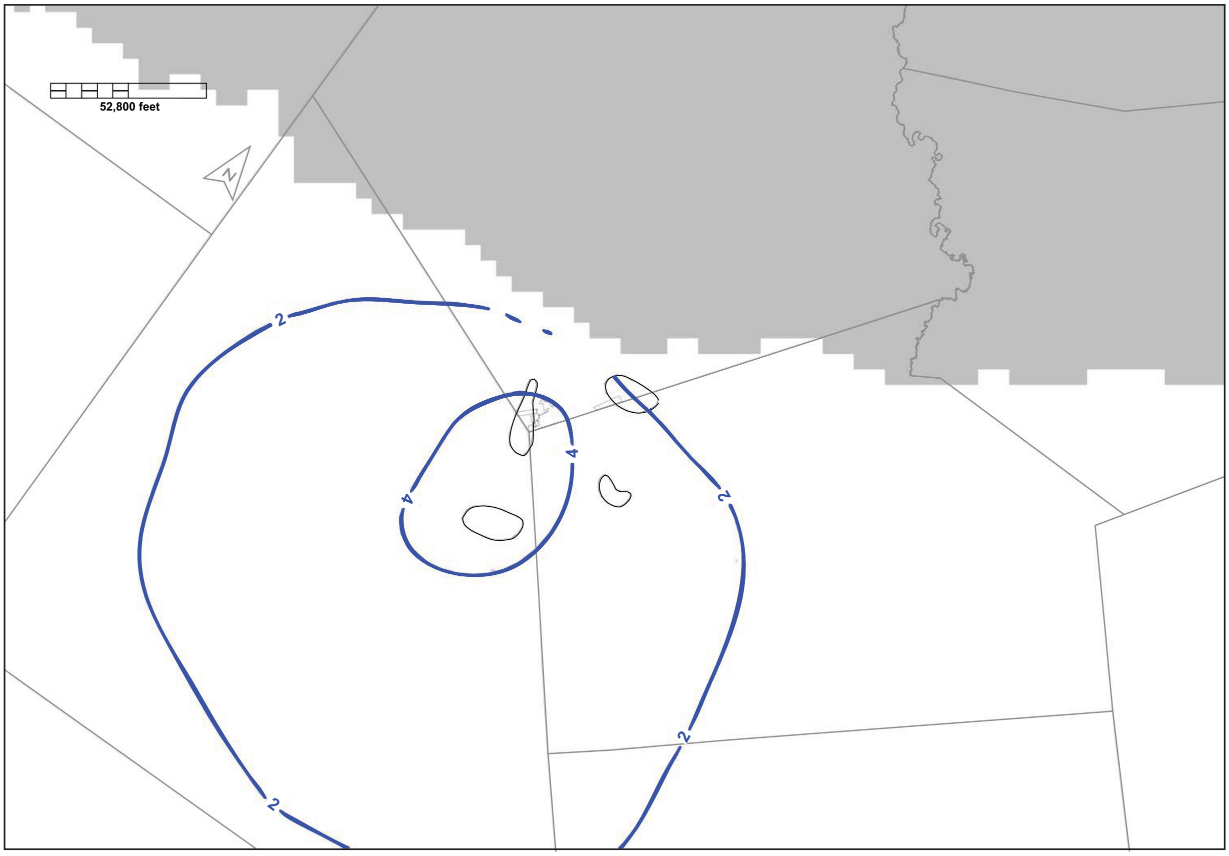


Figure 9-5. Simulated water level decline map, Carrizo Aquifer, for a pumping rate in the Lower Wilcox Aquifer of 20 million gallons per day after 25 years. Simulation made with the TWDB Queen City-Sparta groundwater availability model.

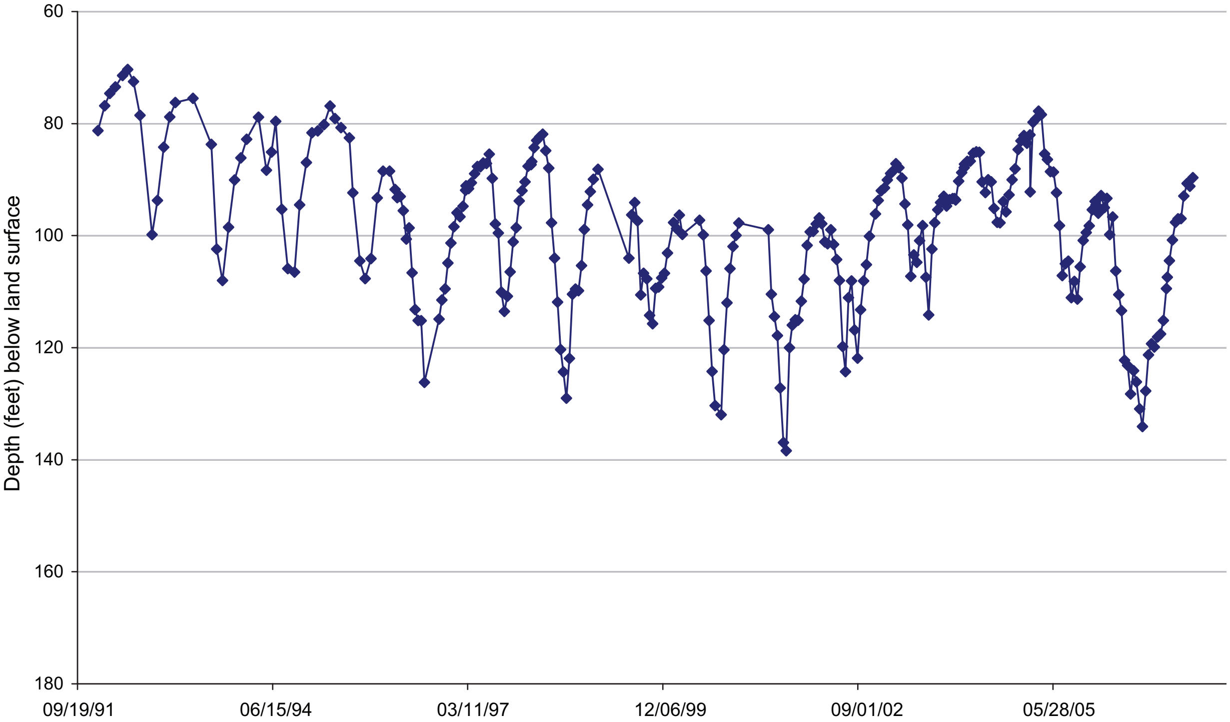


Figure 9-6. Seasonal historical water level declines in Carrizo Aquifer, Atascosa County, Well Number 68-60-912.

Table 9-3. Hydrogeologic characteristics of brackish Wilcox test well sites—Test wells 1, 2, and 3.

Characteristic	Site number		
	Site 1 (TW-1)	Site 2 (TW-2)	Site 3 (TW-3)
Well yield (gpm)	986	853	986
2-Hour specific capacity (gpm/ft)	8.0	5.2	9.7
Transmissivity (gpd/ft)	8,980	9,200	9,970
Total drawdown (ft) (after "x" minutes)	185 (21,791)	203 (2,880)	143 (2,880)
Well depth (ft) (bls)	1,804	1,250	2,660
Top of screen (ft) (bls)	1,226	752	1,965
Screened interval (ft)	364	254	431
Total dissolved solids (mg/l) No. samples	1,324–1,427 (6 samples)	1,310–1,437 (2 samples)	1,380–1,700 (5 samples)
Presence of Upper Wilcox aquitard	Yes	Yes	Yes

Source: LBG-Guyton Associates, 2008a.
gpm = gallons per minute; gpm/ft = gallons per minute per foot; gpd/ft = gallons per foot per day; bls = below land surface; ft = feet; mg/l = milligrams per liter

9.5
SUMMARY

From a technical perspective, the long-term production of brackish groundwater from the Wilcox Aquifer in southern Bexar and northern Atascosa counties appears feasible. The test wells were capable of producing at high capacities (up to 1,000 gallons per minute), and the quality of groundwater is acceptable for desalination. Table 9-3 provides a comparison of the hydrogeologic characteristics of the three test wells. All three test sites have relatively similar hydrogeologic characteristics. Based on Table 9-3, no well field location was considered significantly better than the other two.

9.6
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LBG-Guyton Associates, 2008b, Data from test wells for SAWS brackish Wilcox groundwater investigation, southern Bexar and northern Atascosa counties, Texas: Prepared for San Antonio Water System, 16 p., plus tables and figures.

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Chapter 10

SAWS: Twin Oaks Aquifer Storage and Recovery Project

Roberto Macias[1]

The San Antonio Water System's (SAWS) Twin Oaks Aquifer Storage and Recovery facility is a key component of SAWS' 50-year water supply plan, adopted in 1988 and updated in 2005. The plan addresses the critical need to develop and manage water resources for a growing population while protecting regional environments and maintaining affordability.

10.1
EXACTLY WHAT IS AQUIFER STORAGE AND RECOVERY?

Aquifer storage and recovery is an environmentally friendly way of pumping groundwater from the Edwards Aquifer (limestone), then storing and later recovering the water from the Carrizo-Wilcox Aquifer (sand). Storage operations are conducted during the cool, rainy season, and recovery operations are conducted during the dry, hot months. As a result, aquifer storage and recovery maximizes the use of pumping allocations from the Edwards Aquifer throughout the year.

10.2
WHY DID WE NEED AN AQUIFER STORAGE AND RECOVERY PLANT IN SAN ANTONIO?

Groundwater pumping from the Edwards Aquifer is limited by legislation.

