TCEQ Carrizo-Wilcox Study
Project 582-8-75374-119
Summary Report for Completion of Task 6

1.0 Executive Summary

This summary report prepared by the Bureau of Economic Geology (BEG) is submitted to fulfill requirements of Task 6 of the Texas Commission on Environmental Quality (TCEQ) Carrizo-Wilcox Aquifer Study (the Study), Project 582-8-75374-119. Task 6 directs the BEG to examine and critique Groundwater Availability Models (GAMs) to:

(a) Assess model runs of representative pumpage scenarios in the northern, central, and southern Carrizo Wilcox Aquifer
(b) Estimate spatial and temporal variability of recharge and modeling of recharge
(c) Evaluate sources of water for pumpage (outcrop zone [increased recharge, reduced discharge], confined zone [change in aquifer storage, increased recharge from overlying Queen City Sparta), timescales for impacts of pumpage on outcrop and Queen City Sparta Aquifer.

A general critique of the GAMs was conducted. The value of the GAMs in the process of establishing desired future conditions was recognized. Important factors to consider in future updates of the GAMs include: role of faults in the flow system because barrier faults significantly reduce water availability for future pumpage, importance of groundwater-surface water interactions, improved recharge estimates, incorporating the Yegua Jackson Aquifers into the Queen City/Sparta GAM, refining the groundwater pumping database, linking steady state and transient models, including groundwater quality, and incorporating new information into the GAMs. One of the critical issues with respect to the conceptual model is whether the central Carrizo Wilcox model should include **faults** as barriers to flow and evaluation of the location of such faults. Universal application of faults as barriers in the Central Carrizo Wilcox GAM significantly impedes horizontal flow. Modeling analysis indicates that the impact of these faults may be more important in predicting future drawdown than it was for transient calibration. Current stresses to the system from pumping are too low to evaluate the impacts of these faults on horizontal flow in the system. Future GAMs should consider models with and without faults to provide bounding estimates on groundwater availability. **Groundwater–surface-water interactions** are also an important component of the GAM. Because pumpage captures groundwater discharge to streams, it is important that simulations of groundwater–surface-water interactions are realistic and reliable. Incorporating an additional shallow layer into the model may improve simulations of these interactions and allow an improved approximation of the potential to reduce baseflow discharge to streams and capture surface water. Evaluating impacts of pumpage on stream baseflow is extremely important for future environmental flows. **Recharge** is a critical parameter for groundwater availability models. The impact of grid resolution on recharge estimates in the models also needs to be considered. Recharge rates are important for model calibration because they help to constrain the hydraulic conductivity field (Kelley et al., 2004). Field studies should be conducted to better quantify groundwater recharge to the aquifer. Improvements in the **groundwater pumping** database are very important and should include reevaluation of groundwater production in Brazos and Robertson Counties (by Bryan College Station, TAMU and industrial commercial pumping). Because most of the pumping in the aquifer is in the Simsboro Formation, additional information should be collected or any existing data used to better describe the thickness and hydraulic conductivity distribution of this unit. The current Carrizo Wilcox model within the Queen City Sparta GAMs uses the predevelopment period for the **steady state** simulation; however, the **transient simulation** does not begin until 1980. Groundwater pumping expanded significantly between predevelopment and 1980, and this expansion is not captured in the GAMs. Two different approaches could be used to address this problem: (1) begin the transient simulation in the 1920s and 1930s and simulate the expansion of pumpage from that time similar to the original Carrizo Wilcox GAM or (2) use 1980s data to simulate steady state conditions if the aquifer were relatively stable at that time. These different options should be considered. Future revisions of the GAMs should incorporate any basic data collected in the aquifers since the GAMs were developed. Such information should include structure data and hydraulic properties, including hydraulic conductivity and storativity, and calibration data, including hydraulic heads and stream gain/loss data. While the Texas Water Development Board (TWDB) collects data on these parameters throughout the aquifer, the Groundwater Conservation Districts are also collecting substantial quantities of data that should be incorporated into TWDB databases. Detailed pumping tests and water level data from mines in the region, including the Sandow Mine, Walnut Creek Mine, and others, should be evaluated and fully used in the GAMs. **Uncertainties** in conceptual models and input parameters, such as recharge and ET, and hydraulic parameters, should be considered in GAM modeling. Uncertainties in the conceptual models could be considered through bounding calculations, e.g. models with and without faults in the Central Carrizo Wilcox Aquifer. Model-sensitivity analyses should be used to guide future data collection in areas where the model is sensitive to different parameters. It is important that stakeholders and others are aware of uncertainties in model data and calibration and do not try to use the models beyond the level at which the data can support them. **Groundwater quality** was not simulated by the GAMs; however, groundwater quality is a critical aspect of groundwater availability. The GAM program should consider expanding simulations to include groundwater quality and, ultimately, brackish water for desalination. **Postaudits** can be done at this stage to test the reliability of model predictions. The Carrizo-Wilcox GAM was calibrated from 1980 through 1999. As stated earlier, new information has been collected since then. Postaudits involve using the existing GAM structure and new boundary conditions to assess how model output compares with new available target information.

(a) Model runs of representative pumpage scenarios for GMA 11, 12, and 13 were based on the desired future conditions obtained from TWDB staff. Models for establishing DFCs were run by TWDB staff for GMAs 11 and 13 and by consultants for GMA 12. Mean drawdowns for the DFCs for the GMA regions are as follows:

Simsboro: GMA 11: 15 ft ; GMA 12: ~100 to 300 ft; and GMA 13: ~ 25 ft

Carrizo: GMA 11: 38 ft; GMA 12: ~ 60 ft, GMA 13: 31 ft

(b) Spatial and temporal variations in groundwater recharge were reevaluated for the Groundwater Availability Models. Recharge rates were estimated using a variety of different approaches. Recharge rates based on groundwater chloride data from the TWDB database range from 0.4 in/yr (2% of precipitation) in the semiarid southern part to 4.0 in/yr (8% 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 in/yr) but generally consistent with those based on groundwater chloride data. Recharge rates based on unsaturated zone modeling results range from 0.4 in/yr (2% of precipitation) in the southern part to 5.1 in/yr (10% of precipitation) in the northern part of the aquifer.

(c) Impacts of pumpage on water resources depend on the source of water for pumpage. Prior to groundwater development, groundwater recharge to the aquifer equaled groundwater discharge through streams, evapotranspiration (ET), and deep recharge to the confined portion of the aquifer. Water for pumpage associated with groundwater development can be derived from various sources, including aquifer storage, increased recharge, and/or decreased discharge. The transient GAM model indicates that after decades of pumping (1999), groundwater storage represents a significant fraction of total pumpage. Total cross-formational flow is reversed in all portions of the aquifer from the overlying Queen City Aquifer. Analysis of sources of water for pumpage related to the desired future conditions for 2060 shows that aquifer storage contributes 44 to 58% of pumpage. Cross-formational flow contributes 40% of pumpage in GMA 13 because most pumpage is from the Carrizo Aquifer, which is adjacent to the overlying Queen City Aquifer. In contrast, pumpage in GMAs 11 and 12 is mostly from the Simsboro Aquifer and separated from the Queen City Aquifer by the Carrizo Aquifer, resulting in low cross-formational flow (19% in GMA 11 and GMA 12) Baseflow discharge ET Understanding the sources of pumpage is important for determining impacts of pumpage on the flow system. Temporal variability in water sources for pumpage shows that aquifer storage contributions decrease from 100% to ~50% over the 50-yr modeling period, whereas contributions from cross-formational flow, streams, and ET increase through time. It will be important to design monitoring programs to evaluate these changes through time.

2.0 Critique of Groundwater Availability Models and Recommendations for Future Revisions

The current Carrizo-Wilcox Queen City Sparta GAMs are extremely useful for analyzing regional groundwater flow in the Carrizo Wilcox Aquifer and have been instrumental in assessing compatibility and physical possibility of the proposed desired future conditions. Several factors need to be considered in the next update of the GAMs, including the conceptual model, model structure, data inputs, parameter values, uncertainty analyses, groundwater quality, and postaudits. Aspects of the conceptual model that need to be considered include simulation of faults, groundwater recharge, and groundwater–surface-water interactions. Many of the model limitations described in Kelley et al. (2004) for the Carrizo Wilcox Queen City Sparta GAM apply to the Carrizo Wilcox aquifer and were reviewed when developing the following critique.
One of the critical issues with respect to the conceptual model is whether the central Carrizo Wilcox model should include **faults** as barriers to flow and evaluation of the location of such faults. Universal application of faults as barriers in the Central Carrizo Wilcox GAM significantly impedes horizontal flow. The hydraulic conductivity values used for these faults are generally not supported by data. Modeling analysis indicates that the impact of these faults may be more important in predicting future drawdown than it was for transient calibration. Current stresses to the system from pumping are too low to evaluate the impacts of these faults on horizontal flow in the system. Therefore, additional studies need to be conducted to assess these faults, particularly those near the outcrop zone to determine whether they are acting as flow barriers. Well log information should be examined to quantify offsets across the faults and the potential for flow across the faults, considering the geology on either side of the faults. Any existing data from pumping tests should be evaluated to assess how the faults function in the system. Future GAMs should consider models with and without faults to provide bounding estimates on groundwater availability. The sensitivity of the model output to the faults should be evaluated. Monitoring approaches to quantify impacts of faults should be devised as the aquifer is increasingly developed and stresses to the system increase.

