Technical Report

Transmissivity, Hydraulic Conductivity, and Storativity of the Carrizo-Wilcox Aquifer in Texas

by
Robert E. Mace
Rebecca C. Smyth
Liying Xu
Jinhuo Liang

Robert E. Mace
Principal Investigator

prepared for
Texas Water Development Board
under TWDB Contract No. 99-483-279, Part 1

Bureau of Economic Geology
Scott W. Tinker, Director
The University of Texas at Austin
Austin, Texas 78713-8924

March 2000

Contents

Abstract 1
Introduction 2
Study Area 5
HYDROGEOLOGY 5
Methods 13
LITERATURE REVIEW 14
DATA COMPILATION 14
EVALUATION OF HYDRAULIC PROPERTIES IN DATABASE 19
Estimating Transmissivity from Specific Capacity Data 19
STATISTICAL DESCRIPTION 24
Results and Discussion 27
GENERAL CHARACTERISTICS OF THE DATABASE 27
TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY VALUES 32
Variations in Values from Different Sources 36
Variations in Values Due to Different Testing Methods 40
SPATIAL DISTRIBUTION OF TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY 42
Vertical Variability of Transmissivity and Hydraulic Conductivity 43
Lateral Variability of Transmissivity and Hydraulic Conductivity 47
Relationship between Hydraulic Conductivity and Sand Thickness 62
STORATIVITY 63
Conclusions 68
Acknowledgements 69
Acronyms 70
References 70
Appendix A 75

Figures

1. Location of the outcrop and subcrop of the Carrizo-Wilcox aquifer in Texas 6
2. Lower Tertiary stratigraphy in South Texas, Central Texas, and Sabine Uplift, Texas. Modified from Kaiser (1974), Hamlin (1988), and Galloway and others (1994) 8
3. Structural elements that affected Tertiary sedimentation along the Texas Gulf Coast. Modified from Ayers and Lewis (1985) 10
4. Aquifer thickness and percent sand for (a) lower Claiborne-upper Wilcox aquifer and (b) middle Wilcox aquifer. Modified from Hosman and Weiss (1991) 11
5. State well-numbering system for (a) 1° quadrangles in Texas, (b) 7.5-minute quadrangles within 1-minute quadrangles, and (c) 2.5-minute quadrangles within 7.5-minute quadrangles. Modified from Follett, 1970 17
6. Relationship between specific capacity and transmissivity in the Carrizo-Wilcox aquifer 22
7. Comparison of the ratios of estimated transmissivity to measured transmissivity for transmissivity estimated by the analytical and empirical approaches 26
8. Example semivariogram showing the range, sill, and nugget 26
9. Distribution of aquifer-test wells in the Carrizo-Wilcox aquifer from TNRCC well files, (b) TWDB well database, and (c) well log information from the TWDB 28
10. Number of aquifer test wells in each county 29
11. General characteristics of wells and aquifer tests in the database 30
12. Histograms of all estimates of transmissivity and hydraulic conductivity from the Carrizo-Wilcox aquifer 33
13. Cumulative distribution functions of transmissivity and hydraulic conductivity for different data sources 37
14. Cumulative distribution functions of transmissivity and hydraulic conductivity for different test types 41
15. Cumulative distribution functions of transmissivity and hydraulic conductivity for the different geologic units using the data collected from TWDB files 44
16. Cumulative distribution functions of transmissivity and hydraulic conductivity for the northern, central, and southern areas of the aquifer 54
17. Experimental (dots) and theoretical (lines) semivariograms of transmissivity and hydraulic conductivity in the Carrizo Formation and Wilcox Group 55
18. Spatial distribution of transmissivity in the Carrizo Formation using kriging values from the TWDB database. Location of control points shown in upper left-hand corner 58

19. Spatial distribution of hydraulic conductivity in the Carrizo Formation using kriging values from the TWDB database. Location of control points shown in upper left-hand corner 59

20. Spatial distribution of transmissivity in the Wilcox Group using kriging values from the TWDB database. Location of control points shown in upper left-hand corner 60

21. Spatial distribution of hydraulic conductivity in the Wilcox Group using kriging values from the TWDB database. Location of control points shown in upper left-hand corner 61

22. Histograms of storativity and specific storage for the Carrizo-Wilcox aquifer 65

23. Variation of storativity and specific storage with depth 67

Tables

1. Thickness of Carrizo (Ec) and Wilcox (Ew) stratigraphic units in four structural settings 12

2. Characteristics of wells and tests in the database 31

3. Transmissivity values (ft^2d^{-1}) estimated from the tests 34

4. Hydraulic conductivity values ($ft\ d^{-1}$) estimated from the tests 35

5. Transmissivity and hydraulic conductivity values compiled from lignite mine permit reports on file at the TRRC 38

6. Hydraulic conductivity values ($ft\ d^{-1}$) reported by Prudic (1991) 48

7. Transmissivity values (ft^2d^{-1}) from the TWDB database for the different counties in the study area 49

8. Hydraulic conductivity values ($ft\ d^{-1}$) from the TWDB database for the different counties in the study area 51

9. General areal distribution of transmissivity and hydraulic conductivity values 53

10. Fitting parameters for the theoretical semivariograms 56

11. Storativity and specific storage (ft^{-1}) values for the Carrizo-Wilcox aquifer 66

Abstract

Transmissivity, hydraulic conductivity, and storativity are important parameters for developing local and regional water plans and developing numerical ground-water flow models to predict the future availability of the water resource. To support this effort, we compiled and analyzed transmissivity, hydraulic conductivity, and storativity values from numerous sources for the entire Carrizo-Wilcox aquifer in Texas, resulting in a database of 7,402 estimates of hydraulic properties in 4,456 wells. Transmissivity and hydraulic conductivity results for all tests in the Carrizo-Wilcox aquifer are log-normally distributed. Transmissivity ranges from about 0.1 to 10,000 ft^2d^{-1} and has a geometric mean value of about 300 ft^2d^{-1}, and hydraulic conductivity ranges from about 0.01 to 4,000 ft d^{-1} and has a geometric mean value of about 6 ft d^{-1}. Transmissivity and hydraulic conductivity vary spatially, both vertically and areally, in the Carrizo-Wilcox aquifer. The Simsboro Formation and Carrizo Sand portions of the Carrizo-Wilcox aquifer have transmissivity and hydraulic-conductivity values that are 2.5 to 11 times higher and 2 to 6 times higher, respectively, than that of the Cypress aquifer, Calvert Bluff Formation, and undivided Wilcox Group.