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[1] San Antonio Water System

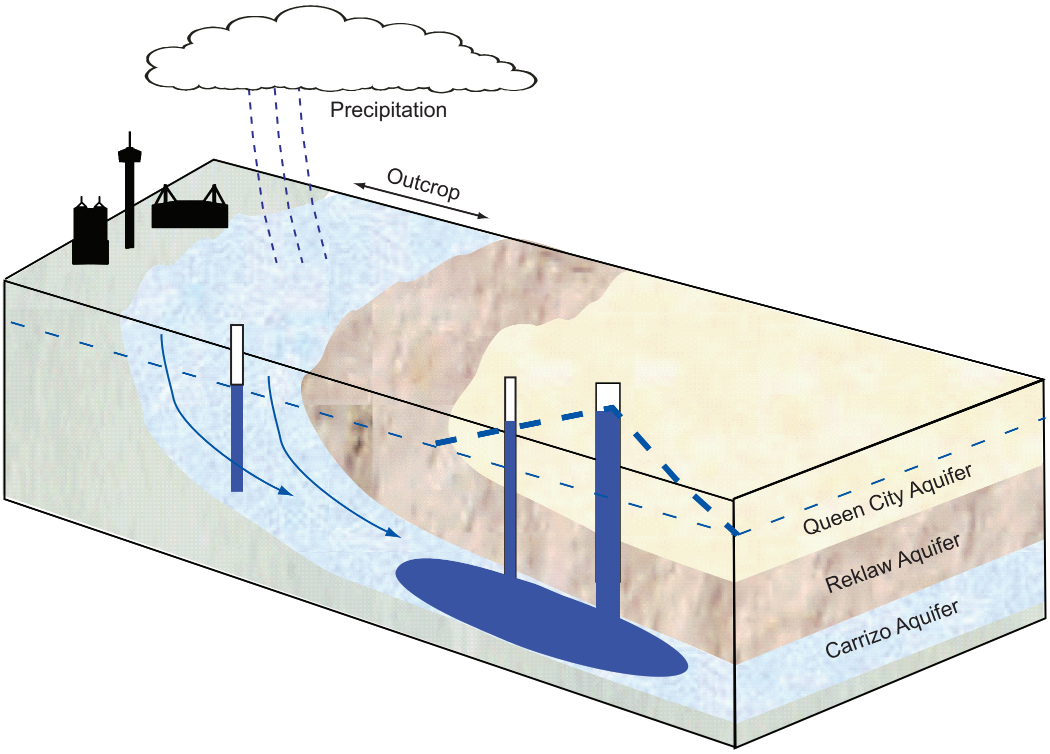

Figure 10-1. Aquifer storage and recovery—injection mode.

During wet periods, allocations were being lost through nonuse, as there was no method to store water.

10.3
SAVING FOR A SUNNY DAY

During wet years, up to 30,000 acre-feet of excess Edwards Aquifer water is diverted into storage in the Carrizo-Wilcox Aquifer (Figure 10-1). A great benefit of injecting into this type of aquifer is that the water, for the most part, stays right where you put it.

During the summer, this stored water is withdrawn during dry periods (recovery mode) and sent back into town. This helps maintain spring flows in New Braunfels and San Marcos to ensure protection of endangered species habitats.

Phase I of the project, completed in 2004, includes a 30 million-gallon-per-day treatment facility, 16 wells, a high-service pump station, a 3 million-gallon storage tank, and 30 miles of main to convey water to the Artesia and Seale pumping stations.

10.4
TREATMENT PROCESS

The native Carrizo-Wilcox water is usually higher in manganese and iron but has a lower pH and hardness than the Edwards water. During production mode, up to 6,400 acre-feet of the available native Carrizo-Wilcox water goes through a three-step process to make the water compatible with Edwards water already in the distribution system (Figures 10-2, 10-3, and 10-4).

Carbon dioxide and/or lime may be added during this process to adjust pH, alkalinity, and hardness. This aeration also helps to oxidize the iron and increases dissolved oxygen.

Polymers, potassium permanganate, and/or chlorine can be added in the solid contact units to aid in settling out manganese and other suspended solids.

Dual media filters are used to remove any of the remaining particles of solids. All backwash flows and settled solids go to a backwash clarifier and then to three storage lagoons.

Figure 10-2. Cascade aeration, first step of treatment process.

Figure 10-3. Clarification, second step of treatment process.

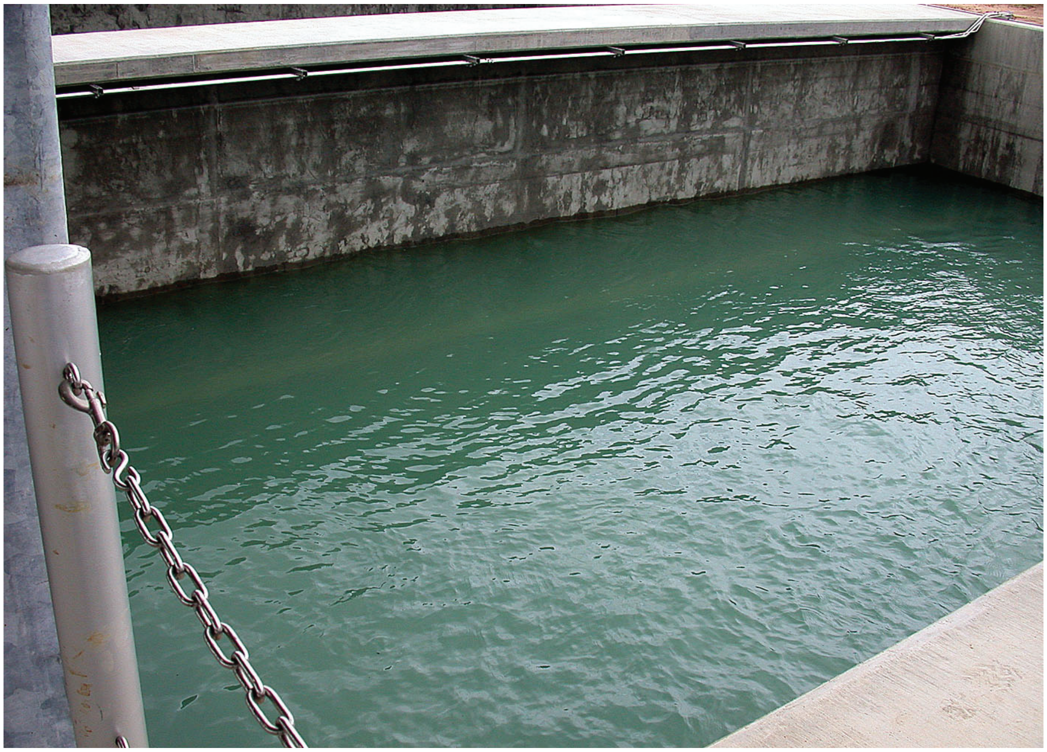

Figure 10-4. Filtration, third step of treatment process.

10.5
FINISHED WATER GOALS

The finished water goals for the Twin Oaks Aquifer Storage and Recovery water treatment facility are shown below (Table 10-1). These goals were arrived at by evaluating several factors, including the following:

- Meet or exceed all regulatory requirements of the Texas Commission on Environmental Quality, including all primary and secondary maximum contaminant levels.
- Condition the water in such a way as to avoid water quality problems in the distribution system.
- Meet or exceed the aesthetic quality expected by SAWS customers.

During recovery mode (Figure 10-5) of the stored Edwards Aquifer water, there is virtually no treatment required. This water can be sent back into the system after only the addition of chlorine for disinfection purposes.

10.6
SUMMARY OF AQUIFER STORAGE AND RECOVERY BENEFITS

This process allows for more flexibility in managing and storing valuable water resources throughout the year. Storing water underground results in no evaporation; it also renders the water less vulnerable to possible contamination. This is an enormous advantage over surface storage. Almost all of the 3,200 acres SAWS leased directly above the aquifer storage and recovery site continues its previous use. The land was leased back to its original owners.

10.7
THE FUTURE OF THE TWIN OAKS AQUIFER STORAGE AND RECOVERY FACILITY

Phase I was constructed in 21 months at a cost of $185 million. Although it is not required by state law, a mitigation program has been implemented to assist area well owners impacted by drawdown.

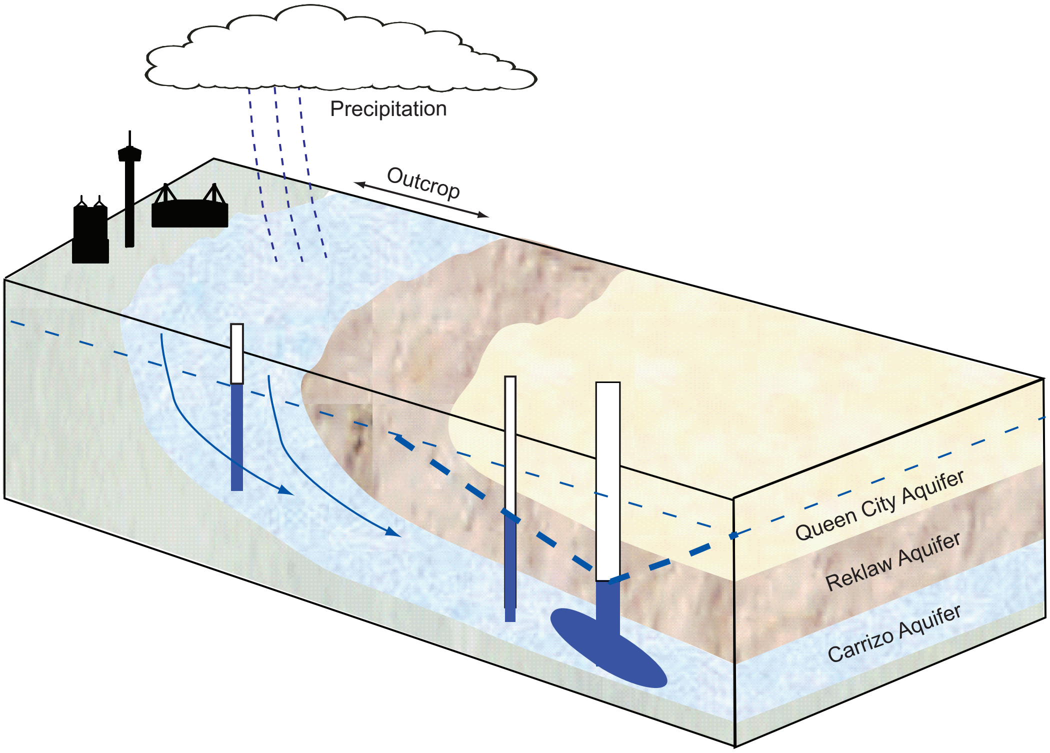

Figure 10-5. Aquifer storage and recovery—recovery mode.