Groundwater–surface water interactions are also an important component of the GAM. Because pumpage captures groundwater discharge to streams, it is important that simulations of groundwater–surface water interactions are realistic and reliable. The current grid resolution of the models, particularly the vertical resolution, may limit the ability of the GAMs to reliably simulate groundwater–surface water interactions. Incorporating an additional shallow layer into the model may improve simulations of these interactions and allow an improved approximation of the potential to reduce baseflow discharge to streams and capture surface water. Stream gain/loss studies are extremely limited, and additional studies should be conducted to provide information to calibrate the GAMs. Groundwater evapotranspiration (ET) adjacent to streams should also be quantified because it provides a source of water for future pumpage.
Recharge is a critical parameter for groundwater availability models. Recharge in the GAMs was varied with precipitation, soil texture, and topography. There is limited information on recharge rates for the Carrizo Wilcox Aquifer. The impact of grid resolution on recharge estimates in the models also needs to be considered. Restriction of recharge rates in the northern Carrizo Wilcox GAM to 2 inches per year, relative to independent estimates from groundwater data of up to 4.5 inches per year, is attributed to limitations of the coarse grid resolution in the model. The 1-mile grid space does not allow simulation of small streams discharging from the

system; therefore, the simulated recharge should be considered an effective recharge that takes into account the inability to simulate high-resolution discharge from the system. Recharge rates are important for model calibration because they help to constrain the hydraulic conductivity field (Kelley et al., 2004). Field studies should be conducted to better quantify groundwater recharge to the aquifer.

The **model structure** should consider incorporating the Yegua Jackson Aquifers into the Carrizo Wilcox Queen City Sparta GAMs, expanding the GAM models vertically. This change will allow interactions among aquifers to be more fully evaluated. The relationship between the Carrizo Wilcox Aquifers and surrounding aquifers, particularly the Brazos River Alluvium, should be further evaluated.

Groundwater pumping is a critical input to the model, and uncertainties in pumping should be considered in the simulations. Kelley et al. (2004) emphasized the importance of refining the pumping data with regard to location and volume to improve the reliability of the GAMs. Specific examples include reevaluation of groundwater production in Brazos and Robertson Counties (by Bryan College Station, TAMU and industrial commercial pumping) and modeling to mimic observations both in the downdip portion of the Simsboro, where there has been drawdown near the well fields, and near the outcrop, where there has been limited drawdown. Because most of the pumping in the aquifer is in the Simsboro Formation, additional information should be collected or any existing data used to better describe the thickness and hydraulic conductivity distribution of this unit. Information on pumping test data and sandstone thickness should be evaluated to develop predictive relationships between these two parameters.

Steady State and Transient Models: The current Carrizo Wilcox model within the Queen City Sparta GAMs uses the predevelopment period for the steady state simulation; however, the transient simulation does not begin until 1980. Groundwater pumping expanded significantly between predevelopment and 1980, and this expansion is not captured in the GAMs. The aquifer may be in a long-term transient in response to pumpage when the transient simulation begins in 1980, and this transient would not be reflected in the GAMs. Two different approaches could be used to address this problem: (1) begin the transient simulation in the 1920s and 1930s and simulate the expansion of pumpage from that time similar to the original Carrizo Wilcox GAM or (2) use 1980s data to simulate steady state conditions if the aquifer were relatively stable at that time. These different options should be considered.

New Information: The future revision of the GAM should incorporate any basic data collected in the aquifers since the GAMs were developed. Such information should include structure data and hydraulic properties, including hydraulic conductivity and storativity, and calibration data, including hydraulic heads and stream gain/loss data. While TWDB collects data on these parameters throughout the aquifer, the Groundwater Conservation Districts are also collecting substantial quantities of data that should be incorporated into TWDB databases. Detailed pumping tests and water level data from mines in the region, including the Sandow Mine, Walnut Creek Mine, and others, should be evaluated and fully used in the GAMs. Data in the northeast part of the model in Limestone, Freestone, and Leon Counties should be reviewed, with particular focus on the region in the vicinity of the Limestone Station Mine, where pumping from the Calvert Bluff Aquifer has occurred for the past few decades.

GAMS to date have focused on the physical flow system; however, the recent request for Statements of Qualifications from the TWDB will result in work with groundwater chemistry and isotopes, which will be used to constrain the conceptual models of the flow system and should lead to significant improvements in the GAMs.

Uncertainties should be considered in the GAM modeling. Uncertainties in the conceptual models could be considered through bounding calculations, e.g. models with and without faults in the Central Carrizo Wilcox Aquifer. Uncertainties in input parameters, such as recharge and ET, are difficult to quantify. Information on hydraulic parameters may be insufficient to conduct a rigorous uncertainty analysis. Model sensitivity analyses should be used to guide future data collection in areas where the model is sensitive to different parameters. It is important that stakeholders and others are aware of uncertainties in model data and calibration and do not try to use the models beyond the level at which the data can support them.

Groundwater quality was not simulated by the GAMs; however, groundwater quality is a critical aspect of groundwater availability. The GAM program should consider expanding simulations to include groundwater quality and, ultimately, brackish water for desalination.

Postaudits can be done at this stage to test the reliability of model predictions. The Carrizo-Wilcox GAM was calibrated from 1980 through 1999. As stated earlier, new information has been collected since then. Postaudits involve using existing GAM structure and new boundary conditions to assess how model output compares with new available target information.

3.0 Assessment of Model Runs of Representative Pumpage Scenarios in the Northern, Central, and Southern Carrizo Wilcox Aquifer

The most representative model runs for the Carrizo Wilcox Aquifer are those developed for desired future conditions. These are described in the following section and are based on submissions from the GMA regions to the TWDB.

GMA 11 Desired Future Conditions

Pumpage and drawdown related to the Desired Future Conditions for GMA 11 were described by Oliver (2010a) and Shi and Oliver (2010). The members of GMA 11 submitted pumping requests to the TWDB. TWDB staff then ran the groundwater availability model for the northern portion of the Carrizo Wilcox Aquifer and determined the average drawdown on the basis of the submitted pumpage for the 51-yr predictive period from 2010 through 2060. The resultant average drawdown for the Carrizo Wilcox, Queen City, and Sparta Aquifers is 17 ft. Recharge rates for the simulation were based on average precipitation from 1961 through 1990. Pumping in the Carrizo Wilcox, Queen City, and Sparta Aquifers was provided by the members of GMA 11. Pumping for the last year of the groundwater availability model (1999) was adjusted in each county to match the requested pumping for desired future conditions. Decreases in pumping were implemented by reducing pumping in each cell by a uniform factor to preserve the original pumping distribution. Increases in pumping were uniformly distributed among cells that had pumping in 1999, which corresponded to the last year of the historical calibration period. The total pumping from the Carrizo Wilcox Aquifer that achieves desired future conditions ranges from 275,000 af/yr in 2010 to 264,000 af/yr in 2060. Figure 1 and Table 1 show the amount of pumping by county in 2060. Pumping is greatest in Angelina, Nacogdoches, Rusk, Smith, and Wood Counties. Table 2 shows the desired future conditions adopted by members of Groundwater Management Area 11. The corresponding drawdown in the Carrizo Wilcox Aquifer is greatest in Gregg, Henderson, Smith, Upshur, and Wood Counties.

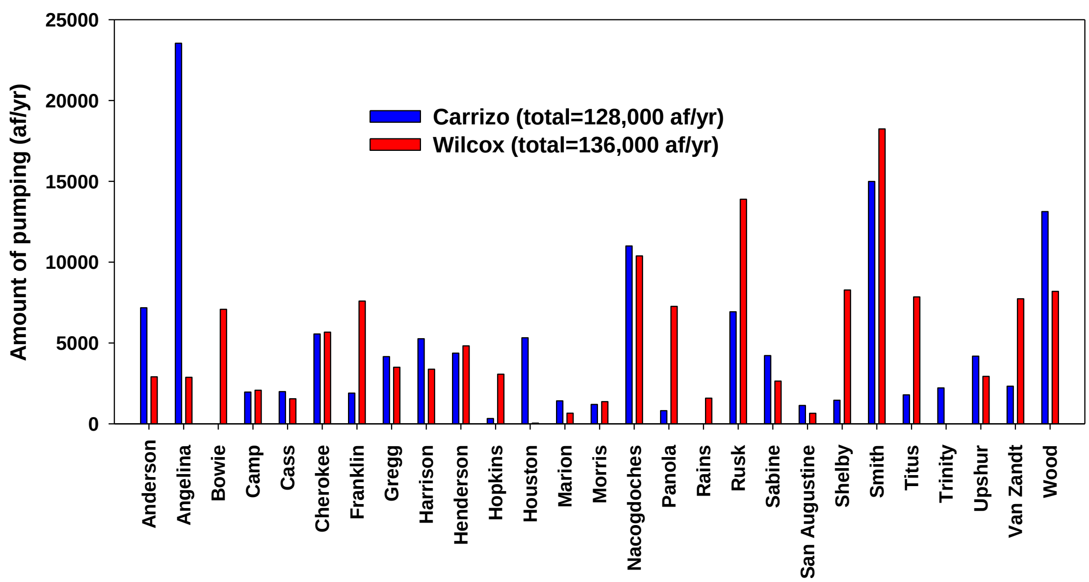

Figure 1. Carrizo-Wilcox pumping by county in 2060 in GMA 11 area from desired future condition model run.