Semivariograms show that transmissivity and hydraulic conductivity values in the Carrizo Sand and undivided Wilcox Group are spatially correlated over about 17 and 25 mi, respectively. Large nuggets in the semivariograms suggest local-scale heterogeneity and measurement errors. Kriged maps of transmissivity and hydraulic conductivity show the greatest values for the Carrizo Sand in the Winter Garden area and the greatest values for the Wilcox Group in the south-central and northeast parts of the aquifer. Storativity and specific storage values approximate log-normal distributions. Storativity ranges from about 10^{-6} to 10^{-1} with a geometric mean of 3.0×10^{-4}. Specific storage ranges from about 10^{-7} to 10^{-3} with a geometric mean of 4.5×10^{-6}. Lower values of storativity and specific storage tend to occur at shallow depths where the aquifer is unconfined.

Introduction

The purpose of this report is to present a database and analysis of a compilation of transmissivity, hydraulic conductivity, and storativity data in the Carrizo-Wilcox aquifer of Texas. These data are needed to address a host of regional ground-water management issues as part of long-term regional water plans involving aquifers. State-mandated programs call for the development of regional water plans that address near- and long-term water needs that consider surface- and ground-water interaction. Those responsible for developing regional water plans require permeability and storativity data to make accurate predictions of ground-water availability and potential water-level declines.

Transmissivity and hydraulic conductivity describe the general ability of an aquifer to transmit water (over the entire saturated thickness for transmissivity and over a unit thickness for hydraulic conductivity), and are among the most important hydrogeologic data needed for managing ground-water resources. Representative transmissivity and hydraulic conductivity data are required to ensure that the hydrologic assumptions and interpretations used in regional water plans are valid. Storativity describes the change in volume of water for a unit change in water level per unit area. Transmissivity, hydraulic conductivity, and storativity data are needed in tasks such as (1) numerical modeling of ground-water flow, (2) prediction of well performance, (3) evaluation of how site-specific test results compare with the variability of the regional aquifer, (4) assessing the transport of solutes and contaminants, and (5) selection of areas where additional hydrologic tests are needed.

It is important to have a transmissivity, hydraulic conductivity, and storativity database that is readily available for developing local and regional water plans and numerical ground-water flow models to predict future ground-water availability. Aquifer tests are expensive to run, and historical test data, although available, are labor-intensive to compile and evaluate. The standard reference for aquifer hydraulic properties in Texas is Myers (1969), which includes many high-quality examples of time-drawdown curves and estimates of transmissivity, hydraulic conductivity, and storativity. Although useful, this database is not extensive, does not have good spatial coverage, does not include more recent aquifer tests, and does not take advantage of new techniques for estimating aquifer properties (see for example, Razack and Huntley, 1991; Huntley and others, 1992; Mace, 1997).

Previous investigators measured and compiled transmissivity, hydraulic conductivity, and storativity data for parts of the Carrizo-Wilcox aquifer in Texas, but none compiled this information for the entire aquifer. Myers (1969) included results of 102 aquifer tests for the Carrizo-Wilcox aquifer, but the tests are located in only half of the counties underlain by the aquifer. Kier and Larkin (1998) reviewed available aquifer tests for Bastrop, Caldwell, Fayette, Lee, Travis, and Williamson Counties.

As part of numerical ground-water flow modeling exercises, several authors (Klemt and others, 1976; Thorkildsen and others, 1989; Prudic, 1991; Guyton and Associates, 1998; Dutton, 1999) have compiled hydraulic properties of the Carrizo-Wilcox aquifer. Klemt and others (1976) developed a numerical ground-water flow model of the southwest part of the Carrizo aquifer. They analyzed pumping test and performance test data to estimate hydraulic conductivity of the aquifer's total thickness (Klemt and others, 1976, their figs. 15, 16). Thorkildsen and others (1989) developed a ground-water flow model for the central part of the aquifer in the vicinity of the Colorado River. They used electrical logs and existing studies to define hydraulic conductivity for the formations of the Carrizo-Wilcox aquifer (Thorkildsen and others, 1989, their figs. 8 through 11 in appendix 5). Prudic (1991), as part of the USGS regional aquifer-system analysis program, estimated hydraulic conductivity for the Gulf Coast regional aquifer system and developed a finite-difference numerical ground-water flow model of the aquifer. His test results for Texas source from Myers (1969). He also used limited specific-capacity data to estimate transmissivity in the aquifer.

Guyton and Associates (1998) developed a ground-water flow model to investigate the interaction between surface water and ground water in the Winter Garden area in the Guadalupe, San Antonio, Nueces, and Rio Grande River Basins on the basis of the model by Klemt and others (1976). They used the same hydraulic properties as used by Klemt and others (1976) for the Carrizo aquifer, and estimated properties for the Wilcox aquifer from published reports. Dutton (1999) developed a ground-water flow model for the Carrizo-Wilcox aquifer approximately between the Colorado and Brazos Rivers and distributed test results according to the distribution of major-sand thickness in the Calvert Bluff and Simsboro formations. His aquifer test results were taken from permit reports for the Sandow lignite mine, well log interpretation, and preliminary results of this study.

To date, no one has comprehensively compiled aquifer and specific-capacity data for the entire Carrizo-Wilcox aquifer or investigated the spatial continuity of transmissivity and hydraulic conductivity in the aquifer. Therefore, the purpose of this study was to (1) review the literature for the hydraulic properties; (2) compile transmissivity, hydraulic conductivity, storativity, and specific-capacity data from publicly available sources; (3) estimate hydraulic properties from the compiled data; and (4) geostatistically describe the hydraulic properties of the aquifer.

This report is divided into three major sections: (1) study area, (2) methods, and (3) results. The study area section presents the basic hydrogeology of the aquifer in Texas. The methods section discusses the techniques used to review the literature and compile and analyze the hydrologic data. The results section presents results of the literature review and the data compilation and analysis. Some results, as they relate to the methodology, are presented in the methods section.

Study Area

The Carrizo-Wilcox aquifer extends from South Texas northeastward into East Texas, Arkansas, and Louisiana. In Texas the Carrizo-Wilcox aquifer provides water to all or part of 60 counties along a belt that parallels the Gulf Coast between the Rio Grande and the Sabine River (fig. 1). Water-bearing sediments that make up the Carrizo-Wilcox aquifer are utilized in outcrop and, more commonly, in the subsurface. Pumpage is mainly for irrigation, which accounts for 51 percent of production, and municipal, which accounts for 35 percent (Ashworth and Hopkins, 1995). Bryan-College Station, Lufkin-Nacogdoches, and Tyler are the major municipalities that rely on ground water from the Carrizo-Wilcox aquifer. The Winter Garden region of South Texas is a major irrigation area that relies on the aquifer. Nearly half of all fresh water drawn from the aquifer in 1985 was produced from Zavala, Frio, Atascosa, and Dimmit Counties (Ryder, 1996).