Table 10-1. Finished water goals.

Contaminant	Units	Raw water design	MCL	Finished water goal
Primary drinking water contaminant levels				
Radium-226 & 228, total	pCi/l	4.50	5.00	<3.0
Arsenic	mg/l	<0.01	0.05[a]	<0.01
Secondary drinking water contaminant levels				
Color, true	color units	20	15	<3.00
Hydrogen sulfide	mg/l	2	0.05	<0.03
Iron	mg/l	15	0.3	<0.2
Manganese	mg/l	0.30	0.05	<0.03
Ph		5.50	>7.0	>7.8
Odor	T.O.N	200	3	<2.5
Other parameters				
Alkalinity, total	mg/l as $CaCO_3$	30	NA	>100
Calcium	mg/l	23	NA	>40
Dissolved oxygen	mg/l	0.10	NA	>2.0
Hardness, total	mg/l as $CaCO_3$	35	NA	>100
Radon	pCi/l	160	300[b]	<100
Turbidity	NTU	0.20	<0.5	<0.1
Corrosion indices				
Langlier saturation index		-2.0	NA	>0.20
Ryznar index		10.1	NA	<7.1
Disinfection by-products				
Bromate	mg/l	NA	0.010	<0.005
Total trihalomethanes (TTHM)	mg/l	0.007	0.080	<0.040
Haloacetic acids (HAA5)	mg/l	0.004	0.060	<0.030

[a] A lower arsenic MCL of 0.01 has been proposed but not yet approved and implemented
[b] Radon is not currently regulated; MCL shown is proposed

MCL = maximum contaminant level; pCi/l = picocuries per liter; mg/l = milligrams per liter; NTU = Nephelometric Turbidity Unit; $CaCO_3$ = calcium carbonate;

Phase II construction included 12 additional wells, an interconnecting pipeline, a second clearwell, and other improvements. This additional infrastructure allows us to send or receive water from the Randolph pump station, which is 37 miles away. The facility serves as a key relay and treatment point for additional water sources currently under development. With the completion of Phase II, Twin Oaks is the third largest aquifer storage and recovery facility in the nation.

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Chapter 11

Groundwater Recharge in the Carrizo-Wilcox Aquifer

Robert C. Reedy[1], Jean-Philippe Nicot[1], Bridget R. Scanlon[1], Neil E. Deeds[2],
Van Kelley[2], and Robert E. Mace[3]

Groundwater recharge is a critical parameter for managing water resources of aquifers. However, recharge is not static and varies with many parameters, including aquifer development. The objective of this study was to estimate groundwater recharge to a dipping confined aquifer and to evaluate recharge dynamics relative to aquifer development and technical assessment of water availability. The study was conducted in the Carrizo-Wilcox Aquifer in Texas. A variety of approaches were used to estimate recharge, including chloride mass balance applied to the unsaturated zone and to groundwater, groundwater tritium, and unsaturated zone and groundwater modeling. Recharge rates based on groundwater chloride range from 0.4 inches per year (2 percent of precipitation) in the semiarid southern part to 4.0 inches per year (8 percent of precipitation) in the humid northern part of the aquifer. Point recharge rates based on unsaturated zone chloride data in the central Carrizo-Wilcox Aquifer are spatially variable (0.7–1.6 inches per year) but generally consistent with those based on groundwater chloride. The presence of tritium (0.76–3.57 tritium units) in the unconfined section of the central Carrizo-Wilcox Aquifer indicates young (post 1950) ages. Upper bounds on deep recharge to the confined part of the southern Carrizo-Wilcox Aquifer range from 0.1 to 0.4 inches per year based on carbon-14 transects in Atascosa County. Recharge rates based on unsaturated zone modeling results range from 0.4 inches per year (2 percent of precipitation) in the southern part to 5.1 inches per year (10 percent of precipitation) in the northern part of the aquifer. Under steady-state conditions, recharge equals discharge, and simulated recharge using groundwater models ranges from 0.75 inches per year in the southern part to 1.1 inches per year in both the central and northern parts of the Carrizo-Wilcox Aquifer models. Water availability for pumpage will depend on recharge and how much discharge through streams, evapotranspiration, and cross-formational flow can be captured by pumping during transient development. Transient simulations indicate that irrigation pumpage in the southern part of the aquifer in 1999 is still derived primarily from groundwater storage changes (65 percent), with lesser amounts from induced recharge from cross-formational flow to the overlying Queen City Aquifer (20 percent) and increased deep recharge from the outcrop (16 percent). Groundwater pumpage in the northern Carrizo-Wilcox Aquifer in 1999 is also derived from groundwater storage (40 percent), deep recharge (34 percent), and cross-formational flow (29 percent). Understanding impacts of groundwater development on aquifer recharge is essential for assessing water availability in the aquifer.

Groundwater recharge is an important parameter for managing water resources in an aquifer. Recharge is generally defined as addition of water to an aquifer, mostly derived from the land surface. Many papers have discussed the relationship between recharge and

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[2] INTERA, Inc.

[3] Texas Water Development Board

aquifer sustainability with respect to groundwater development. Under predevelopment conditions in an aquifer, the natural recharge (R_o) is equal to the natural discharge (D_o) when averaged over a long time:

$$R_0 = D_0 \qquad (1)$$

Some hydrologists believe that the predevelopment recharge rate should determine the sustainable pumpage rate (Pu) by taking natural discharge into account

$$R_0 = D + Pu, \qquad (2)$$

where D is discharge that is not captured by pumpage. This has been termed the "water budget myth" (Bredehoeft, 2002; Devlin and Sophocleous, 2005). Equation 2 makes three assumptions: (1) pumpage does not affect recharge; (2) steady-state conditions apply (that is, no change in groundwater storage); and (3) pumpage equals change in discharge (Devlin and Sophocleous, 2005). A more comprehensive equation describing conditions after development is

$$(R_0+\Delta R_0)-(D_0+\Delta D_0)-Pu+dV/dt=0, \qquad (3)$$

where ΔR_o and ΔD_o are changes in recharge and discharge caused by pumpage, respectively, and dV/dt is change in volume of groundwater storage. Combining Equations 1 and 3 (Sophocleous, 1998) yields the following equation:

$$\Delta R_0 - \Delta D_0 - Pu = dV/dt \qquad (4)$$

If a new steady state is established under pumping conditions, there is no further change in groundwater storage and dV/dt = 0. In that case, groundwater pumpage is derived from an increase in recharge or a decrease in discharge, which is termed capture (Sophocleous, 1998). Water can be captured in an unconfined aquifer by intercepting groundwater discharge to streams, changing streams from gaining to losing, and/or reducing groundwater evapotranspiration from riparian zones near streams. In a confined aquifer, water can be captured by increasing deep recharge from an overlying unconfined aquifer through cross-formational flow—this will correspond to capture from the unconfined aquifer as described above and can result in a reversal of the flow direction if water in the confined aquifer was previously flowing to the unconfined aquifer.

Although Equation 4 indicates that initial recharge and discharge rates are not used to estimate pumpage, Sophocleous and Devlin (2004) point out that large initial recharge and discharge rates support large changes in these parameters. Therefore, initial or predevelopment recharge and discharge rates are important for assessing water resource sustainability.

The general concepts related to impacts of pumpage on groundwater systems were applied to aquifers in the United States by Johnston (1997). Predevelopment recharge and discharge estimates for various aquifers within the United States were evaluated, including unconfined aquifers, such as the Ogallala (High Plains) Aquifer, and dipping confined aquifers, such as the Gulf Coast Aquifer. In the Ogallala Aquifer, predevelopment recharge to and discharge from the entire Ogallala Aquifer are very low (0.2 million acre-feet per year). Pumpage (7.0 million acre-feet per year), mostly for irrigation, is derived primarily from irrigation return flow (42 percent) and change in groundwater storage (40 percent), with only 16 percent attributed to induced recharge and 2 percent to reduced discharge. The Gulf Coast Aquifer, extending from Texas to Mississippi, has much higher predevelopment recharge (3.3 million acre feet per year). Pumpage (9.8 million acre feet per year) is derived primarily from induced downward percolation and leakage from overlying aquifers (66 percent), reduction in natural discharge (21 percent), and decreased groundwater storage (13 percent) (Williamson and Grubb, 2001).

The objective of this study was to evaluate water resources sustainability issues, focusing on groundwater recharge, under current and projected future pumpage scenarios in a dipping confined aquifer. The Carrizo-Wilcox Aquifer provides an excellent example of such an aquifer system, which differs substantially from unconfined aquifer systems. Recharge to the outcrop zone of the aquifer can be termed "total recharge" to the system (Figure 11-1). Total recharge does not include short-term infiltration that is taken up almost immediately as evapotranspiration and never reaches the water table. Much of the total recharge water discharges to springs and streams and as groundwater evapotranspiration mostly along streams. Only a fraction of total recharge moves into the confined part of the aquifer and is sometimes termed "deep recharge." Interesting aspects of the Carrizo-Wilcox Aquifer are the range in climatic forcing across the aquifer, from semiarid in the south to humid in the north; the range in pumpage stresses, including irrigation pumpage in the south and mostly municipal and domestic pumpage in the north; and the large number of hydraulically connected rivers that cross the outcrop zone of the aquifer. The dynamics of the flow system are also interesting. As groundwater pumpage in the confined part of the aquifer increases, the hydraulic head gradient should increase, drawing more water from the unconfined part of the aquifer. There is limited previous information on groundwater recharge and movement of water from unconfined to confined portions of the aquifer (Pearson and White, 1967; Castro and Goblet, 2003). Unique aspects of this study include application of different approaches for quantifying recharge to the unconfined aquifer and linkage between recharge data and groundwater modeling analyses. Recharge estimation techniques include chloride mass balance and tritium in groundwater, chloride mass balance in the unsaturated zone, and unsaturated zone modeling.