Table 1. Carrizo-Wilcox pumping by county in 2060 in GMA 11 area from desired future condition model run.

County	Carrizo	Upper Wilcox	Middle Wilcox	Lower Wilcox	Wilcox Total	Total
Anderson (ACUWCD)	282	107	15	7	129	411
Anderson (NTVGCD)	6,896	2,169	336	267	2,772	9,668
Angelina	23,540	2,874	0	0	2,874	26,414
Bowie	na	1,542	5,541	0	7,083	7,083
Camp	1,963	1,110	968	0	2,078	4,041
Cass	1,989	882	663	0	1,545	3,534
Cherokee	5,556	5,647	19	0	5,666	11,222
Franklin	1,895	1,257	6,332	0	7,589	9,484
Gregg	4,153	2,380	1,116	0	3,496	7,649
Harrison	5,262	1,746	1,627	4	3,377	8,639
Henderson	4,365	1,837	1,364	1,619	4,820	9,185
Hopkins	325	203	2,864	0	3,067	3,392
Houston	5,317	38	0	0	38	5,355
Marion	1,420	425	232	0	657	2,077
Morris	1,193	404	961	0	1,365	2,558
Nacogdoches	11,000	9,707	678	0	10,385	21,385
Panola	810	770	5,764	725	7,259	8,069
Rains	na	506	1,001	76	1,583	1,583
Rusk	6,927	5,156	8,731	0	13,887	20,814
Sabine	4,221	1,695	471	471	2,637	6,858
San Augustine	1,130	645	5	0	650	1,780
Shelby	1,451	3,316	4,855	106	8,277	9,728
Smith	14,987	13,673	4,566	0	18,239	33,226
Titus	1,791	1,905	5,941	0	7,846	9,637
Trinity	2,215	0	0	0	0	2,215
Upshur	4,182	2,321	612	0	2,933	7,115
Van Zandt	2,322	1,541	4,129	2,059	7,729	10,051
Wood	13,124	5,906	2,281	0	8,187	21,311
Total	128,316	69,762	61,071	5,334	136,167	264,483

Table 2. Desired future conditions adopted by members of GMA 11 in terms of average drawdown in feet.

County	Carrizo	Upper Wilcox	Middle Wilcox	Lower Wilcox	Overall
Anderson (ACUWCD)	35	26	12	5	15
Anderson (NTVGCD)	36	26	11	4	16
Angelina	42	5	-18	-3	11
Bowie	na	21	0	0	1
Camp	18	17	39	0	19
Cass	10	7	7	0	8
Cherokee	32	32	15	10	18
Franklin	-3	7	19	0	11
Gregg	42	49	56	79	35
Harrison	24	13	5	4	9
Henderson	41	32	27	15	23
Hopkins	-12	-15	-28	0	-26
Houston	35	12	2	-2	8
Marion	21	15	15	0	16
Morris	29	25	23	0	21
Nacogdoches	14	11	-10	-6	4
Panola	11	2	1	4	2
Rains	na	7	-10	-5	-8
Rusk	6	6	23	21	12
Sabine	24	13	6	5	10
San Augustine	20	9	-3	-2	3
Shelby	23	-3	3	1	1
Smith	103	118	92	76	68
Titus	31	14	5	0	9
Trinity	33	-3	-7	-1	6
Upshur	56	66	66	97	44
Van Zandt	31	13	17	11	14
Wood	110	83	55	114	59
Total	38	26	15	11	17

GMA 12 Desired Future Conditions

Pumpage and drawdown related to the desired future conditions for GMA 12 were described by Oliver (2010b). The Groundwater Conservation Districts in GMA 12 had several consultants develop desired future conditions for the Carrizo Wilcox Aquifer. The Groundwater Availability Model for the Carrizo Wilcox, Queen City, and Sparta Aquifers was run with the GMA 12 7B pumpage file. An independent analysis was performed by the TWDB to confirm that desired future conditions are physically possible and that the proposed pumping achieves desired future conditions. Estimated total pumpage from the Carrizo Wilcox Aquifer that achieves desired future conditions increases from 196,000 af/yr in 2010 to 257,000 af/yr in 2060. Figure 2 and

Table 3 show the amount of pumping in 2060 by county. Pumpage is highest in Brazos County and decreases in the following order: Robertson, Burleson, Bastrop, and Lee Counties. Most of the pumpage is concentrated in the Simsboro Aquifer. Drawdown is also greatest in the Simsboro Aquifer in those GCDs whose member counties have high pumpage, ranging from 115 to 300 ft. In contrast, drawdown is much lower in the Carrizo Aquifer in these Groundwater Conservation Districts (47–65 ft). (Table 4)

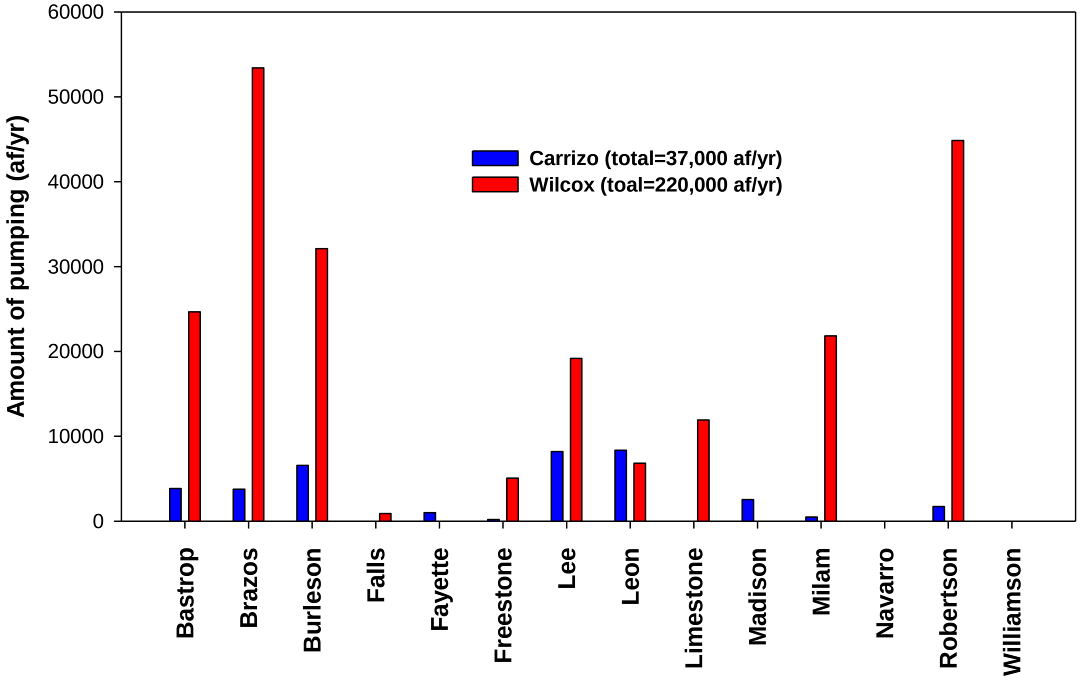

Figure 2. Carrizo-Wilcox pumping by county in 2060 in GMA 12 area from desired future condition model run.

Table 3. Carrizo-Wilcox pumping by county in 2060 in GMA 12 area from desired future condition model run.

County	Carrizo	Upper Wilcox	Middle Wilcox	Lower Wilcox	Wilcox Total	Total
Bastrop	3,845	3,685	18,423	2,545	24,653	28,498
Brazos	3,766	0	53,403	0	53,403	57,169
Burleson	6,578	91	30,409	1,623	32,123	38,701
Falls	na	na	146	749	895	895
Fayette	1,000	0	0	0	0	1,000
Freestone	190	707	3,535	827	5,069	5,259
Lee	8,207	300	18,826	47	19,173	27,380
Leon	8,356	3,205	3,635	0	6,840	15,196
Limestone	na	235	10,187	1,496	11,918	11,918
Madison	2,542	0	0	0	0	2,542
Milam	481	947	18,092	2,799	21,838	22,319
Navarro	na	0	4	11	15	15
Robertson	1,730	1,755	42,782	316	44,853	46,583
Williamson	na	0	2	5	7	7
Total	36,695	10,925	199,444	10,418	220,787	257,482

Table 4. Desired future condition adopted by members of GMA 12 in terms of average drawdown in feet.

GCD or County	Carrizo	Upper Wilcox	Middle Wilcox	Lower Wilcox
Brazos Valley	47	106	270	170
Fayette County	60	na	na	na
Lost Pines	47	99	237	129
Mid-East Texas	55	70	115	95
Post Oak Savannah	65	140	300	180
Falls County	na	na	0	20
Limestone County	na	9	43	40
Navarro County	na	0	1	1
Williamson County	na	-10	50	55

GMA 13 Desired Future Conditions

Members of GMA 13 submitted pumping amounts and distributions to the TWDB, which represented the base case (1). Three additional pumping scenarios were considered, with additional pumping in (2) Gonzales County, (3) Caldwell County, and a combination of scenarios 2 and 3. The four model scenarios were run with pumping scaled by 70 to 130% in 10% increments. Dr. Shirley Wade and Mr. Marius Jigmond then ran the GAM for the southern portion of the Carrizo Wilcox, Queen City, and Sparta Aquifers and determined the average drawdown on the basis of the submitted pumpage for the 61-yr predictive period from 2000 to

2060. The simulations used average recharge, ET, and initial streamflows based on historic calibration runs for 1981 through 1999. The pumping associated with scenario four was selected as the final.