Numerous rivers cross the Carrizo-Wilcox outcrop belt flowing southeastward toward the coast, providing mechanisms for surface drainage, ground-water discharge, and less commonly ground-water recharge. Precipitation ranges between 21 to 30 inches/year in the southwest and 30 to 56 inches/year in the central and northeastern parts of the outcrop area (Ryder, 1988).

HYDROGEOLOGY

Between approximately 50 and 60 million yr before present (Ma), sediments of the Wilcox and Clairborne Groups were deposited along the edge of the Gulf of Mexico. At that time the coastline was approximately 100 to 150 mi farther inland than it is today (Galloway and others, 1994). South of the Trinity River and north of the Colorado River the Paleocene-Eocene Wilcox Group is divided into, from oldest to youngest, the (1) Hooper Formation, (2) Simsboro Formation, and (3) Calvert Bluff Formation (Barnes, 1970; 1974). The Wilcox Group is undifferentiated north of the Trinity River and south of the Colorado River because there the

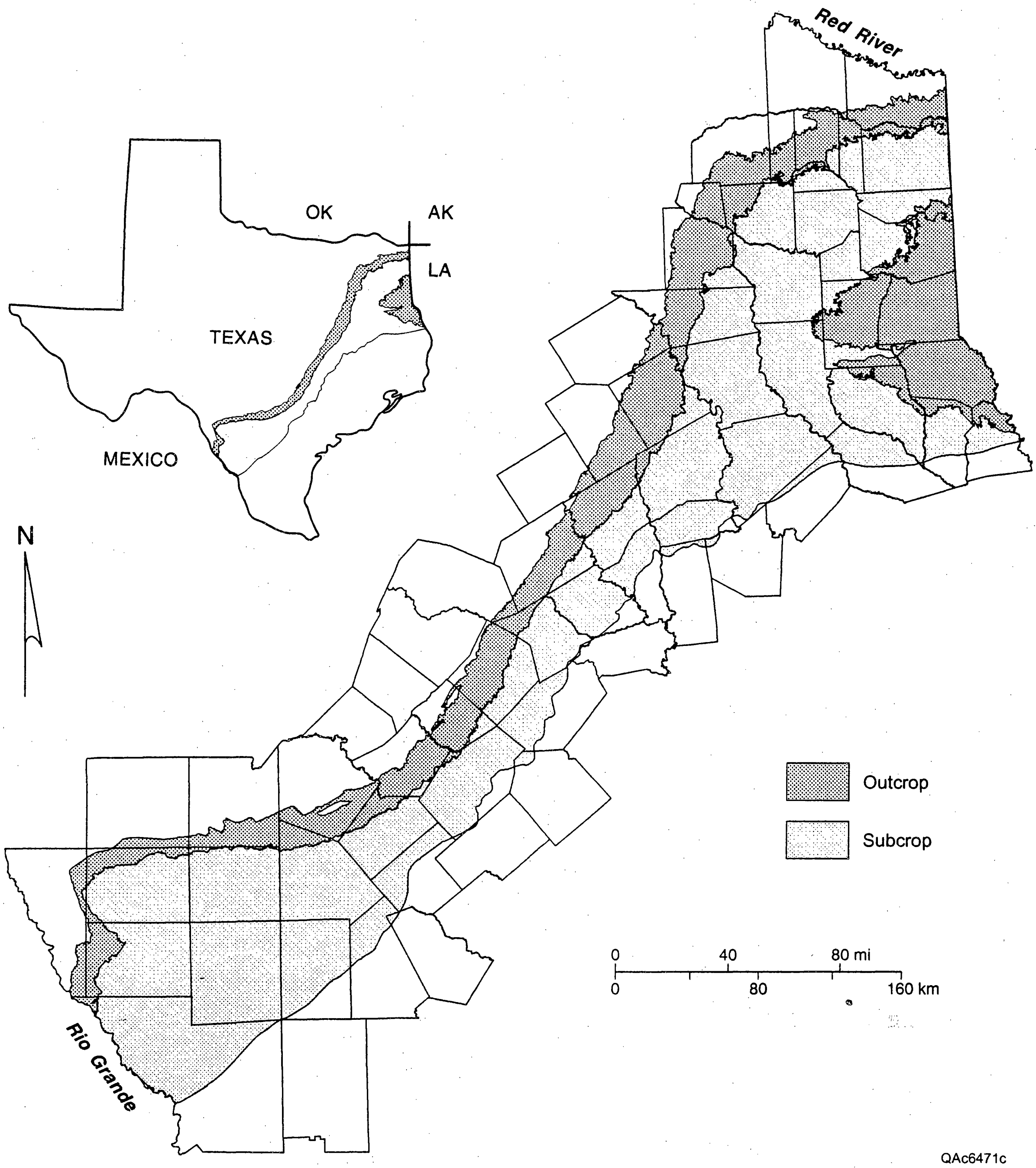

Figure 1. Location of the outcrop and subcrop of the Carrizo-Wilcox aquifer in Texas.

Simsboro Formation is absent as a distinct unit. The oldest unit of the overlying Eocene Clairborne Group is the Carrizo Sand (fig. 2). These geologic units crop out in a northeast-trending band between 150 and 200 mi inland from the Gulf of Mexico, dip south to southeast, and thicken toward the gulf, except near the Sabine Uplift in northeastern Texas. There the units thin or pinch out over the top of the structural dome and dip outward in a radial pattern (Ayers and others, 1985).

Geologic units composing the Carrizo-Wilcox aquifer are (1) the Simsboro and Calvert Bluff Formations of the Wilcox Group and (2) the unconformably overlying Carrizo Sand. Sediments of the Wilcox Group and Carrizo Sand form one of seven temporally distinct episodes of deposition in the Gulf Coast Basin during Paleogene time (65 to 25 Ma) (Galloway and others, 1994). Each of the seven episodes is represented in the rock record by sand, silt, and clay that eroded from the Rocky Mountains to the northwest, and less commonly from the Ouachita Mountains to the north, to feed fluvial-deltaic systems discharging into the Gulf of Mexico.