11.1
PREVIOUS STUDIES

Variations in recharge caused by pumpage during postdevelopment have been described in many previous studies, as reviewed in Kelley and others, 2004. In the southern Carrizo-Wilcox Aquifer, under predevelopment conditions prior to 1900, western streams such as the Nueces and Frio rivers were likely gaining streams based upon the historical occurrence of flowing wells. By 1904, there were 30 artesian wells in the Carrizo Springs area alone, with average flows from 40–300 gallons per minute. The Dimmit County area was famous for spring-fed creeks that supported travelers and wildlife from early times. Within 40 years of drilling the first well, virtually all of the springs and creeks they fed were dry. By 1910, farmers in some areas had to pump their wells (http://www.historicdistrict.com/Genealogy/Dimmit/dimmit.htm). Hamlin (1988) reports that prior to significant production (before 1900), Carrizo wells flowed at elevations up to 700 feet above mean sea level. By the 1930s, flowing wells were limited to elevations below 500 feet above mean sea level, and by 1972 only certain wells flowed at elevations below 360 feet above mean sea level. In the eastern portion of the southern Carrizo-Wilcox Aquifer, flowing wells still exist in areas such as Gonzales County.

A transient groundwater model developed by LBG-Guyton and HDR (1998) was used to evaluate impacts of groundwater development on the flow system from 1942 through 1994. The simulation results showed gain/loss for each major river in the model study area from 1942 through 1994 on a 10-year moving average basis. Simulation results indicate that the San Marcos and Guadalupe rivers were gaining streams from 1942 through 1994, gaining less than 100 acre-feet per year per mile of outcrop from 1980 through 1994. The San Antonio River changed from strongly gaining (over 400 acre-feet per year per mile) in the 1960s to losing more than 400 acre-feet per year per mile of outcrop by 1990. The change from gaining to losing occurred in the late 1960s. The Atascosa River changed from gaining to losing in the early 1970s to becoming slightly losing (less than 50 acre-feet per year per mile) from 1980 through 1994. Cibolo Creek changed from gaining 200 acre-feet per year per mile in the 1940s to losing up to 100 acre-feet per year per mile in the late 1970s through 1994. The analysis by LBG-Guyton and HDR predicted that San Miguel Creek, the Nueces River, and the Frio River were losing streams throughout their analysis period (1942–1994). Their results predicted that the Nueces and Frio rivers lose, on average, approximately 500 acre-feet per year per mile of outcrop.

The model simulation results are supported by gain/loss studies conducted in various streams and reviewed by Slade and others (2002). Gain/loss studies indicated that the Nueces River was losing based on studies conducted from 1925 to 1933 and in 1940. Cibolo Creek was found to be gaining along a 62-mile length in September 1949, with a rate of 163 acre-feet per year per mile. Medina Creek was found to be losing in May 1925, with a rate of 42 acre-feet per year per mile.

11.2
MATERIALS AND METHODS

11.2.1
Site description

The Carrizo-Wilcox Aquifer is typical of coastal plain dipping aquifers that have a generally narrow, unconfined outcrop section and a large, confined section (Figure 11-1). The aquifer extends from the Rio Grande in South Texas to East Texas (Figure 11-1). For groundwater modeling purposes, the Carrizo-Wilcox Aquifer has been subdivided into southern (Rio Grande to the surface water divide between Guadalupe and Colorado rivers); central (San Antonio River to part of the East Texas Basin); and northern (surface water divide between the Trinity and Brazos rivers to the Red River in Louisiana and Arkansas) sections. The geology of the Carrizo-Wilcox Aquifer is described in detail in Deeds and others (this volume) and George (this volume). In the Central Carrizo-Wilcox Aquifer, the geology consists of the following formations, from oldest to youngest: Hooper, Simsboro, Calvert Bluff, and Carrizo. The Hooper and Calvert Bluff formations are semi-confining units, and the Simsboro and Carrizo formations are aquifers. In most of the footprint of the southern and northern models, the Simsboro Formation cannot be distinguished, and the Wilcox Formation is subdivided into the Lower, Middle, and Upper Wilcox. The Carrizo-Wilcox Aquifer is overlain by the Queen City Aquifer, separated by the Reklaw Formation, which is a confining unit.

Previous studies indicate that there is more recharge through the predominantly sandy Simsboro Formation and other sandy sections of the Carrizo and Wilcox formations than through the clay-rich Hooper, Calvert Bluff, and Reklaw formations. Hydrologic properties of the soils developed on these formations reflect the dominant texture of the underlying formations (Figure 11-2).

Land use/land cover varies widely in the outcrop areas (Figure 11-3). Natural vegetation, open water, and wetlands combined constitute from 48 percent to 78 percent of the land surface. From the south to the north, natural vegetation generally transitions from predominantly shrublands and grasslands (57 percent) to forests (43 percent), and the percentage of open water and wetland areas increases greatly (Table 11-1). The dominant agricultural land use in all areas is

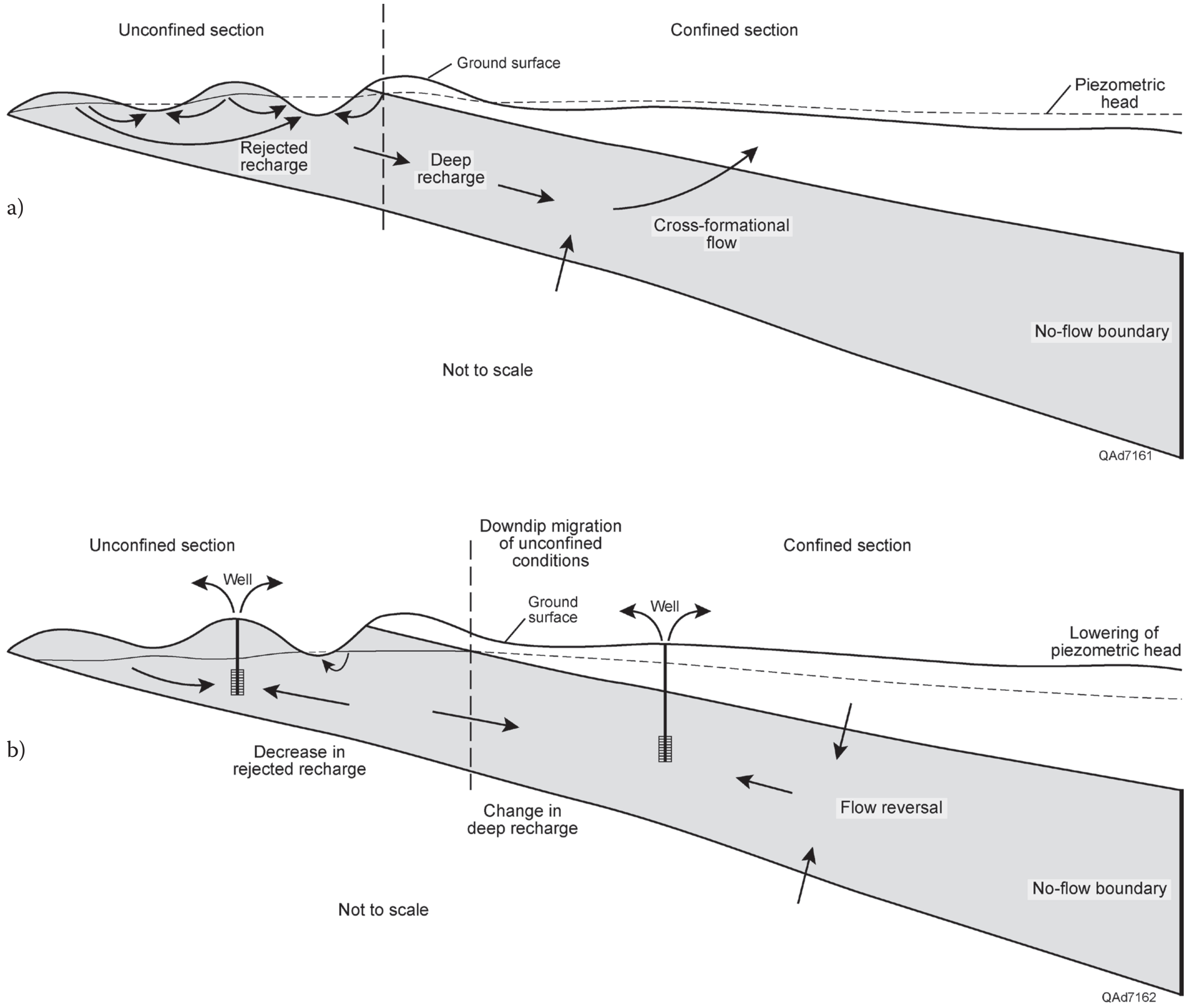

Figure 11-1. Conceptual diagrams of groundwater flow components under a) natural (predevelopment) and b) postdevelopment conditions in the Carrizo-Wilcox Aquifer.

pasture or hay, which generally increases from the south to the north. Cultivated croplands occupy only a minor percentage of outcrop areas.

Mean annual precipitation from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) precipitation data set shows precipitation increasing from a low of 20.7 inches in the far south to a high of 55.9 inches in the Sabine Uplift area, based upon 1971–2000 data (SCAS, 2004). The mean annual net pan evaporation depth in the study area ranges from a low of 38.3 inches per year in the north portion of the study area to a high of 65.9 inches per year in the south of the study area. In general, pan evaporation rate exceeds mean annual precipitation, except in the far north portion of the aquifer. The greatest rainfall deficit with regard to pan evaporation rate occurs in the south portion of the study area and equals ~48 inches per year.