The estimated total pumpage that results in the desired future conditions for GMA 13 ranges from 376,000 acre-feet per year in 2010 to 404,000 acre feet per year in 2060. Figure 3 and Table 5 show the amount of pumping in 2060 by county. Most (68%) of the pumping is in the Carrizo Aquifer. The average drawdown in the Carrizo-Wilcox, Queen City, and Sparta Aquifers is 23 ft (Table 6). Average drawdown is low to moderate in the Queen City (7 ft) and Sparta (9 ft) Aquifers but is higher in the Carrizo (31 ft) and Wilcox (31 ft) Aquifers.

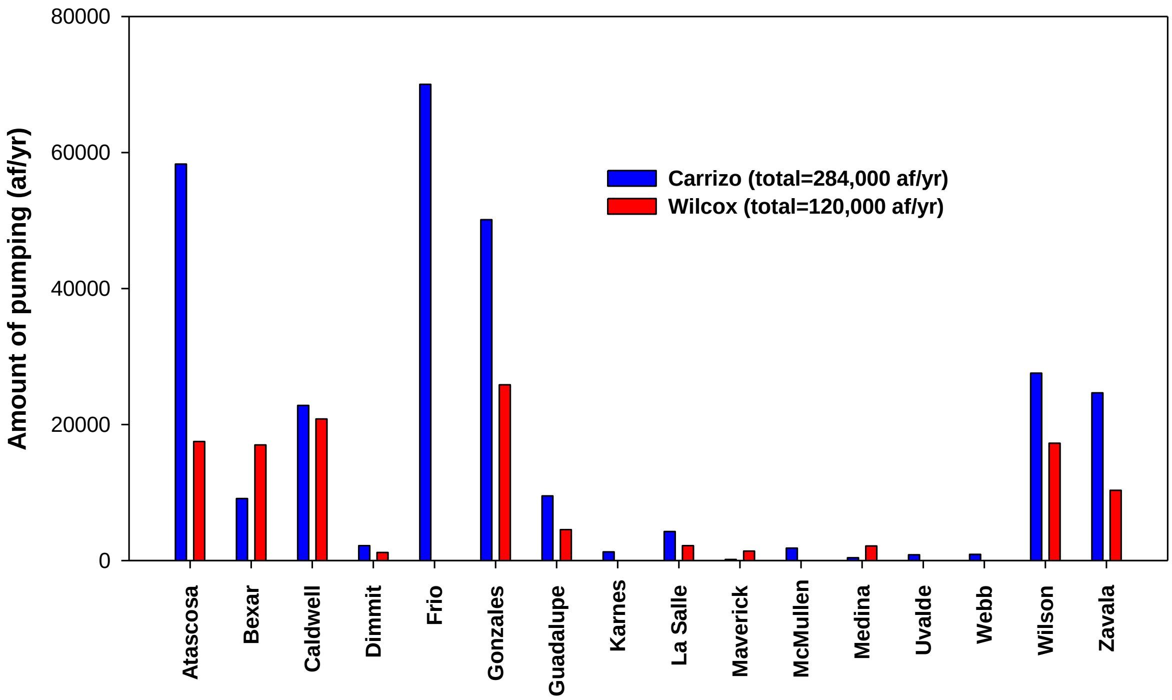

Figure 3. Carrizo-Wilcox pumping by county in 2060 in GMA 13 area from desired future condition model run.

Table 5. Carrizo-Wilcox pumping by county in 2060 in GMA 13 area from desired future condition model run.

County	Carrizo	Upper Wilcox	Middle Wilcox	Lower Wilcox	Wilcox Total	Total
Atascosa	58,308	250	250	17,000	17,500	75,808
Bexar	9,107	0	0	17,000	17,000	26,107
Caldwell	22,809	0	7,372	13,441	20,813	43,622
Dimmit	2,188	991	142	38	1,171	3,359
Frio	70,030	0	0	0	0	70,030
Gonzales	50,121	0	9,577	16,272	25,849	75,970
Guadalupe	9,500	0	2,994	1,549	4,543	14,043
Karnes	1,280	0	0	0	0	1,280
La Salle	4,263	1,952	189	50	2,191	6,454
Maverick	143	136	259	992	1,387	1,530
McMullen	1,819	0	0	0	0	1,819
Medina	400	0	1,248	886	2,134	2,534
Uvalde	828	0	0	0	0	828
Webb	896	13	6	1	20	916
Wilson	27,549	125	121	17,000	17,246	44,795
Zavala	24,649	6,316	3,676	328	10,320	34,969
Total	283,890	9,783	25,834	84,557	120,174	404,064

Table 6. Desired future condition adopted by members of GMA 13 in terms of average drawdown in feet

County	Carrizo	Upper Wilcox	Middle Wilcox	Lower Wilcox	Wilcox Overall	Overall
Atascosa	74	74	85	145	102	62
Bexar	64	48	37	136	94	90
Caldwell	97	93	52	65	64	63
Dimmit	-17	-17	-22	-18	-19	-15
Frio	39	38	31	35	35	24
Gonzales	94	94	88	82	88	65
Guadalupe	54	52	20	31	30	32
Karnes	85	85	61	88	78	57
La Salle	12	12	-1	-9	1	6
Maverick	-8	-12	-11	-3	-7	-7
McMullen	45	44	12	9	22	29
Medina	29	29	28	28	28	28
Uvalde	1	0	12	30	22	19
Webb	-4	-3	-1	-3	-2	-4
Wilson	75	75	78	153	102	68
Zavala	2	0	-5	-3	-3	-5
Overall	31	31	25	38	31	23

4.0 Estimation of Spatial and Temporal Variability of Recharge and Modeling of Recharge

Groundwater recharge is a critical parameter for managing water resources of aquifers. Recharge is generally defined as addition of water to an aquifer, mostly derived from the land surface.

4.1 Previous Studies

Variations in recharge caused by pumpage during postdevelopment have been described in many previous studies, as reviewed in Kelley et al. (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, given historical occurrence of flowing wells. By 1904 there were 30 artesian wells in the Carrizo Springs area alone, with average flows from 40 to 300 gpm. The Dimmit County area was famous for spring-fed creeks that supported travelers and wildlife from early times. Within 40 yr 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) reported that, prior to significant production (before 1900), Carrizo wells flowed at elevations up to 700 ft amsl. By the 1930s, flowing wells were limited to elevations below 500 ft amsl, and by 1972, only certain wells flowed at elevations below 360 ft amsl. In the eastern portion of the southern Carrizo Wilcox Aquifer, flowing Carrizo wells still exist in areas such as Gonzales County.

A transient groundwater model developed by LBG Guyton 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 af/yr/mi of outcrop from 1980 through 1994. The San Antonio River changed from strongly gaining (over 400 af/yr/mi) to losing in the 1960s more than 400 af/yr/mi of outcrop by 1990. The change from gaining to losing occurred in the late 1960s. The Atascosa River also changed from gaining to losing in the early 1970s to becoming slightly losing (less than 50 af/yr/mi) from 1980 through 1994. Cibolo Creek also changed from gaining 200 af/yr/mi in the 1940s to losing up to 100 af/yr/mi in the late 1970s through 1994. Their analysis 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 af/yr/mi of outcrop.

Model simulation results are supported by gain/loss studies conducted in various streams and reviewed by Slade et al. (2002). Gain/loss studies indicated that the Nueces River was losing on the basis of studies conducted from 1925 through 1933 and in 1940. Cibolo Creek was found to be gaining along a 62-mi length in September 1949 at a rate of 163 af/yr/mi. Medina Creek was found to be losing in May 1925 at a gain/loss rate of -42 af/yr/mi.

4.2 Materials and Methods

4.3 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 4). The aquifer extends from the Rio Grande in South Texas to East Texas. For groundwater modeling purposes, the

Carrizo Wilcox Aquifer has been subdivided into southern (Rio Grande to surface-water divide between Guadalupe and Colorado Rivers), central (San Antonio River to part of East Texas Basin), and northern (surface-water divide between Trinity and Brazos Rivers to Red River in Louisiana and Arkansas) sections. The geology of the Carrizo Wilcox Aquifer was described in detail by Deeds et al. (2009). In the Central Carrizo Wilcox Aquifer, the geology consists of the following formations, from oldest to youngest: Hooper, Simsboro, Calvert Bluff, and Carrizo Formations. The Hooper and Calvert Bluff Formations are semiconfining 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.