Marine flooding surfaces that contain shale with localized glauconite or carbonate chemical precipitates separate each of the seven terrigenious sedimentary packages. The marine deposits bound each of the terrigenious units above and below, effectively creating hydraulic barriers (Galloway and others, 1994). Shales of the lower Paleocene Midway Formation and the lower Wilcox Group Hooper Formation form the lower boundary for middle Wilcox terrigenious sediments. Shales of the Eocene Reklaw Formation bound the upper surface of Upper Wilcox-Carrizo terrigenous sediments (fig. 2). Thinner and less extensive marine flooding sequences, present within the middle and upper Wilcox and lower Carrizo sediments, form less complete hydrologic barriers between the laterally connected water-bearing sands of the composite Carrizo-Wilcox aquifer (Galloway and others, 1994).

System	Series		South Texas		Central Texas		Sabine Uplift	
TERTIARY	Eocene	U	Jackson Group		Jackson Group		Jackson Group	
		M	Claiborne Group	Yegua Fm.	Claiborne Group	Yegua Fm.	Claiborne Group	Yegua Fm.
				Cook Mountain Fm.		Cook Mountain Fm.		Cook Mountain Fm.
				Sparta Sand		Sparta Sand		Sparta Sand
				Weches Fm.		Weches Fm.		Weches Fm.
				Queen City Sand		Queen City Sand		Queen City Sand
				Reklaw Fm.		Reklaw Fm.		Reklaw Fm.
		L		Carrizo sand / Upper Wilcox		Carrizo Sand		Carrizo Sand
			Wilcox Group		Wilcox Group	Calvert Bluff Fm.	Wilcox Group	Upper Wilcox
	Paleocene	U		Middle Wilcox		Simsboro Fm.		Middle Wilcox
				Lower Wilcox		Hooper Fm.		Lower Wilcox
		L	Midway Formation		Midway Formation		Midway Formation	

QAc6170c

Figure 2. Lower Tertiary stratigraphy in South Texas, Central Texas, and Sabine Uplift, Texas. Modified from Kaiser (1974), Hamlin (1988), and Galloway and others (1994).

Two foci of sedimentation active intermittently throughout the Paleocene in Texas were the Houston and Rio Grande embayments. The San Marcos Arch separates the embayments. The Sabine Arch lies northeastward of the Houston Embayment or East Texas Basin (fig. 3). The presence of structurally high and low areas along the prograding coastline, and the effects on delta location, allowed the contemporaneous deposition of both streamplain/shorezone and fluvial-deltaic sediments. Mexia-Talco faulting, movement in a compound graben system rooted in Jurassic or Triassic sediments, continued through Eocene time (Jackson, 1982). Faulting also influenced thickness and distribution of Wilcox and Carrizo sediments across the state.

During late Paleocene time, the Houston embayment was the principal drainage axis along which middle Wilcox fluvial-deltaic sediments were deposited. Carrizo Sand and upper Wilcox deposits were primarily focused along the Rio Grande Embayment drainage axis during early Eocene time (Galloway and others, 1994). Because of this shift in regional deposition through time, the older parts of the Carrizo-Wilcox aquifer are thicker between the Colorado and Trinity rivers (including the Simsboro Sand). Younger parts of the Carrizo-Wilcox aquifer are thicker to the south of the Colorado River (fig. 4, table 1).

Paleogene sediments of the Texas Gulf Coast are either (1) heterogeneous accumulations of sand, silt, and clay deposited primarily in lagoonal, delta-plain, delta-front, and shorezone environments or (2) more uniform sands deposited in upper coastal plain channel-fill, crevasse splay, or overbank settings. Middle Wilcox sediments are primarily type 1, have a mean sand content of approximately 55 percent and crop out in a belt 1 to 25 mi wide. The widest point of the outcrop belt and the thickest sediment accumulation is where the fluvially deposited Simsboro Sand Formation is present in the central part of the state (near Lee County). The Simsboro Sand is the only significant fluvial deposit in the Middle Wilcox. Upper Wilcox and Carrizo sediments, primarily type 2, have a mean sand content of 85 percent and crop out in a