11.2.2
Recharge estimation methods

A variety of approaches were used to estimate groundwater recharge. The chloride mass balance approach was

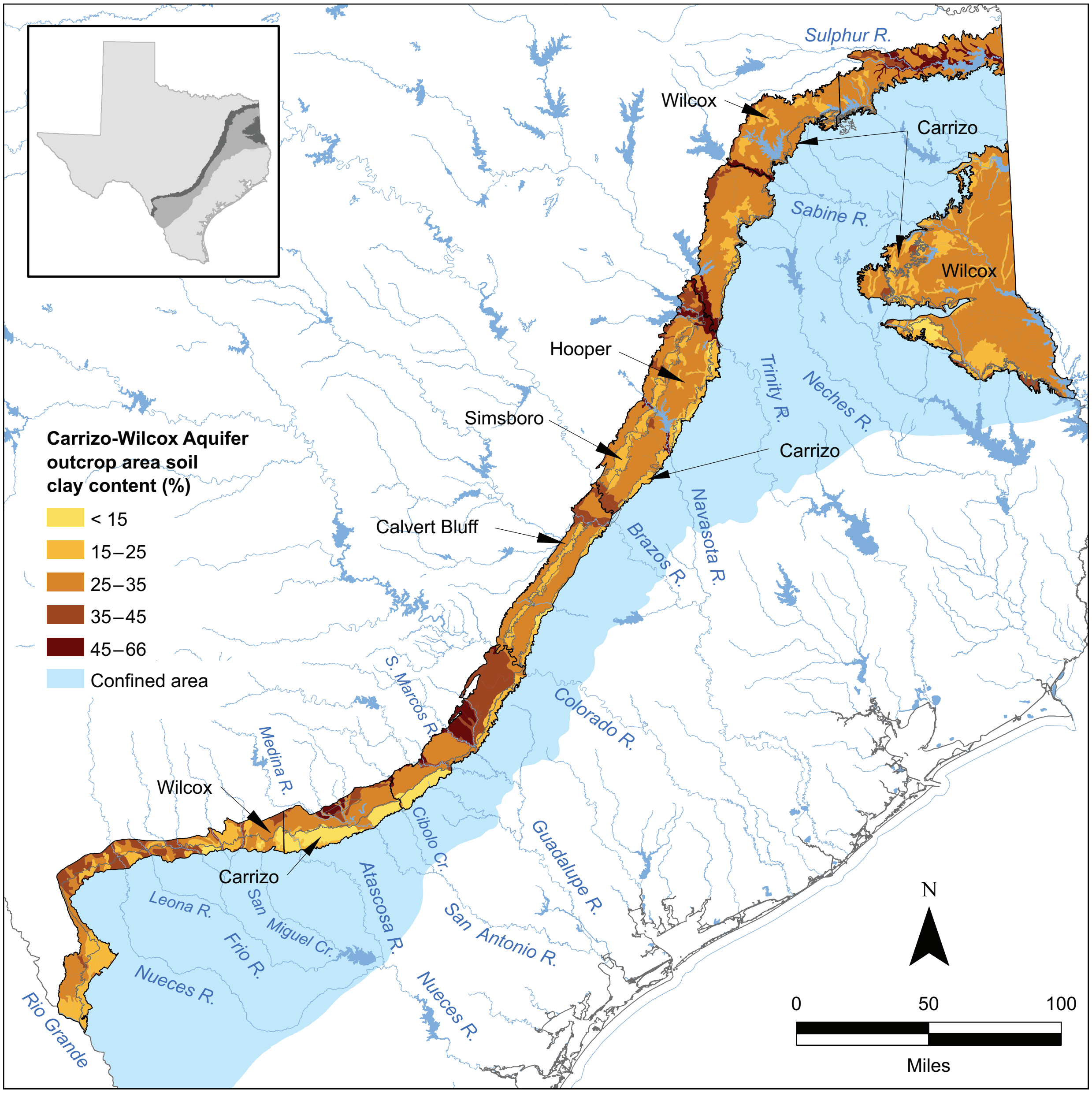

Figure 11-2. Soil clay content in the Carrizo-Wilcox Aquifer outcrop areas and extent of the aquifer confined zone. Formation names are indicated for the south, central, and northern areas. Major rivers and reservoirs are also shown. Soil clay content derived from the State Soil Geographic (STATSGO) database (USDA, 1994).

applied to unsaturated zone soil water samples from the central Carrizo-Wilcox Aquifer and to groundwater chloride data from the Texas Water Development Board (TWDB) database (www.twdb.state.tx.us) from the entire aquifer. Tritium was also measured in groundwater samples in the central Carrizo-Wilcox Aquifer as a qualitative indicator of recharge. Carbon-14 data from previous studies (Pearson and White, 1967; Castro and Goblet, 2003) were also used to estimate deep recharge from the unconfined to the confined portion of the aquifer. Unsaturated zone and groundwater modeling was also used to assess groundwater recharge in the aquifer.

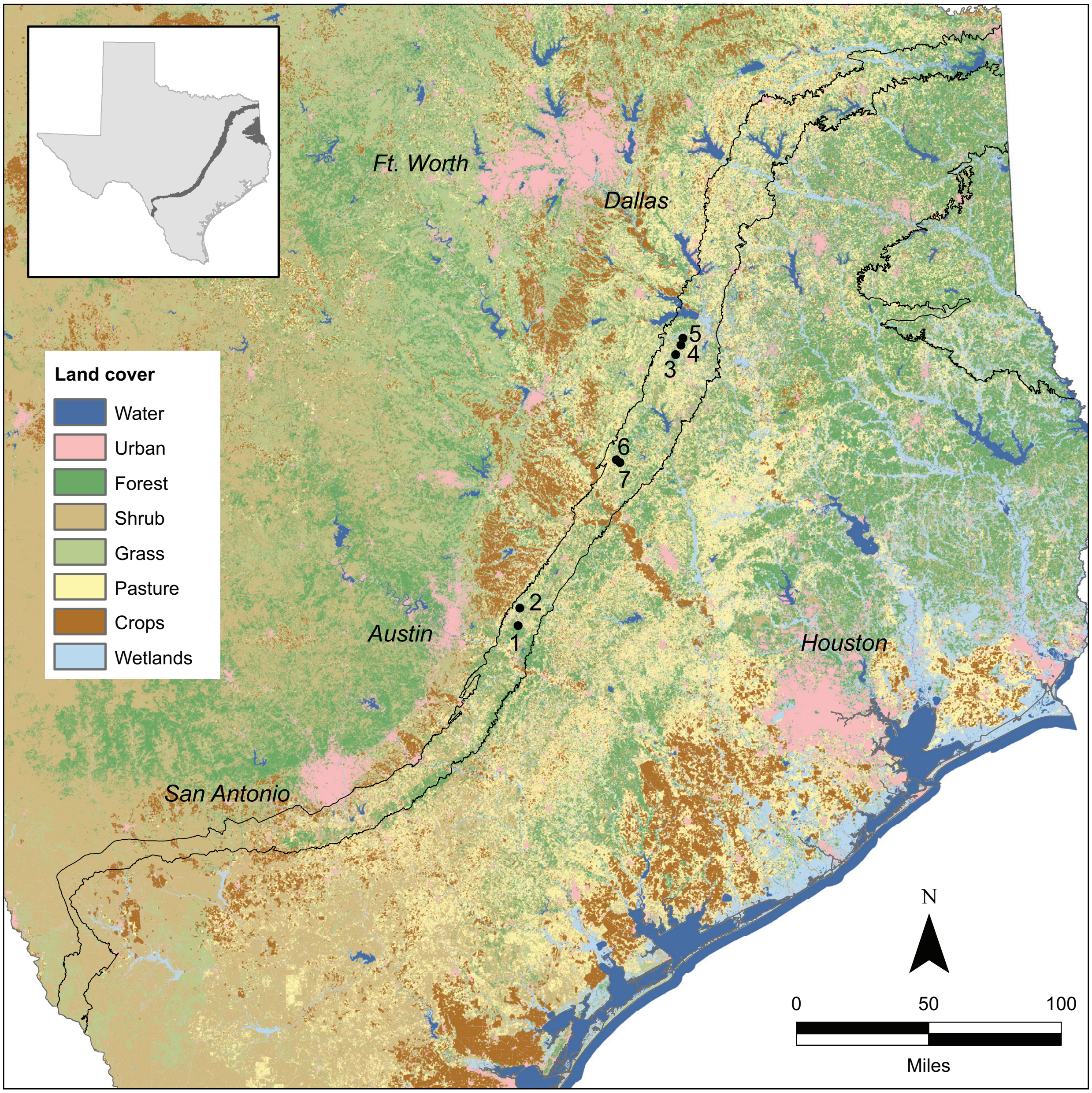

Figure 11-3. Land cover map and unsaturated zone borehole locations (NLCD, 2001; USGS, 2007). The outcrop area of the Carrizo-Wilcox Aquifer is delineated.

11.2.2.1
Chloride mass balance approach

A total of seven boreholes were drilled in the outcrop area of the Simsboro Formation in the central Carrizo-Wilcox Aquifer in these counties: Bastrop, Lee, Robertson, and Freestone (Figure 11-3). Soil samples from these boreholes were analyzed for water-extractable chloride concentrations, and groundwater was analyzed for tritium. Cores were collected using a hollow-stem auger with a CME Mobile 75 drilling rig. Cores were taken continuously with depth until auger refusal or until the water table was encountered. To avoid contamination of samples, no drilling fluid was used.

Soil samples were leached by adding double deionized water to oven-dried sediments samples in a 1:1 ratio by weight. Samples were then placed on a reciprocal shaker for 4 hours and centrifuged at 7,000 rpm for 20 minutes and filtered through a 0.45 micrometer filter, and the supernatant was extracted. Water-extractable concentrations of chloride were measured by ion chromatography at the New Mexico Bureau of Mines. Water-extractable chloride concentrations are expressed on a mass basis as milligrams ion per kilogram of dry soil and were calculated by multiplying ion concentrations in the supernatant by the extraction ratio (grams of water/gram of soil). Ion concentrations expressed as milligrams ion per liter of soil pore water were calculated by dividing concentrations in milligrams/kilograms by gravimetric water content and multiplying by water density. Gravimetric water content was measured in the laboratory at the Bureau of Economic Geology by oven drying samples at 105°C for 24 to 72 hours. Groundwater samples were collected from all seven test holes for tritium, which were analyzed using gas proportional counting with enrichment at the University of Miami Tritium Laboratory (http://www.rsmas.miami.edu/groups/tritium/).