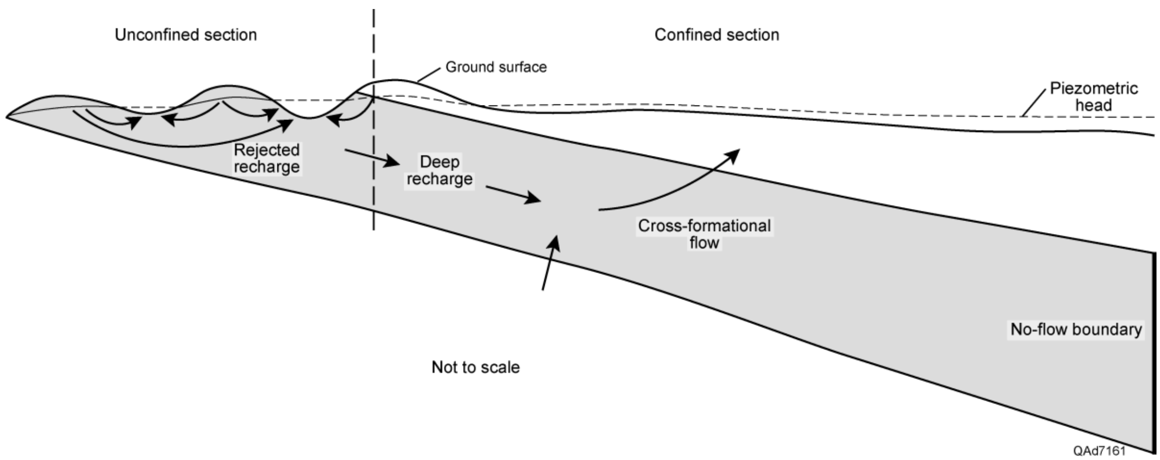

Figure 4. Conceptual diagram of groundwater flow components under natural (predevelopment) conditions in the Carrizo-Wilcox Aquifer.

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 5).

Land use/land cover varies widely in the outcrop areas (Figure 6). Natural vegetation, open water, and wetlands combined constitute from 48 to 78% of the land surface. From south to north, natural vegetation generally transitions from predominantly shrublands and grasslands (57%) to forests (43%), whereas the percentage of open water and wetland areas increases greatly (Table 7, Figure 6). The dominant agricultural land use in all areas is pasture or hay, which generally increase 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 1971through 2000 data (www.prism.oregonstate.edu). 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 in/yr.

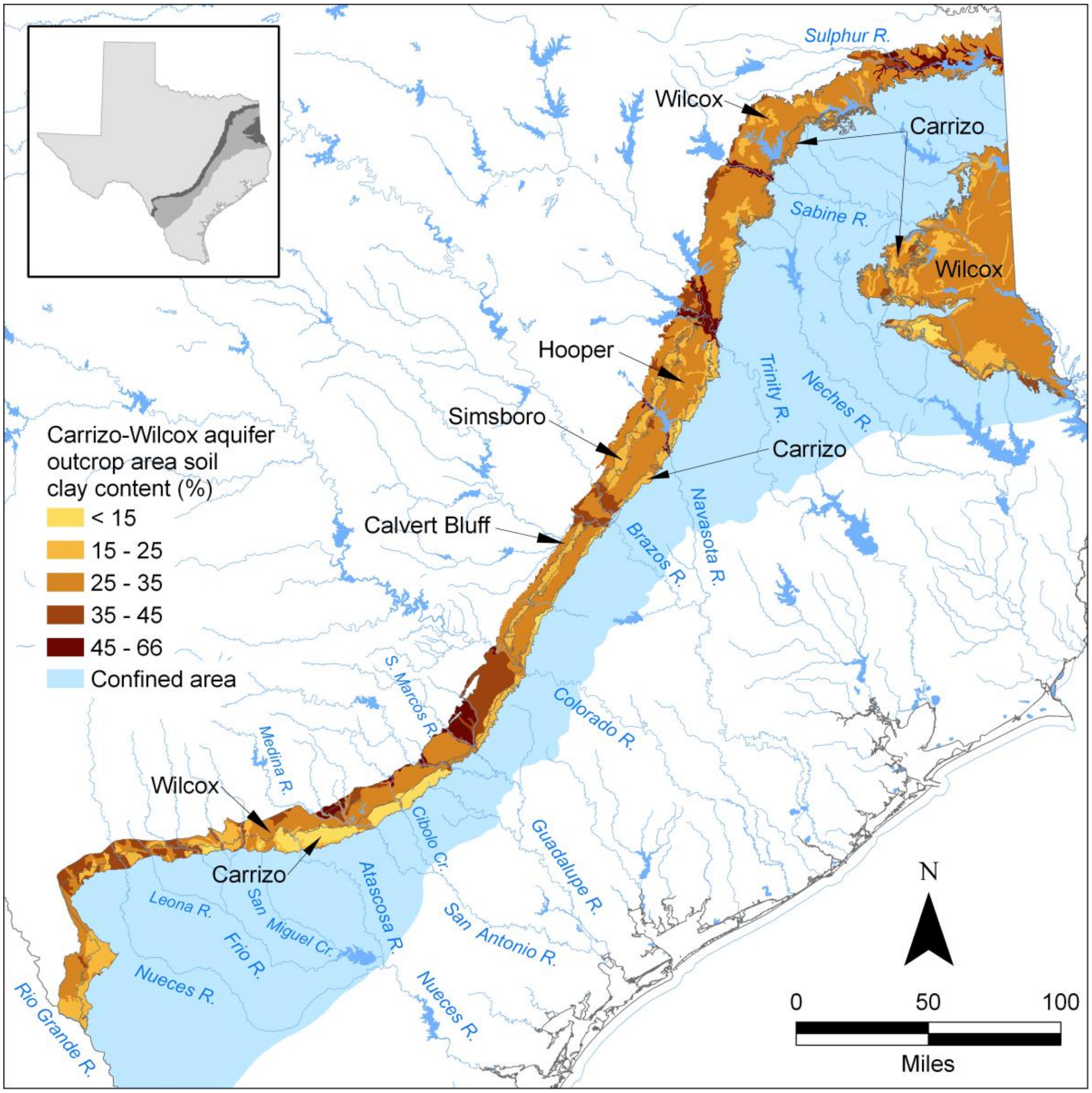

Figure 5. Soil clay content in the Carrizo Wilcox Aquifer outcrop areas and extent of the aquifer confined zone. Formation names are indicated for the southern, central, and northern areas. Major rivers and reservoirs are also shown. Soil-clay content derived from the State Soil Geographic (STATSGO) database (USDA, 1994

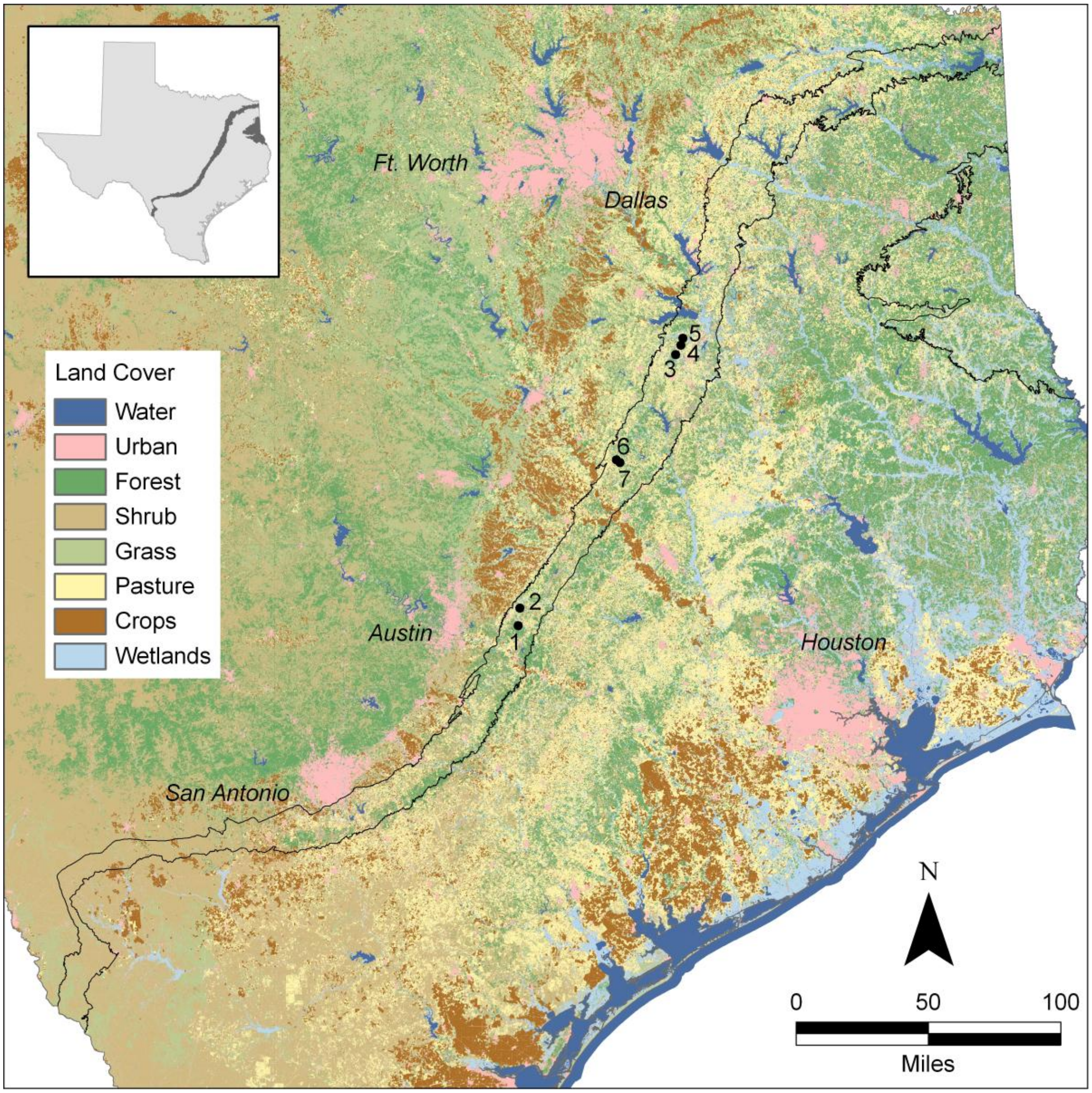

Figure 6. Land cover map and unsaturated zone borehole locations (NLCD, 2001; USGS, 2007. The outcrop area of the Carrizo Wilcox Aquifer is delineated.