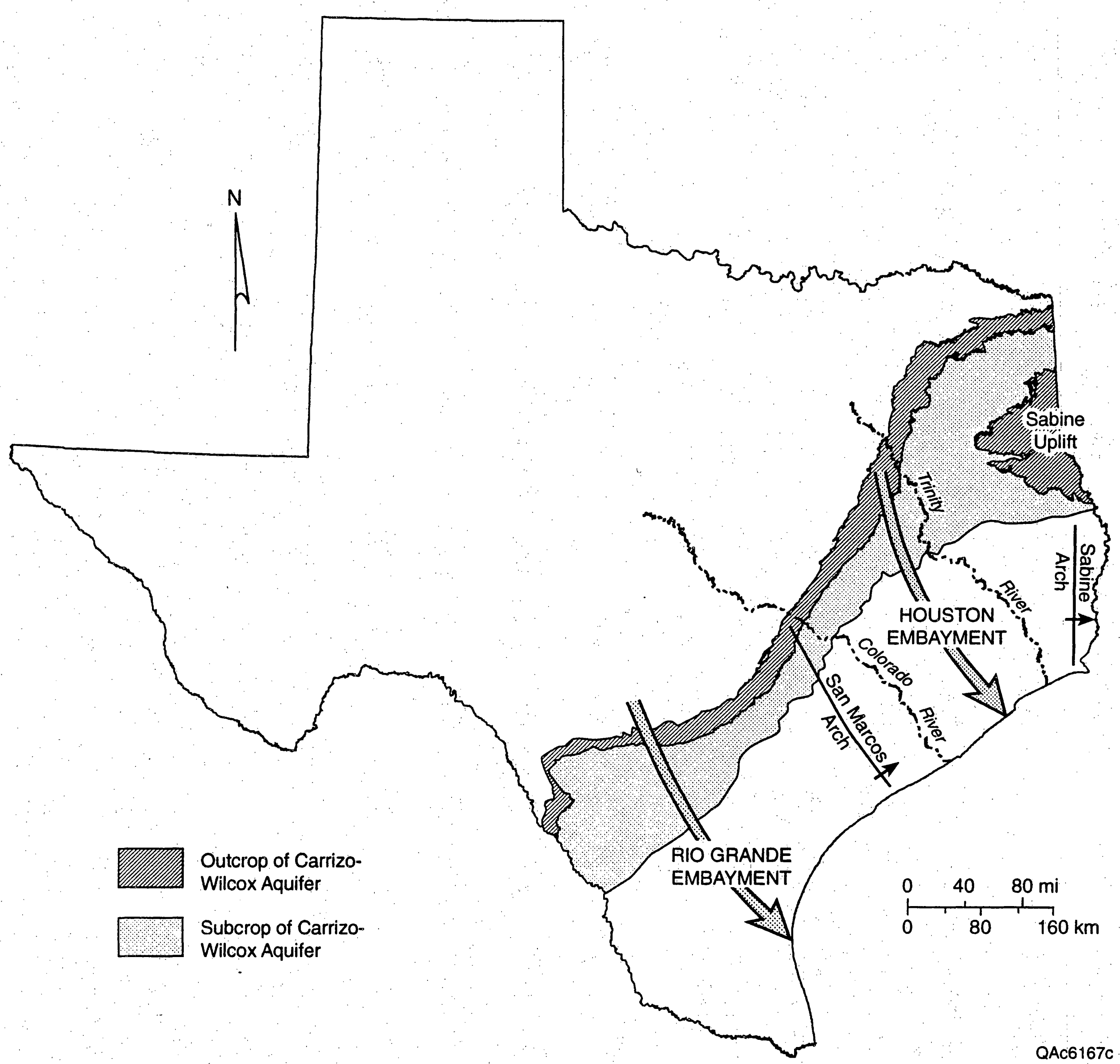

Figure 3. Structural elements that affected Tertiary sedimentation along the Texas Gulf Coast. Modified from Ayers and Lewis (1985).

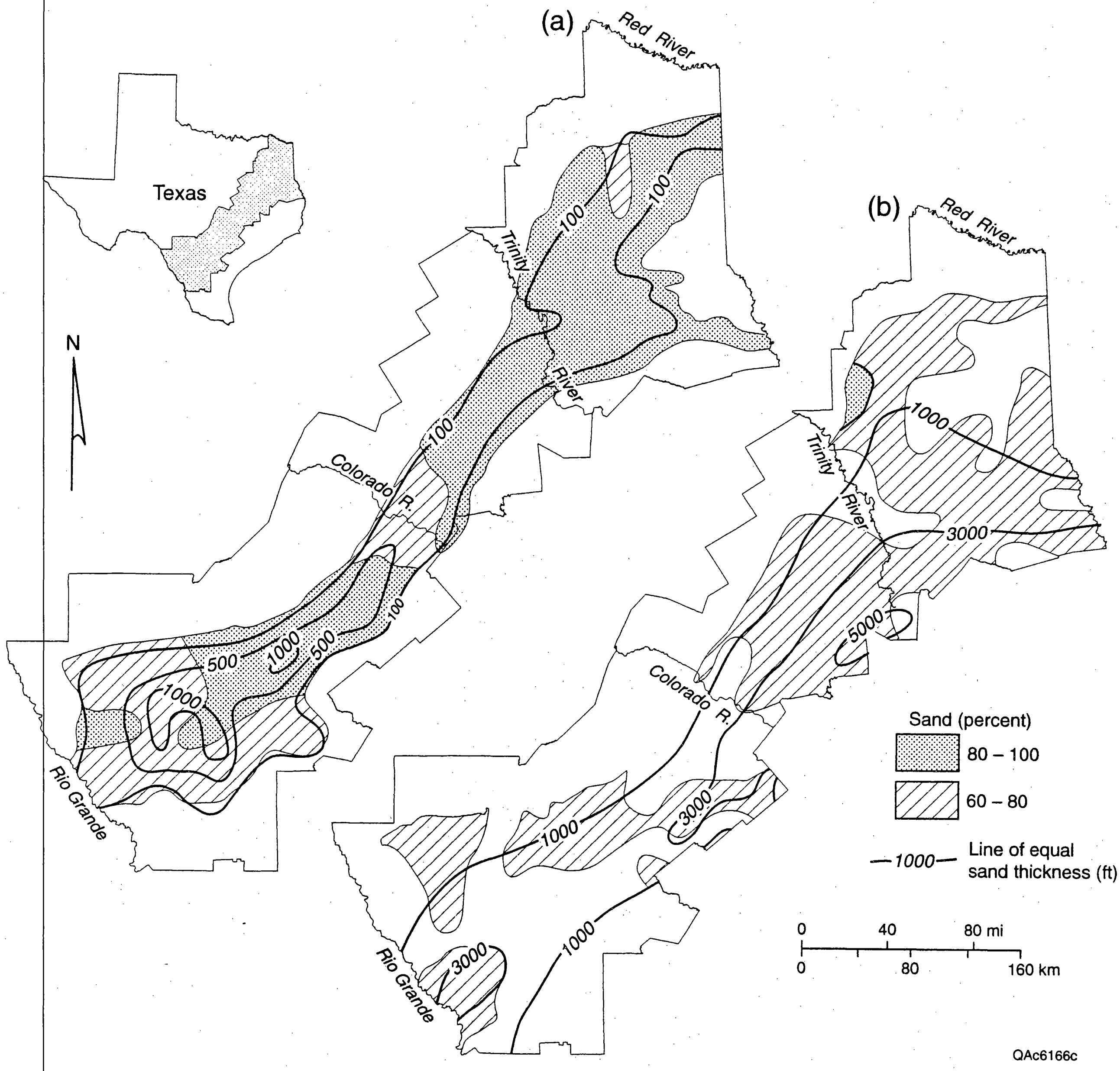

Figure 4. Aquifer thickness and percent sand for (a) lower Claiborne-upper Wilcox aquifer and (b) middle Wilcox aquifer. Modified from Hosman and Weiss (1991).

Table 1. Thickness of Carrizo (Ec) and Wilcox (Ew) stratigraphic units in four structural settings.

Structural setting	County	Thickness of Ec-upper Ew fluvial deposits ft (m)	Thickness of Ec-upper Ew section ft (m)	Thickness of middle Ew fluvial deposits ft (m)	Thickness of middle Ew section ft (m)
Rio Grande Embayment	Zavala	590 (184)[a]			
		725 (226)	783 (244)	0	248 (77)
	Dimmit	516 (161)	859 (268)	0	306 (95)
	La Salle	172 (54)	1,203 (375)	0	573 (179)
San Marcos Arch	Gonzales	726 (226)	802 (250)	0	344 (107)
	Karnes	1,088 (339)	1,088 (339)	0	649 (202)
	De Witt	173 (54)[b]			0
		382 (119)	1,088 (339)	0	687 (214)
Houston Embayment	Lee	477 (149)	477 (149)	0	229 (71)
	Fayette			1,566 (488)[c]	
		0 (0)	707 (220)	0	573 (179)
Sabine Arch	San Augustine	363 (113)	287 (89)	726 (226)	2,731 (851)

a - sand above Carrizo-Upper Wilcox
b - Winter Garden beach sand
c - Simsboro

belt that reaches up to 15 ft in width in outcrop in South Texas. In the vicinity of Karnes and Atascosa Counties, fluvial sands are overlain by approximately 50 ft of well-bedded, marine shelf sand (Ryder, 1988; Galloway and others, 1994).