Total recharge was estimated using a mass balance approach based on chloride (chloride mass balance, CMB) (Allison and Hughes, 1983). According to the mass balance approach, chloride input from precipitation (*P*) balances chloride output in recharge:

$$P \times Cl_P = R \times Cl_{UZ} = R \times Cl_{GW}\,;\; R = \frac{P \times Cl_P}{Cl_{UZ}} = \frac{P \times Cl_P}{Cl_{GW}} \qquad (4)$$

where Cl_P, $Cl_{UZ,}$ and Cl_{GW} are chloride concentrations in precipitation, unsaturated zone pore water, and groundwater, respectively, and *R* is recharge rate. Concentrations of chloride in precipitation were obtained from the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/). Chloride concentrations in precipitation were doubled to account for dry fallout, which is consistent with total chloride fallout based on pre-bomb ^{36}Cl/Cl ratios at Amarillo (Scanlon and Goldsmith, 1997).

Recharge was estimated using chloride concentrations in soil water from samples for each borehole, and depth-weighted average recharge rates were calculated. Regional recharge was also estimated using groundwater chloride concentrations for 1,128 sampled wells from the TWDB database (www.twdb.

Table 11-1. General land use by region in the Carrizo-Wilcox outcrop areas.

Region	**Area** (mi^2)	**Urban/ Developed** (percent)	**Crops** (percent)	**Pasture/ Hay** (percent)	**Shrubland/ Grassland** (percent)	**Forest** (percent)	**Water/ Wetlands** (percent)
South of Colorado River	2,815	6	5	14	57	15	3
Colorado to Trinity Rivers	2,468	6	3	32	22	26	11
North of Trinity River	2,631	8	3	40	6	24	18
Sabine Uplift	3,332	6	0	16	14	43	22
Combined	11,247	6	3	25	25	28	14

Note: Percentages are rounded.
Source: National Land Cover Database (NLCD, 2001; USGS 2007)
mi^2 = square miles

state.tx.us). The wells used are completed solely in the Carrizo-Wilcox Aquifer and are located either in the outcrop or within 5 miles downdip of the outcrop. The wells were grouped into nine zones representing the range of climatic conditions across the outcrop of the aquifer. Because it is difficult to envision any large-scale process other than recharge that would reduce groundwater chloride concentrations and several processes can add chloride to the system (for example, land use change, contamination, and cross-formational flow), the 25th percentile groundwater chloride concentrations for each zone were used to estimate regional recharge rates.

The time required to accumulate chloride in the unsaturated zone was calculated by dividing the cumulative total mass of chloride from the land surface or the base of the root zone to the depth of interest by the chloride input

$$t=\frac{\int_0^z \theta\times Cl_{uz}dz}{P\times Cl_P} \quad , \tag{6}$$

where θ is mean water content in the unsaturated zone and dz is depth interval. Deep recharge was also calculated from a transect of carbon-14 ages in Atascosa County (Pearson and White, 1967). The carbon-14 ages (age) along the flow path were used to calculate water velocities based on distance from outcrop (L). The velocities (v) were then used with an assumed unit width perpendicular to the flow direction and an estimated average porosity (n) and average aquifer thickness (b) to calculate average water flux into the confined aquifer. These recharge estimates are considered upper bounds on recharge from the outcrop because cumulative cross-formational loss/gain of water from overlying and underlying aquifers is ignored. Deep recharge (R_d) can then be expressed in terms of outcrop unit area by distributing the annual water flux over the width of the outcrop zone (w), which is equivalent to the recharge zone:

$$R_d=\frac{v\times n\times b}{w} \quad \text{with} \quad v=L/age \tag{7}$$

11.2.2.2
Unsaturated zone modeling

Regional recharge was also estimated using the relationship between recharge and precipitation developed from unsaturated zone modeling by Keese and others (2005). These recharge estimates were developed for various scenarios, including sandy nonvegetated soils and vegetated, texturally variable soils. Power law expressions were developed for these different conditions:

$$R = 1.956\times10^{-2}P^{1.484}$$

(bare, sandy soil) (8)

$$R = 3.242\times10^{-9}P^{3.407}$$

(vegetated, texturally variable soil) (9)

The bare sandy soil provides an estimate of the maximum recharge as a function of precipitation, whereas the vegetated, texturally variable soil provides the most realistic scenario that should represent current conditions. The relationship was developed using mean annual precipitation from 1961 to 1990.

11.2.2.3
Groundwater modeling

Groundwater models can be used to evaluate partitioning of total recharge into evapotranspiration, stream and spring discharge, and deep recharge into the confined portion of the aquifer. Prior to aquifer development (predevelopment), flow in the aquifer is at steady state, and aquifer recharge is equal to aquifer discharge. The steady-state flow model provides information on the water balance prior to aquifer development. After aquifer development, groundwater pumpage provides an additional discharge mechanism that needs to be considered. The transient postdevelopment groundwater model is useful for assessing sources of water for pumpage, including changes in groundwater storage; reduced groundwater discharge (flow to streams in the unconfined zone or cross-formational flow to overlying aquifers in confined zone); and/or increased recharge from the outcrop. The natural recharge and discharge data from the steady-state water balance model can be used to estimate the discharge that can potentially be captured by aquifer pumpage.

The most recent regional models of the Carrizo-Wilcox Aquifer are described in four groundwater availability model reports. Deeds and others (2003), Dutton and others (2003), and Fryar and others (2003) developed spatially overlapping models covering the southern, central, and northern portions of the aquifer, respectively. In the fourth model, Kelley and others (2004) linked the three Carrizo-Wilcox models with the overlying Queen City and Sparta aquifers. Lateral boundaries of the three models are generally no flow (along surface water divides), but transitions between models include large overlaps between the models (to avoid boundary effects in any single location of the study area). The conceptual flow model of this dipping confined aquifer system includes recharge in the outcrop areas of the shallow-dipping sandy layers of the Carrizo-Wilcox Aquifer from precipitation and losing streams and possibly cross-formational flow from overlying aquifers in the confined section of the aquifer. The model also includes discharge as evapotranspiration adjacent to streams, base flow to streams and flow to springs, and slow upward flow from the confined sections through aquitards to overlying aquifers.

This paper analyzes results from the bottom four layers (three Wilcox layers and one Carrizo layer) of the eight-layer model of Kelley and others (2004). The downdip boundary is also a no-flow boundary and corresponds to the upper limit of the geopressured zone and/or of the Wilcox growth-fault zone. The bottom boundary is specified as no flow, whereas the top boundary outside of the outcrop areas is a general head boundary on top of the overlying Sparta Aquifer. Grid cells are square and uniformly 1 mile across. The three models have a total of ~445,000 active cells, including ~263,000 for the bottom four layers. The model simulations include predevelopment steady-state and transient simulations, with annual stress periods from 1980 through 1999. Although there is diffuse pumping in the outcrop area and shallow confined sections, there are only a few large pumping centers: irrigation pumpage from the Winter Garden area in the southern Carrizo-Wilcox model, municipal pumpage for Bryan and College Station from the Simsboro Formation in the central Carrizo-Wilcox model, and municipal pumpage for the city of Lufkin from the Wilcox in both the central and northern Carrizo-Wilcox models. Calibration of the steady-state model used head measurements from the earliest period of record from the TWDB database, whereas calibration of the transient model used more numerous recent head measurements.

Recharge is spatially distributed in the model based on functions that describe relationships between recharge and precipitation, topography, soil type, and geology (Kelley and others, 2004). Recharge is also varied temporally as a function of annual precipitation; however, this relationship does not account for the time lag between drainage below the root zone and recharge at the water table. Recharge from losing streams, lakes, and reservoirs (focused recharge) is simulated using specific MODFLOW packages. Variations in recharge with topography are based on the assumption that more recharge occurs in upland areas and on hill slopes than in valley floors adjacent to streams where they act as discharge zones. Higher recharge is applied to sandy soil zones and aquifer units than to more clayey soil zones and confining units.

The recharge input for the model is the so-called total recharge from which the numerical model subtracts groundwater evapotranspiration as it is done conventionally in MODFLOW. Groundwater evapotranspiration is a linearly decreasing function with depth from lake evapotranspiration at a zero depth (ground surface) to zero groundwater evapotranspiration at the extinction depth. If the water table is deeper than the extinction depth, there is no groundwater evapotranspiration. Total recharge is input into the recharge package. Computing deep recharge requires output processing. Deep recharge can be computed from the model by summing up the fluxes across the first cells downdip of the outcrop cells (Method 1). Recharge can also be computed by summing up fluxes through the upper boundary (cross-formational flow) for the confined section of the aquifer (Method 2). However, this approach is valid only if there are no large sinks or discharge points in the confined portion of the aquifer. It follows that it can be applied only when there is negligible flow through the side and bottom boundaries and under predevelopment conditions.

11.3
RESULTS AND DISCUSSION

11.3.1
Recharge estimates using the chloride mass balance approach

The groundwater chloride data yield estimates of regional total recharge rates that range from 0.4 inches per year in the south to 4.0 inches per year in the north (Figure 11-4; Table 11-2). The 25th percentile of groundwater chloride concentrations was used in the recharge estimation, and these chloride concentrations range from 49 milligrams per liter in the south to ~ 8 milligrams per liter in the north. Mean annual precipitation ranges from 24 inches per year in the south to 51 inches per year in the north. Recharge rates range from 2 percent to 9 percent of mean annual precipitation. These recharge estimates are considered representative of the aquifer units rather than the confining units.

Recharge rates were also estimated from soil water chloride concentrations in the central Carrizo-Wilcox Aquifer region (Figure 11-4; Table 11-3). Recharge rates range from 0.7 to 1.6 inches per year, representing 2–5 percent of mean annual precipitation. The recharge rates from these field studies are generally consistent with regional recharge rates from groundwater chloride data. There is no systematic variation in recharge rates within this region. The lowest recharge was calculated for a site in a forest (borehole 5), which has a bulge-shaped profile of chloride concentration with depth, with a peak chloride concentration of 120 milligrams per liter at 1.8-meter depth. However, there may be no recharge in this setting as chloride is accumulating. This is the only borehole drilled in a forest setting; all other boreholes were drilled in pasture settings. Some boreholes show vertical variations in chloride concentrations and corresponding recharge rates. For example, recharge in the upper 12 meters of the borehole 1 profile is 1.4 inches per year, whereas below this zone recharge is much less (0.4 inches per year). These variations with depth may be related to land use changes; however, detailed information on land use history is not available for these sites. The chloride accumulation times represented by the chloride data based on Equation 6 range from 32 to 78 years, with the exception of borehole 1, which has an accumulation time of 245 years.