4.4 Recharge Estimation Methods

A variety of approaches were used to estimate groundwater recharge. The chloride mass balance approach was applied to unsaturated zone soil water samples from the central Carrizo Wilcox Aquifer and to groundwater chloride data from the 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.

Table 7. General land use by region in Carrizo Wilcox Aquifer outcrop areas.

Region	Area (mi^2)	Urban/ Developed (%)	Crops (%)	Pasture/ Hay (%)	Shrubland/ Grassland (%)	Forest (%)	Water/ Wetlands (%)
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

4.4.1 Chloride Mass Balance Approach

A total of seven boreholes in three different locations were drilled in the outcrop area of the Simsboro Formation in the central Carrizo Wilcox Aquifer: Bastrop and Lee Counties, Robertson County, and Freestone County (Figure 6). 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. No drilling fluid was used to avoid contamination of samples.

Soil samples were leached by adding double de-ionized water to oven-dried sediment samples in a 1:1 ratio by weight. Samples were then placed on a reciprocal shaker for 4 hr and centrifuged at 7000 rpm for 20 min and filtered through 0.45 μm 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 mg ion per kg of dry soil and were calculated by multiplying ion concentrations in the supernatant by the extraction ratio (g water/g soil). Ion concentrations expressed as mg ion per L of soil pore water were calculated by dividing concentrations in mg/kg by gravimetric water content and multiplying by water density. Gravimetric water content was measured in the laboratory at the BEG by oven drying samples at 105°C for 24 to 72 hr. 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:

$$P \times Cl_P = R \times Cl_{UZ} = R \times Cl_{GW}; \qquad R = \frac{P \times Cl_P}{Cl_{UZ}} = \frac{P \times Cl_P}{Cl_{GW}} \qquad (1)$$

where Cl_P, $Cl_{UZ,}$ and Cl_{GW} are chloride concentrations in precipitation, unsaturated zone pore water, and groundwater, respectively. 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 prebomb $^{36}Cl/Cl$ 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 1128 sampled wells from the TWDB database (www.twdb.state.tx.us). The wells used are completed solely in the Carrizo-Wilcox Aquifer and are located either in the outcrop or within 5 mi 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 (i.e., land use change, contamination, cross-formational flow, etc.), 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:

$$t = \frac{\int_0^z \theta \times Cl_{uz} dz}{P \times Cl_P} \tag{2}$$

where θ is average water content in the unsaturated zone. Deep recharge was also calculated from a transect of ^{14}C ages in Atascosa County (Pearson and White, 1967). The ^{14}C ages (age) along the flow path were used to calculate water velocities on the basis of 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:

$$R_d = \frac{v \times n \times b}{w} \quad \text{with} \quad v = L/age \tag{3}$$

4.4.2 Unsaturated Zone Modeling

Regional recharge was also estimated using the relationship between recharge and precipitation developed from unsaturated zone modeling by Keese et al. (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:

$$R = 1.956e^{-2} P^{1.484} \quad \text{(bare, sandy soil)} \tag{4}$$

$$R = 3.242e^{-9} P^{3.407} \quad \text{(vegetated, texturally variable soil)} \tag{5}$$

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

5.0 Results and Discussion

5.1 Recharge Estimates Using the Chloride Mass Balance Approach

Regional total recharge rates based on groundwater chloride data range from 0.4 in/yr in the south to 4.0 in/yr in the north (Figure 7, Table 8). The 25th percentile of groundwater chloride concentrations was used in the recharge estimation, and these chloride concentrations range from 49 mg/L in the south to ~8 mg/L 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 to 9% 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 7, Table 9). Recharge rates range from 0.7 to 1.6 in/yr, representing 2 to 5% 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 profile in a forest (borehole 5), which has a bulge-shaped profile, with peak chloride concentration of 120 mg/L at 1.8 m depth. However, there may be no recharge in this setting as chloride is accumulating. This is the only profile drilled in a forest setting; all other profiles were drilled in pasture settings. Some profiles have vertical variations in chloride concentrations and corresponding recharge rates. For example, recharge in the upper 12 m of the borehole 1 profile is 1.4 in/yr, whereas below this zone recharge is much less (0.4 in/yr). 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 yr, with the exception of borehole 1, which has an accumulation time of 245 yr.

Table 8 Recharge rates by zones based on chloride mass balance analysis of groundwater chloride concentrations.

Region	Zone	Number of Wells	Outcrop Area	Precip.	Cl_P	Cl_{GW}	Rech.	Rech.	Rech.	Rech.
			(mi^2)	(in/yr)	(mg/L)	(mg/L)	(in/yr)	(af/yr)	(in/yr)	(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 3. Precipitation represents the 1971 through2000 mean. 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 correspond approximately to the modeled zones.

Table 9. Unsaturated zone borehole information and recharge rates based on chloride mass balance and groundwater tritium levels.

Borehole	Total Depth	Depth to Water Table	Precipitation	Cl_P	Cl_{UZ}	Recharge	Age	Tritium
	(ft)	(ft)	(in/yr)	(mg/L)	(mg/L)	(in/yr)	(yr)	(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

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

Groundwater tritium concentrations range from 0.76 to 3.6 TU (Table 9) Tritium levels were greater than the detection limit (~0.2 TU) and indicate that a component of water was recharged 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 by Pearson and White (1967) and Castro et al. (2000) using an estimated average aquifer thickness of 100 m, porosity of 35%, and outcrop width of 10 km. Estimated deep recharge rates range from 0.1 to 0.4 in/yr (Table 10).

Table 10. 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	0.10	0.14
Tx-93[b]	6,300	11,500	11.0	9.2	0.39	0.14	-0.47
Tx-94[b]	14,500	1,050	18.0	6.6	0.28	0.26	0.30

Note: Sample ID values from original references. Average recharge rates are based on ^{14}C ages. Minimum and maximum recharge rates are based on ^{14}C age uncertainty.

[a] Castro et al. (2000)

[b] Pearson and White (1967)