Lignite, present throughout the Paleogene of Texas, is concentrated in economically significant amounts most commonly in middle and upper Wilcox lagoonal and deltaic interdistributary deposits (Ayers and Lewis, 1985, Kaiser, 1974). Carrizo-Wilcox ground-water resources are utilized for lignite development at mine-mouth power plants (Henry and others, 1979). However, ground water also hinders lignite-mining operations. For example, extensive dewatering of Calvert Bluff overburden is required in many of the mines to keep open pits from flooding during lignite extraction. Large lakes are often left at the surface after mining has ceased. In Milam and Lee Counties, Simsboro Sand is depressurized to prevent catastrophic buckling of mine pit floors; the depressurization water is discharged to East Yegua Creek and eventually flows to the Brazos River.

The Wilcox Group and the Carrizo Sand, Reklaw Formation, and Queen City Sand of the Claiborne Group are sometimes considered one hydrostratigraphic unit in northeast Texas called the "Cypress aquifer" (i.e., Broom and others, 1965).

Methods

Our methodology included (1) a review of the literature relating to transmissivity, hydraulic conductivity, and storativity measurements in the Carrizo-Wilcox aquifer; (2) a compilation of transmissivity, hydraulic conductivity, and storativity data; (3) analysis of the data; and (4) geostatistical description of transmissivity and hydraulic conductivity.

LITERATURE REVIEW

Our literature review involved using the American Geological Institute's GEOREF database of bibliographic information on the geosciences (last updated in June 1998). We used GEOREF to search for documents related to the Carrizo Sand and the Wilcox Group. The initial list of documents was organized into categories concerning (1) chemistry, (2) lignite, (3) contamination, (4) faulting, (5) geology, (6) hydrogeology, and (7) oil and gas. References in the hydrogeology and geology categories were acquired from the Geology Library at The University of Texas at Austin and reviewed for any information on permeability and storativity. Bibliographies and reference lists from these documents were used to supplement the initial GEOREF list.

DATA COMPILATION

Our compilation of transmissivity, hydraulic conductivity, and storativity data included publicly available published and unpublished data from the following sources:

- documents inspected during the literature review;
- well records at the Texas Water Development Board (TWDB);
- well records from Central Records of Municipal Solid Waste at the Texas Natural Resources Conservation Commission (TNRCC);
- published and open-file reports of the TWDB, Bureau of Economic Geology (BEG) and the U.S. Geological Survey (USGS);
- lignite mine permit reports on file at the Texas Railroad Commission (TRRC); and
- files from municipal and industrial ground-water users and water-supply companies.

Besides compiling existing transmissivity, hydraulic conductivity, and storativity data, we also compiled specific-capacity and step-drawdown test data (pumping rate, pumping time, and resulting drawdown) because transmissivity can be determined from specific capacity and step-drawdown data (for example, Theis and others, 1963; Mace, in review; Mace and others, 1997).

We downloaded digital files from the TWDB ground-water database and compiled specific-capacity data from the remarks data file. We inspected paper files and compiled specific capacity data at the TNRCC. From these files, we compiled only information for wells that were pumped or jetted. Jetted and pumped wells provide much more accurate specific capacity data than did bailed wells. In data-poor areas of the aquifer, we compiled information on selected wells that were bailed. Well files at the TNRCC did not indicate the formation in which the well was completed. Therefore, we compared depth to the top of the screen and the bottom of the well as reported in TNRCC files with those reported for wells from the TWDB database for each corresponding 7.5-minute quadrangle to ensure that the TNRCC wells were completed in the Carrizo-Wilcox aquifer. For TNRCC wells with no corresponding well location in the TWDB database, we used the geologic cross-sections from Galloway and others (1994) in order to ensure completion within Carrizo-Wilcox aquifer sediments.

We reviewed lignite mine permit files at the TRRC Surface Mining Division file room for lignite mines in Wilcox Group sediments. TRRC requires mining companies to establish baseline ground-water conditions prior to mining through installation and hydraulic testing of numerous wells. In addition, mine operators frequently install and test additional wells as part of overburden dewatering and underburden depressurization activities. The geologic and hydraulic data from these lignite mine investigations tend to be the most detailed available for the aquifer.

In December of 1998, we coordinated with the TWDB a mass mailing to 467 water utilities requesting any available well-test information for the Carrizo-Wilcox aquifer. We sent another request in early February of 1999. A total of 42 entities responded to the request, 33 of which had well-test information. Data from the BEG and USGS came from published reports and previous studies.

If possible, the following information was collected for each test and entered into a Microsoft Excel spreadsheet:

- well identification number,
- data source
- county name,
- latitude and longitude,
- well depth,
- screened interval of well,
- depth to water,
- well diameter,
- well yield (production or discharge rate),
- drawdown in well due to well yield,
- pumping time of test,
- test method,
- specific capacity,
- transmissivity, hydraulic conductivity, and
- storativity.

Pumping rate, pumping duration, well diameter, and water-level drawdown were compiled to calculate specific capacity and help analytically estimate transmissivity from specific-capacity data. Screen intervals were compiled to calculate hydraulic conductivity (transmissivity divided by the aquifer thickness).

Wells that did not have any identification number are numbered according to the data source. Wells compiled from the TNRCC water-well files often did not have a unique identification number. In this case, the wells were named according to an abbreviated State well numbering system using an array of 1°, 7.5-minute, and 2.5-minute quadrangles (fig. 5). Although, several wells may have the same number, such as 33-59-1, to designate a position inside a 2.5-minute quadrangle, they are not precisely located within the quadrangle (i.e., not assigned the last two digits of the well number as shown in fig. 5). We retained this convention to