Groundwater tritium concentrations range from 0.76 to 3.6 TU (Table 11-3). Tritium levels were greater than the detection limit (~ 0.2 TU) and indicate that a component of water was recharged

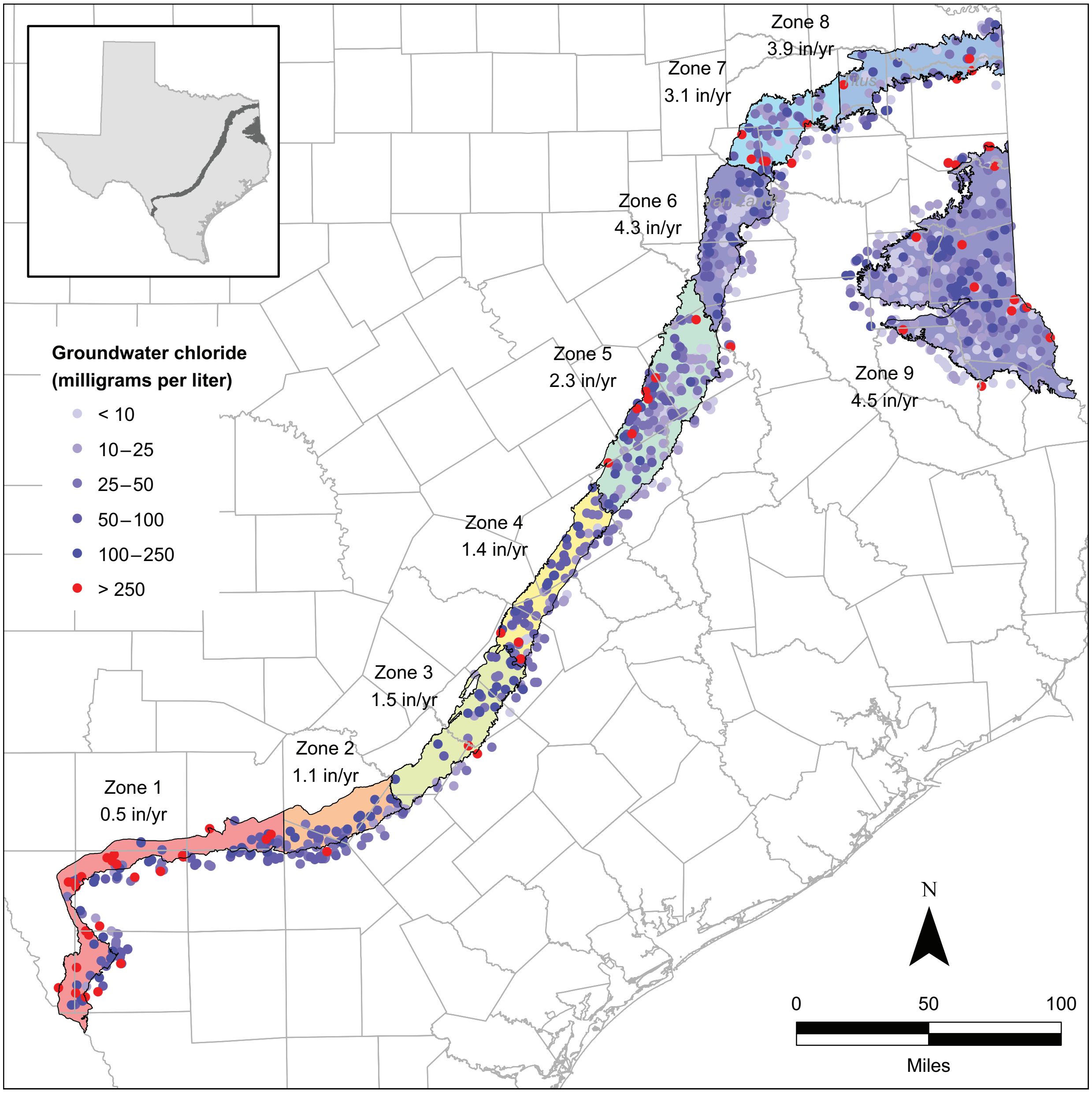

Figure 11-4. Groundwater chloride concentrations and chloride mass balance recharge rates for nine zones in the Carrizo-Wilcox outcrop area. Points represent groundwater wells located inside and within 5 miles downdip of the outcrop area. Chloride mass balance recharge rates are based on 25th percentile chloride concentrations for wells in each zone.

in/yr = inches per year

after about 1950. However, quantitative recharge rates cannot be estimated from tritium data alone.

Deep recharge to the Carrizo Aquifer was estimated from carbon-14 ages from Pearson and White (1967) and Castro and others (2000) using an estimated average aquifer thickness of 100 meters, porosity of 35 percent, and outcrop width of 10 kilometers. Estimated deep recharge rates range from 0.1 to 0.4 inches per year (Table 11-4).

11.3.2

Recharge estimates from unsaturated zone results

Maximum recharge rates developed using the relationships between

Table 11-2. Recharge rates by zones based on chloride mass balance analysis of groundwater chloride concentrations.

Region	Zone	Number of wells	Outcrop area (mi^2)	Precipitation (in/yr)	Cl_P (mg/L)	Cl_{GW} (mg/L)	Recharge (in/yr)	Recharge (af/yr)	Recharge (in/yr)	Recharge (af/yr)
South	1	124	1,223	24.4	0.82	49	0.4 (2)	26,500	0.9 (3)	131,000
	2	73	648	30.9	1.18	37	1.0 (3)	34,300		
	3	48	944	36.1	1.14	30	1.4 (4)	69,800		
Central	4	95	812	36.3	0.98	29	1.2 (3)	52,800	1.8 (5)	241,000
	5	165	1,657	40.5	0.78	15	2.1 (5)	188,000		
North	6	124	936	42.8	0.68	7.9	3.7 (9)	183,000	3.6 (7)	1,160,000
	7	83	789	45.4	0.62	11	2.5 (6)	107,000		
	8	58	906	49.6	0.60	9.0	3.3 (7)	158,000		
	9	358	3,332	51.3	0.70	9.0	4.0 (8)	711,000		

Note: Zones and well locations are shown in Figure 11-4. Precipitation represents 1971–2000 mean (SCAS, 2004). Precipitation chloride concentrations were multiplied by two to account for dry fallout. Groundwater chloride concentration represents the 25th percentile of zone well population. Values in parentheses represent percentages of annual precipitation. Recharge values in (af/yr) units calculated by multiplying recharge by outcrop area. Mean area-weighted recharge rates are provided for groups of zones that approximately correspond to the modeled zones.

Cl_P = chloride concentration in precipitation; Cl_{GW} = chloride concentration in groundwater; mi^2 = square miles; af/yr = acre-feet per year; in/yr = inches per year; mg/L = milligrams per year

Table 11-3. Unsaturated zone borehole information and recharge rates based on chloride mass balance.

Borehole	Total depth (ft)	Depth to water table (ft)	Precipitation (in/yr)	Cl_P (mg/L)	Cl_{UZ} (mg/L)	Recharge (in/yr)	Age (yr)	Tritium (TU)
1	103.8	74.8	35.6	1.02	71.6	0.7 (2)	245	0.76
2	53.3	43.3	35.4	1.02	42.6	1.6 (5)	70	3.25
3	53.7	41.3	42.0	0.74	37.2	0.9 (2)	78	3.30
4	38.8	24.8	41.8	0.74	20.5	1.6 (4)	32	3.57
5	18.5	10.5	41.5	0.74	37.6	0.4 (1)	48	3.43
6	48.6	37.4	38.4	0.84	27.9	1.3 (3)	64	3.05
7	78.5	76.7	38.5	0.84	27.7	1.4 (4)	75	1.10

Notes: Borehole locations are shown in Figure 11-3. Precipitation represents 1971–2000 mean. Precipitation chloride concentrations were multiplied by two to account for dry fallout. Values in parentheses represent percentages of annual precipitation.

Cl_P = chloride concentration in precipitation; Cl_{GW} = chloride concentration in groundwater; ft = feet; in/yr = inches per year; mg/L = milligrams per liter; TU = Tritium units.

Table 11-4. Carbon-14 age, uncertainty, and recharge rate for wells in Atascosa County in the southern portion of the Carrizo-Wilcox Aquifer.

Sample ID	Age (yr)	Uncertainty (yr)	Distance (mi)	Velocity (ft/yr)	Mean deep recharge (in/yr)	Minimum deep recharge (in/yr)	Maximum deep recharge (in/yr)
Tx-01[a]	9,500	3,000	11.9	6.6	0.28	0.21	0.40
Tx-24[a]	17,400	3,000	10.8	3.3	0.14	0.12	0.17
Tx-92[b]	3,750	700	2.0	2.8	0.12	0.03	0.06
Tx-93[b]	6,300	1150	11.0	9.2	0.39	0.35	0.44
Tx-94[b]	14,000	1,050	18.0	6.8	0.29	0.27	0.31

Note: Sample ID values from original references. Average recharge rates are based on carbon-14 ages. Minimum and maximum recharge rates are based on carbon-14 age uncertainty.

[a] Castro and others (2000)
[b] Pearson and White (1967)
ft/yr = feet per year; in/yr = inches per year

precipitation and recharge for bare sandy soils from unsaturated zone modeling (Equation 8) range from 11 inches per year (44 percent of mean annual precipitation) in the southern part of the aquifer to 32 inches per year (63 percent of mean annual precipitation) in the northern part. These rates represent the maximum, diffuse recharge rates as a function of climate forcing because vegetation evapotranspiration and soil textural variability are not included; however, the rates are so high that they do little to constrain actual recharge rates. Recharge rates for vegetated, texturally variable soils (Equation 9) were much lower than those based on bare sandy soils (0.4 to 5.1 inches per year) representing 2 percent to 10 percent of mean annual precipitation. These recharge rates compare favorably with regional recharge estimates based on groundwater chloride data (Figure 11-4).