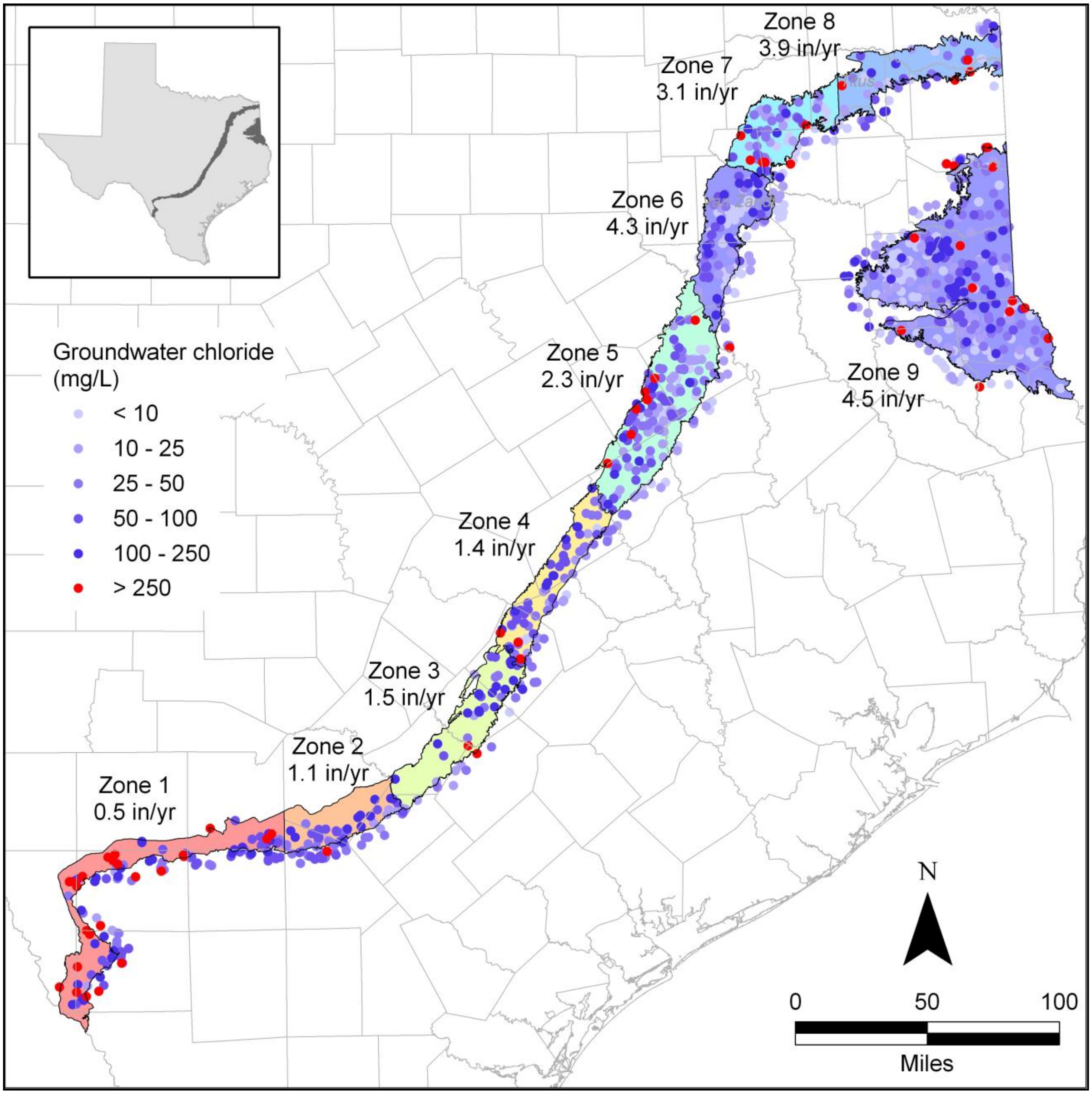

Figure 7. Groundwater chloride concentrations and chloride mass balance recharge rates for nine zones in the Carrizo-Wilcox outcrop area. Points represent groundwater wells located inside and within 5 mi downdip of the outcrop area. Chloride mass balance recharge rates are based on 25th-percentile chloride concentrations for wells in each zone.

5.2 Recharge Estimates from Unsaturated Zone Modeling Results

Maximum recharge rates developed using the relationships between precipitation and recharge for bare, sandy soils from unsaturated zone modeling (equation 8) range from 11 in/yr (44% of mean annual precipitation) in the southern part of the aquifer to 32 in/yr (63% of mean annual precipitation) in the northern part. These rates represent the maximum, diffuse recharge rates as a function of climate forcing because vegetation ET 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 were much lower than those based on bare, sandy soils (0.4 to 5.1 in/yr) representing 2 to 10% of mean annual precipitation. These recharge rates compare favorably with regional recharge estimates based on groundwater chloride data (Figure 4).

5.3 Recharge Estimates from Groundwater Models

5.3.1 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 et al. (2004), and the combined budget for the entire aquifer was obtained from Deeds et al. (2009). 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 af/yr in the southern model to 251,000 af/yr in the central model and to 590,000 af/yr 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 in/yr, southern model, and 1.1 in/yr in both central and northern models) (Table 8). Most (54 to 66%) of the recharge discharges as streams and springs. The ratio of losing stream inflow to gaining stream outflow decreases from the southern to northern (16%, 10%, and 2%, respectively) models, consistent with the observation of some losing sections but still overall gaining streams in the southern area and overwhelming gaining streams in the northern area. The proportion of total recharge that discharges as ET increases from 6% in the southern, 27% in the central, and 46% in the northern aquifer models. Subtracting discharge in the outcrop (streams, springs, ET) from total recharge results in deep recharge that ranges from 34% in the southern, 6% in the central, and 0% 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 quantities of deep recharge in the northern model is attributed to shallower water tables and large-scale discharge to perennial streams in the northern aquifer model that serve to reject much of the increased recharge in the more humid climate in this region (Kelley et al., 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 et al. (2006) showed that there may be a small updip component of flow from the geopressured zone. The GAM 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%) and a combination of groundwater ET (more significant in the north, 46%) and cross-formational flow (more important in the south, 34%) (Table 11).

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

Component and volume or depth

	Recharge		Streams		Evapotranspiration		Deep recharge	
Region	(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 flow values (af/yr) divided by outcrop area. Values in parentheses represent percentages of total flow.

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 baseflow to streams and possibly groundwater ET, which would not be desirable. An understanding of the water requirements for instream flows (NRC, 2005) and for riparian ET could be used to constrain permissible pumpage levels during postdevelopment.

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

6.0 Summary

Total recharge rates based on groundwater chloride range from 0.4 in/yr (2% of precipitation) in the semiarid southern part to 4.0 in/yr (8% 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 to 1.6 in/yr) but generally consistent with those based on groundwater chloride. The presence of tritium (0.76 to 3.57 TU) in the central Carrizo Wilcox Aquifer outcrop area indicates young (post-1950) ages and provides evidence of recent recharge. Upper bounds on deep recharge to the confined part of the southern Carrizo Wilcox Aquifer range from 0.1 to 0.4 in/yr, according to ^{14}C transects in Atascosa County. Total recharge rates based on unsaturated zone modeling results range from 0.4 in/yr (2% of precipitation) in the southern part to 5.1 in/yr (10% 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 in/yr in the southern part and 1.1 in/yr in both the central and northern parts of the Carrizo Wilcox Aquifer.

7.0 Sources of Water for Pumpage and Timescales of Pumpage Impacts

During predevelopment groundwater recharge (R_0) is equal to groundwater discharge (D_0).

$$R_0 = D_0 \,. \tag{1}$$

Groundwater pumpage during postdevelopment disturbs this equilibrium between recharge and discharge. The water balance equation can be described as

$$(R_0 + \Delta R_0) - (D_0 + \Delta D_0) - Pu = \Delta S, \tag{2}$$

where ΔR_0 and ΔD_0 are change in recharge and discharge that can be caused by pumpage (Pu) and ΔS is change in aquifer storage. If a new steady state is established under pumping conditions, there is no further change in groundwater storage and $\Delta S = 0$. In such a case, groundwater pumpage is considered sustainable and is derived from an increase in recharge or a decrease in discharge, which is termed *capture* (Sophocleous, 1998).

$$Pu_s = \Delta R_0 + \Delta D_0 \tag{3}$$

Initially all 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 sources, such as increased recharge and/or decreased discharge. In an unconfined aquifer, water can be captured by intercepting groundwater discharge to streams, changing streams from gaining to losing, and/or reducing groundwater ET from riparian zones near streams. In a confined aquifer, water can be captured by increasing recharge from an overlying unconfined aquifer through cross-formational flow, which will correspond to capture from the unconfined aquifer as described earlier and can result in a reversal of the flow direction if water in the confined aquifer was previously flowing to the unconfined aquifer. 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, whereas 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 downdip migration of the unconfined/confined boundary.

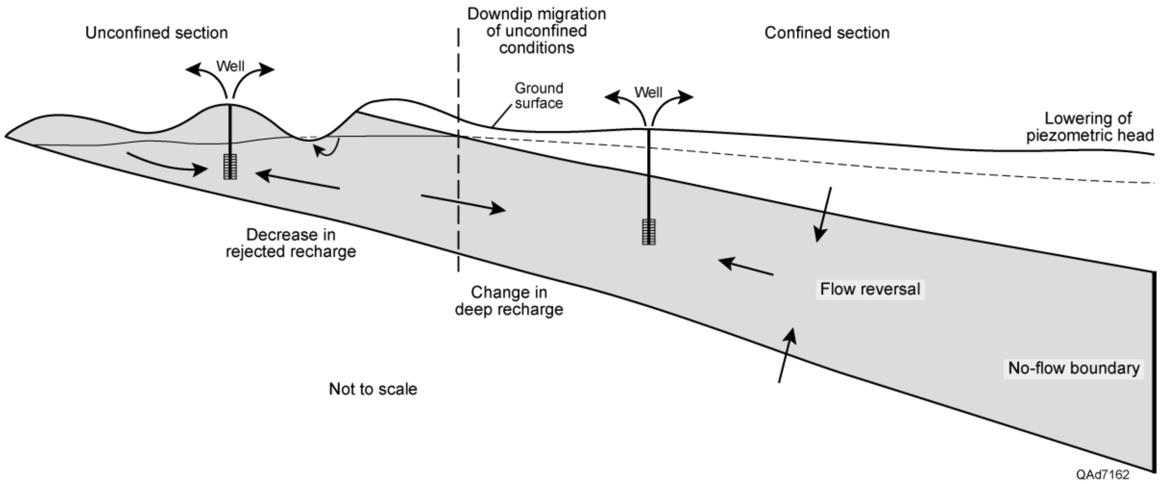

Figure 8. Conceptual model representing sources of water for pumping in the unconfined and confined aquifer and sources.

The water budget for the transient model for the Carrizo Wilcox Aquifer within the Queen City and Sparta GAM was evaluated to assess sources of groundwater pumpage, as described. 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 flow from northern (33%), central (54%), and southern (91%) parts of the aquifer (Table 12). 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 ET, both of which increase in percentage 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.

Table 13. Transient simulation results (1999) in the south, central, and north regions.

Region	Recharge	Storage change	Cross-formation flow	Total inflow	Wells	Streams	ET	Lateral flow
South	69	181	57	307	-279 (91%)	-22	-2	-3
Central	157	187	18	362	-197 (54%)	-126	-39	0
North	357	61	45	463	-154 (33%)	-219	-85	-4

Note: Values in parentheses represent percentages of total flow.