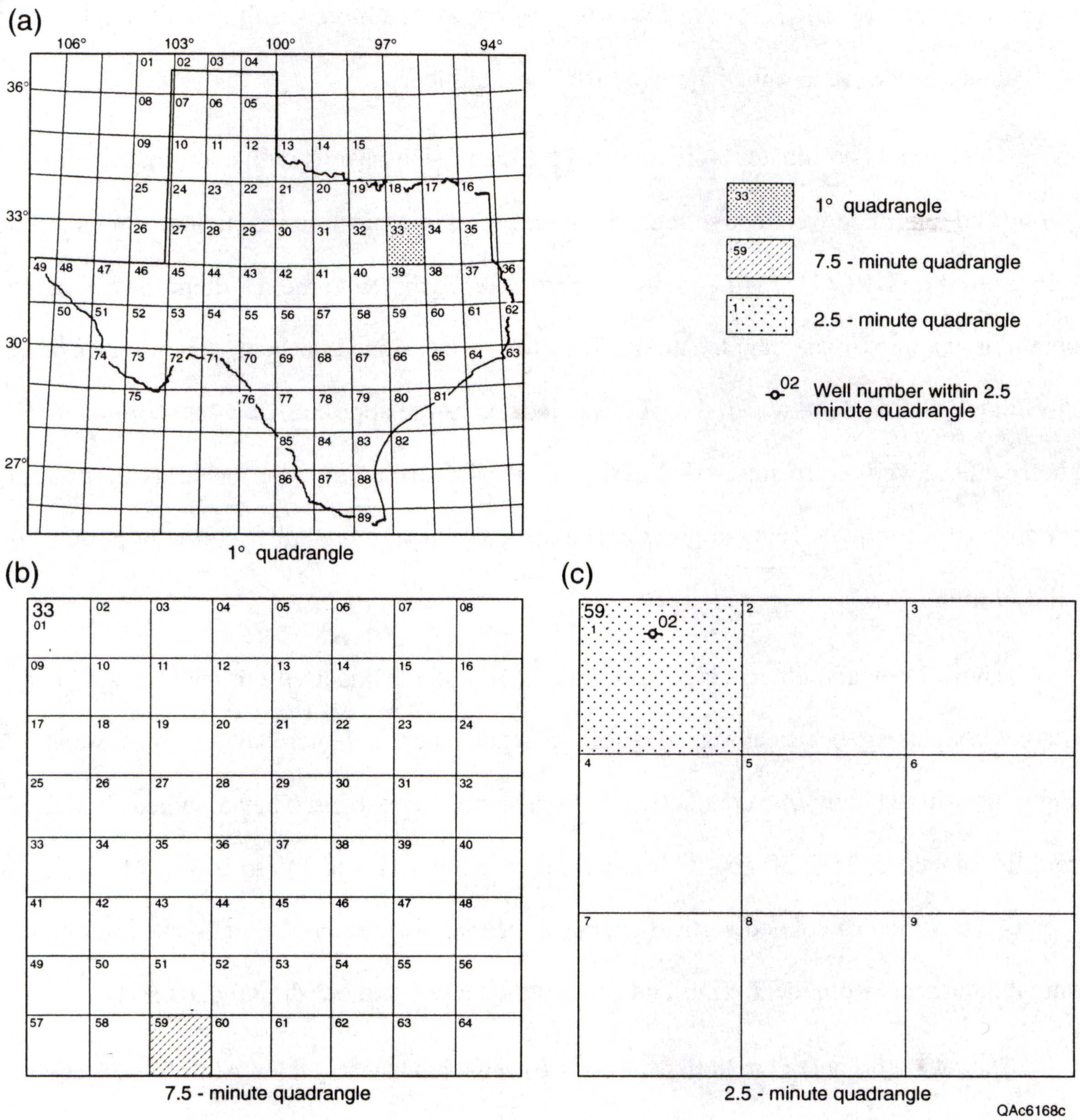

Figure 5. State well-numbering system for (a) 1° quadrangles in Texas, (b) 7.5-minute quadrangles within 1-minute quadrangles, and (c) 2.5-minute quadrangles within 7.5-minute quadrangles. Modified from Follett, 1970.

honor the existing naming scheme of the state and that in the original file. Other well data, such as depth, diameter, and pumping rate, can be used to locate the original file at the TNRCC. However, either the TNRCC or the TWDB may give wells a more specific name at a later date. For each test entry, we assigned a unique BEG test number.

Locational coordinates were reported for many wells. Wells with coordinates not in latitude and longitude were converted from their reported projection into latitude and longitude. Wells from the TNRCC files did not have coordinates assigned to them. Oftentimes, well reports contain only approximate map locations. Therefore, we assigned the center coordinates of the 2.5-minute quadrangle in which the well was located as the approximate well coordinates. Whereas these wells were not used to define the local distribution of permeability in the aquifer, they are useful for quantifying nonspatial statistics and the regional distribution of permeability in the aquifer.

Thorkildsen and others (1989) estimated hydraulic conductivity of the Carrizo Sand and Wilcox Group using electrical logs to define shale, channel, and interchannel deposits and assigning assumed hydraulic conductivities to the mapped deposits. They assumed a value of 1 gpd/ft^2 for shales, 25 to 50 gpd/ft^2 for interchannel deposits, and 140 to 500 gpd/ft^2 for channel deposits. They then calculated vertical averages for each formation. We attained copies of the original datasheets from the TWDB and entered the values into our digital database.

Data were organized in both Microsoft Excel spreadsheets and in ArcInfo geographic information system coverages. A companion browser-driven CD-ROM includes all the data files from this study.

EVALUATION OF HYDRAULIC PROPERTIES FROM THE TEST DATA

If needed, we analyzed aquifer test data for transmissivity and hydraulic conductivity and, in some cases, storativity. The parties that conducted many of the higher quality pumping tests had already analyzed the test data. In these cases, we reviewed the analyses for accuracy. For unanalyzed aquifer tests, we used standard techniques such as the Theis (1935) type curve analysis or the Cooper and Jacob (1946) straight line method (for example, Kruseman and de Ridder, 1990) to determine transmissivity. Hydraulic conductivity, *K*, was calculated by dividing the transmissivity, *T*, by the aquifer thickness, *b*:

$$K = \frac{T}{b} \tag{1}$$

Note that we defined aquifer thickness as the total length of the screened interval in the well. Water wells in the Carrizo-Wilcox are generally screened only in the most productive intervals of the aquifer. Larger wells will often be separately screened in a few different intervals. Therefore, many aquifer tests in the Carrizo-Wilcox aquifer measure the hydraulic properties of the most permeable sands.

Estimating Transmissivity from Specific Capacity

Many of the transmissivity and hydraulic conductivity values that we compiled were based on specific-capacity data. Although estimates of transmissivity and hydraulic conductivity derived from specific-capacity and step-drawdown data are generally not as accurate as estimates from time-drawdown data, relating specific capacity to transmissivity dramatically increased the number of transmissivity values in our database.

There are robust analytical and empirical methods that can be used to estimate transmissivity from specific-capacity data (for example, Thomasson and others, 1960; Theis, 1963; Brown, 1963; Razack and Huntley, 1991; Huntley and others, 1992; El-Naqa, 1994;

Mace, 1997). These techniques have been successfully used in the Cretaceous sandstone aquifers of North Central Texas (Mace and others, 1994), the Edwards aquifer (Hovorka and others, 1995, 1998; Mace, 1995), the Ogallala aquifer (Myers, 1969; Mullican and others, 1997), and the Hill Country Trinity aquifer (Mace, in prep). Prudic (1991) used specific-capacity data in his regional study of the Gulf Coast regional aquifer systems.