11.3.3
Recharge estimates from groundwater models

11.3.3.1
Steady-state predevelopment model

The steady-state predevelopment model provides valuable information on aquifer recharge and discharge that can potentially be captured by pumpage during postdevelopment. The water budget for each of the three models was obtained from Kelley and others (2004), and the combined budget for the entire aquifer was obtained from Deeds and others (this volume). The budget for the entire aquifer differs from that of the combined individual models (southern, central, and northern) because of the overlap in each of the individual models. Total recharge increases from 114,000 acre-feet per year in the southern model to 251,000 acre-feet per year in the central model and to 590,000 acre-feet per year in the northern model; however, when these recharge rates are normalized by the area of the outcrop of the aquifer, the increases are not as marked (0.75 inches per year, southern model and 1.1 inches per year in both the central and northern models) (Table 11-5). Most (54–66 percent) of the recharge discharges as streams and springs. The ratio of losing stream inflow to gaining stream outflow decreases from the southern to northern models (16 percent, 10 percent, and 2 percent, respectively), consistent with the observation of some losing sections but still overall gaining streams in the southern area and entirely gaining streams in the northern area. The proportion of total recharge that discharges as evapotranspiration increases from 6 percent in the southern, 27 percent in the central, and 46 percent in the northern aquifer models. Subtracting discharge in the outcrop (streams, springs, evapotranspiration) from total recharge results in deep recharge that ranges from 34 percent in the southern, 6 percent in the central, and 0 percent in the northern aquifer models. Therefore, although total volumetric recharge increases from the southern to the northern aquifer models, deep recharge decreases from the southern to the northern aquifer models.

The relatively low quantity of deep recharge in the northern model is attributed to shallower water tables and large-scale discharge to perennial streams that serve to reject much of the increased recharge in the more humid climate in this region (Kelley and others, this volume). Deep recharge is balanced by slow upward, cross-formational flow, cumulatively accounting for all deep recharge and upward flow from underlying aquifers. The far downdip boundary is for the most part closed, although Dutton and others (2006) have shown that there may be a small updip component of flow from the geopressured zone. The models provide regional average water budgets for the different aquifers and may deviate markedly from averages at the county or finer scale. In summary, predevelopment conditions are characterized by discharge mostly as streams (~60 percent) and a combination of groundwater evapotranspiration (more significant in the north, 46 percent) and cross-formational flow (more important in the south, 34 percent) (Table 11-5).

The simulated water balance for predevelopment provides information on the amount of water that can be captured by well pumpage in the postdevelopment stage. The simulated total discharge provides an upper bound on the volume of groundwater that can be pumped from the system during aquifer development; however, pumping at such a level would eliminate base flow to streams and possibly groundwater evapotranspiration, which would not be desirable. An understanding of the water requirements for instream flows (NRC, 2005) and for riparian evapotranspiration could be used to constrain the permissible pumpage levels during postdevelopment.

The predevelopment model is calibrated using hydraulic head data and base flow discharge to streams. The solution of the model calibration is not unique. Similar calibration results could be obtained with higher recharge as long as groundwater evapotranspiration is also increased. Although the differences between such models may not be important for steady-state calibration, they can substantially impact transient simulations. Higher recharge and evapotranspiration will result in more water being available for pumpage during transient simulations because groundwater evapotranspiration can be captured by pumpage.

11.3.3.2
Transient model

The transient model provides information on impacts of groundwater pumpage on the water budget for the aquifer (Table 11-6). Model calibration is based on matching simulated and measured groundwater level hydrographs over the transient simulation period. The transient simulation results indicate that by 1999 groundwater abstractions through pumpage represent increasing fractions of total recharge from northern (33 percent), central (54 percent), and southern (91 percent) parts of the aquifer. Pumpage in the southern part of the aquifer is primarily for irrigation in the Winter Garden region, whereas pumpage in the central and northern parts of the aquifer is primarily for municipal purposes. The remaining outflows from the system include discharge to streams and springs and groundwater evapotranspiration, both of which increase in percent of total outflow from south to north. The water budget for the transient simulation is balanced by change in groundwater storage, recharge, and cross-formational flow.

Groundwater pumpage during postdevelopment alters the equilibrium established between recharge and discharge during the steady-state predevelopment

Table 11-5. Steady-state simulation results for the south, central, north, and combined model regions.

Region	Component and volume or depth							
	Recharge		**Streams**		**Evapotranspiration**		**Deep recharge**	
	(af/yr)	(in/yr)	(af/yr)	(in/yr)	(af/yr)	(in/yr)	(af/yr)	(in/yr)
South	114,000	0.75	68,000	0.45 (60)	6,600	0.04 (6)	39,100	0.26 (34)
Central	251,000	1.1	166,000	0.70 (66)	68,000	0.29 (27)	16,300	0.07 (6)
North	590,000	1.1	317,000	0.59 (54)	275,000	0.51 (46)	<2,000	<0.01 (0)
Combined	778,000						47,000	

Note: Values in (in/yr) units represent (af/yr) flow values divided by outcrop area. Values in parentheses represent percentages of total flow.

af/yr = acre-feet per year; in/yr = inches per year period. The water abstracted from the aquifer can be derived from groundwater storage, increased recharge, and/or decreased discharge. Initially, most of the water abstracted through pumpage is derived from groundwater storage. With continued pumpage, water is derived less and less from groundwater storage but comes from other processes, such as increased recharge and/or decreased discharge. Transient simulations are used to quantify the amount and timing of these transitions. The initial decline in groundwater storage caused by pumpage generates a vertical head gradient, ultimately reversing cross-formational flow, and capturing this discharge mechanism and possibly draining water from overlying adjacent aquifers. Pumpage from the Carrizo Aquifer impacts the overlying Queen City Aquifer and will ultimately impact the Queen City recharge zone also. Groundwater from the Queen City Aquifer is slowly drawn into the Reklaw aquitard, while some groundwater from the aquitard moves into the Carrizo Aquifer. At the same time, increased hydraulic gradients downdip from the Carrizo-Wilcox outcrop zone increase the fraction of deep recharge resulting from a combination of decreased discharge, decreased groundwater storage in both the unconfined and confined zones, and migration of the unconfined/confined boundary.

The water balance terms for the transient simulation were rearranged to show the source of well pumpage (Table 11-7). Most of the pumpage is in the confined portion of the aquifer. These results indicate that after decades of development (1999) and increasing pumpage, 40–95 percent of well pumpage is still derived from reductions in groundwater storage, 9–29 percent is derived from cross-formational flow, and up to 34 percent is derived from increased deep recharge (Table 11-7). The change in groundwater storage (that is, decline in water table and piezometric head) represents a significant fraction of total pumpage. Ultimately, this fraction should tend to zero; however, currently, the aquifer cannot reach a new steady state (that is, no

Table 11-6. Transient simulation results for the south, central, north, and combined model regions.

Region	Component and volume (acre-feet per yr/1,000)								
	Total recharge	Deep recharge	Total flow	Streamflow	Groundwater ET	Lateral flow	Pumpage	Storage change	Cross-formational flow
South	69	45	-306	-22 (7)	-2 (1)	-3 (1)	-279 (91)	181	57
Central	157	-8	-362	-126 (35)	-39 (11)	0 (0)	-197 (54)	187	18
North	357	53	-463	-219 (47)	-85 (18)	-4 (1)	-154 (33)	61	45
Combined	558	120	-911	-337 (37)	-101 (11)	0 (0)	-473 (52)	251	95

Note: Values in parentheses represent percentages of total recharge.

ET = evapotranspiration

Table 11-7. Transient model simulation results for source of well pumpage.

Region	Component and volume (acre-feet/1,000)				
	Pumpage	Storage change	Cross-formational flow	Deep recharge	Lateral flow
South	-279	181 (65)	57 (20)	45 (16)	-3 (-1)
Central	-197	187 (95)	1 (9)	-8 (-4)	0.3 (0)
North	-154	61 (40)	45 (29)	53 (34)	-4 (-3)
Combined	-473	251 (53)	95 (20)	120 (25)	0 (0)

Note: Values in parentheses represent percentages of pumpage change in groundwater storage), because pumping continues to increase. Cross-formational flow is reversed from the overlying Queen City-Sparta aquifers. However, locally, some water moves upward through the confining layer, but it is more than balanced by water being drawn into cones of depression caused by pumpage.

11.4
SUMMARY

Total recharge rates based on groundwater chloride range from 0.4 inches per year (2 percent of precipitation) in the semiarid southern part to 4.0 inches per year (8 percent of precipitation) in the humid northern part of the aquifer. Point recharge rates based on unsaturated zone chloride data in the central Carrizo-Wilcox Aquifer are spatially variable (0.7–1.6 inches per year) but generally consistent with those based on groundwater chloride. The presence of tritium (0.76–3.57 TU) in the central Carrizo-Wilcox Aquifer outcrop area indicates young (post 1950) ages and provides evidence for recent recharge. Upper bounds on deep recharge to the confined part of the southern Carrizo-Wilcox Aquifer range from 0.1 to 0.4 inches per year based on carbon-14 transects in Atascosa County. Total recharge rates based on unsaturated zone modeling results range from 0.4 inches per year (2 percent of precipitation) in the southern part to 5.1 inches per year (10 percent of precipitation) in the northern part of the aquifer. Under steady-state conditions, recharge equals discharge, and model results indicate that recharge ranges from 0.75 inches per year in the southern part and 1.1 inches per year in both the central and northern parts of the Carrizo-Wilcox Aquifer. Transient simulations indicate that irrigation pumpage in the southern part is derived primarily from groundwater storage changes (65 percent), with lesser amounts from cross-formational flow (20 percent) and increased deep recharge (16 percent) based on results for the year 1999. Groundwater pumpage in the northern Carrizo-Wilcox Aquifer is derived mostly from groundwater storage (40 percent), deep recharge (34 percent), and cross-formational flow (29 percent). Understanding groundwater recharge changes in response to pumpage is essential for assessing future water availability in the aquifer.

11.5
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