Analysis of sources of water for pumpage in 1999 indicates that after decades of development (1999) and increasing pumpage, the change in groundwater storage (that is, decline in water table and piezometric head) represents a significant fraction of total pumpage (50–72%). Ultimately this fraction should tend to zero; however, currently, the aquifer cannot reach a new steady state (that is, no change in groundwater storage) because pumping continues to increase. Total cross-formational flow is reversed in all portions of the aquifer from the overlying Queen City Aquifer.

The reversal of cross-formational flow should not be confused with the fact that, 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. Cross-formational flow also provides a significant contribution to pumpage (13–28%). The remaining water for pumpage is derived from reduced discharge in the outcrop, including reduced baseflow discharge (7–16%) to streams and groundwater ET (0– 6%).

Table 13. Transient simulation results (1999) for source of well pumpage in the south, central, and north regions.

Region	Pumpage	Storage	Streams	ET	Cross-formation Flow	Lateral Flow
South	-279	182 (65%)	18 (7%)	0.1 (0%)	78 (28%)	0.8 (0%)
Central	-197	99 (50%)	32 (16%)	12 (6%)	34 (17%)	20 (10%)
North	-154	112 (72%)	14 (9%)	6 (4%)	21 (13%)	1 (1%)

A similar analysis was also done related to the desired future conditions of 2060 for the three GMAs (Table 14 and Figure 9). This analysis shows that aquifer storage contributes 44 to 58% of pumpage. Cross-formational flow contributes 40% of pumpage in GMA 13, which is attributed to most pumpage in this region from the Carrizo Aquifer, adjacent to the overlying Queen City Aquifer. In contrast, pumpage in the other GMAs is mostly from the Wilcox Aquifer, separated from the Queen City Aquifer by the Carrizo Aquifer, resulting in much less cross-formational flow (19%). Capture of baseflow to streams ranges from 13 to 27% and may be very important because of impacts on environmental flows; however, these baseflow reductions need to be evaluated relative to total stream flow under drought conditions. Capture of groundwater ET ranges from 0 to 37% of pumpage and is negligible in GMA 13 because ET is not a significant discharge mechanism and, therefore, cannot be captured by pumpage. Understanding the sources of pumpage determines the impacts of pumpage on the flow system.

Table 14. Sources of water for pumping in 2060 from desired future condition simulations using QCSP/CW GAMs.

Regions	Pumpage	Storage	Streams	ET	Cross-Formational Flow
GMA11	-264	153 (58%)	35 (13%)	24 (9%)	52 (19%)
GMA12	-257	113 (44%)	69 (27%)	26 (10%)	49 (19%)
GMA13	-403	176 (44%)	64 (16%)	0.3 (0%)	162 (40%)

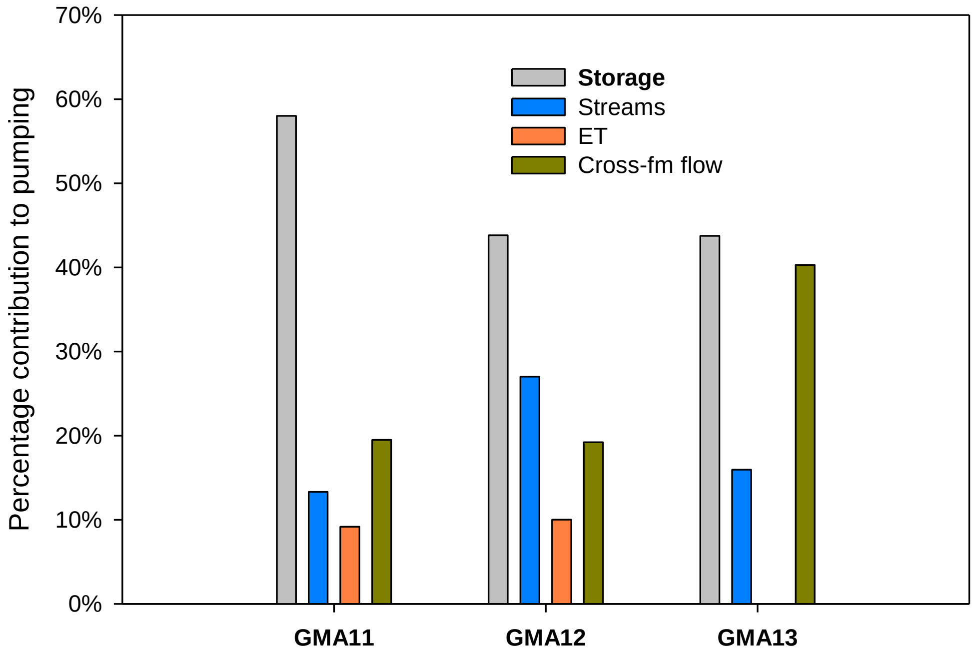

Figure 9. Sources of water for pumping in 2060 in three GMA areas.

8.0 Timescales of Impacts of Pumpage

It is important to understand the timescales of impacts of pumpage for water resources management. The management timescale for planning is ~50 yr. In many situations the impacts of pumpage may not be seen for decades; however, if the impacts are not considered ahead of time, their effects may be irreversible.

An analysis was conducted to evaluate temporal variability in how storage, cross-formational flow, streams, and ET contribute to pumping in the Carrizo-Wilcox aquifer using the Central Carrizo Wilcox/Queen City Sparta GAM. The contribution of storage to pumpage decreases rapidly initially and then levels off (Figure 10a). In contrast, the contribution of cross-formational flow, streams, and ET increases through time. Although cross-formational flow and ET increase rapidly initially and then level off, stream flow contribution increases more gradually through time. Figure 10b shows that ET and cross-formational flow contributions level off over time, whereas stream capture continues to increase. Impacts of groundwater pumpage on environmental flows may be critical in the future, and it will be important to design monitoring programs to evaluate these changes through time.

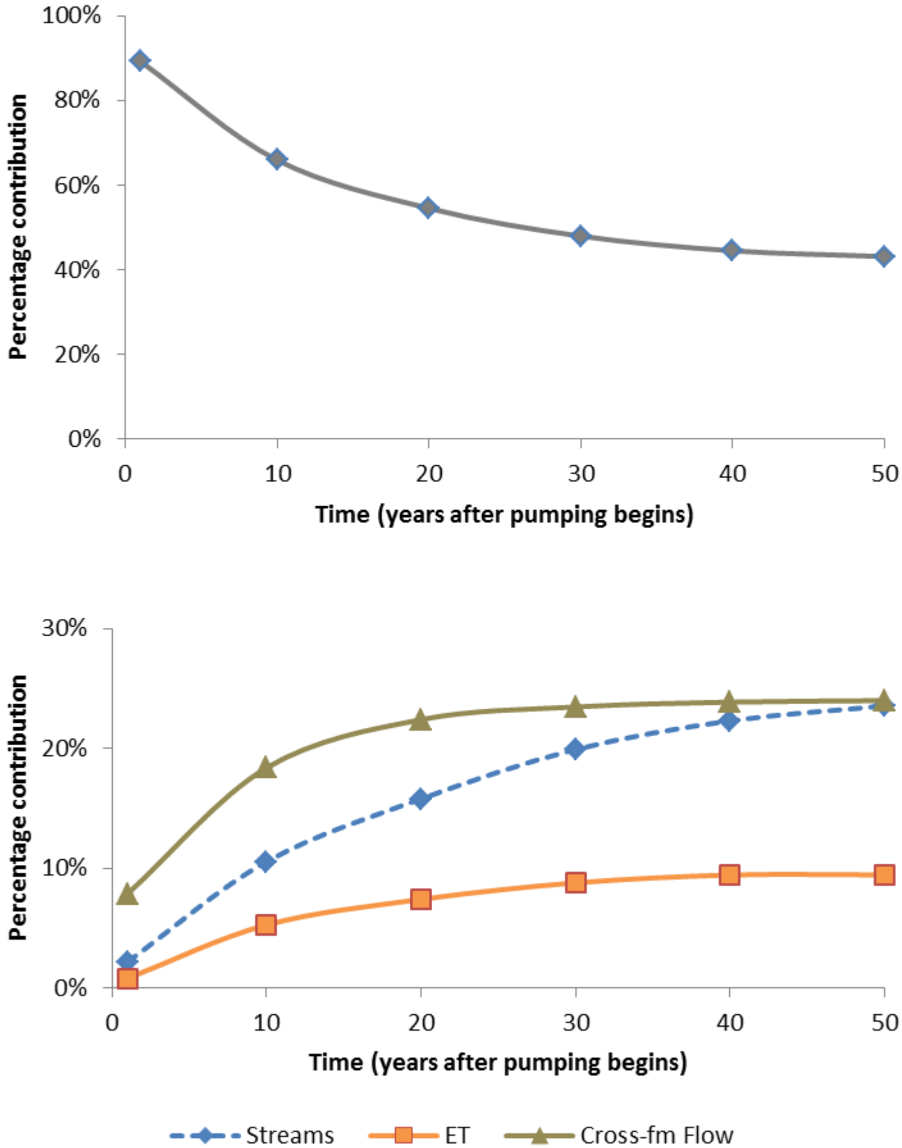

Figure 10. a, Storage contribution to pumping in Carrizo-Wilcox aquifer over time; b, streams, ET and cross-formational flow contribution to pumping in Carrizo-Wilcox aquifer over time.

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