Water-well drillers often conduct a well-performance test after well completion to determine the specific capacity. During a well-performance test, the well is pumped at a constant rate, and the amount of drawdown is noted. Specific capacity, S_c, is then defined as the pumping rate, Q, divided by the amount of drawdown, S_w:

$$S_c = \frac{Q}{s_w} \tag{2}$$

Specific capacity is generally reported as discharge per unit of drawdown. For example, a well pumped at 100 gallons per minute (gpm) with 20 ft of drawdown would have specific capacity of 5 gpm/ft. Note that although specific capacity is generally reported in units of volume per length, it has the same units as transmissivity: length squared per time.

A total of 217 wells in the Carrizo-Wilcox aquifer had time-drawdown data and other information necessary to (1) calculate transmissivity using standard pumping-test analysis techniques and (2) estimate transmissivity using specific-capacity data. We evaluated two approaches for estimating transmissivity from specific capacity: an empirical approach and an analytical approach.

We developed an empirical relationship by linearly relating log-transformed transmissivity to log-transformed specific capacity calculated for the same well. To define an empirical relationship between transmissivity and specific capacity, we log-transformed values of each parameter, plotted them against each other, and fit a line through the data using least squares regression (fig. 6). The best-fit line through the data is:

$$T = 1.99 S_c^{0.84}, \tag{3}$$

where the units of T and S_c are in ft^2d^{-1}, and the correlation coefficient, R^2, is 0.91. The relationship has a 90 percent prediction interval that spans a little less than about an order of magnitude. The prediction interval means that we are 90 percent confidant that an estimate of transmissivity for any given value of specific capacity is within an order of magnitude of the estimate.

We evaluated the analytical relationship between transmissivity and specific capacity by Theis and others (1963) for the Carrizo-Wilcox aquifer. Their relationship is based on the Theis (1935) nonequilibrium equation:

$$S_c = \frac{4\pi T}{\left[\ln\left(\frac{2.25 T t_p}{r_w^2 S}\right)\right]} \tag{4}$$

where S is the storativity of the aquifer, t_p is the time of production (that is, pumping) when the drawdown was measured, and r_w is the radius of the well in the screened interval. This equation assumes (1) a fully-penetrating well; (2) a homogeneous, isotropic porous media; (3) negligible well loss; (4) and an effective radius equal to the radius of the production well (Walton, 1970). Because equation 3 cannot be explicitly solved for transmissivity, it must be solved graphically or iteratively; we solved it iteratively in a spreadsheet.

To evaluate the relative accuracy of transmissivity estimated using the empirical relationship (equation 3) against transmissivity estimated using the analytical relationship

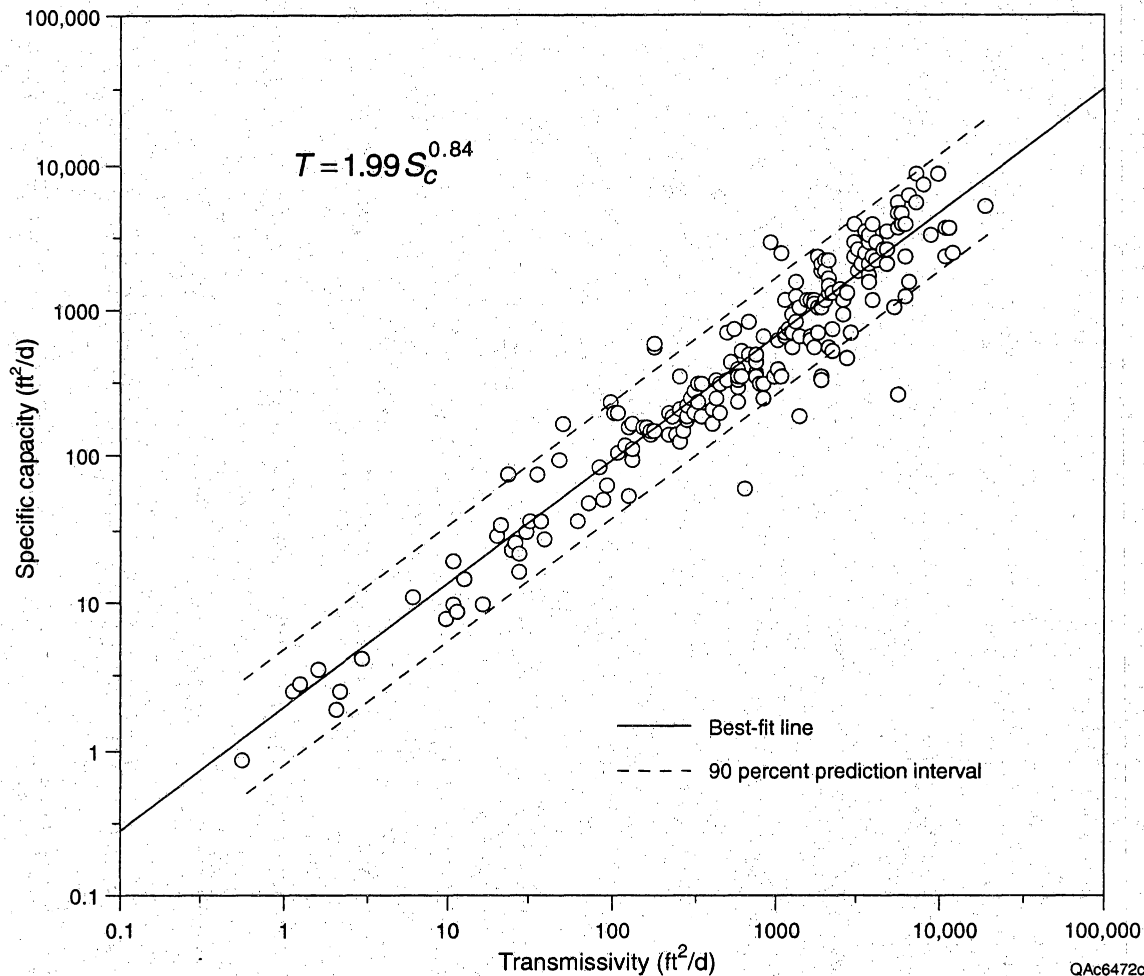

Figure 6. Relationship between specific capacity and transmissivity in the Carrizo-Wilcox aquifer.

(equation 4), we determined the mean absolute error and mean error. Mean absolute error, $|\bar{\varepsilon}|$, is defined by

$$|\bar{\varepsilon}| = \frac{1}{n}\sum_{i=1}^{n}\left|\left[\log(T_m) - \log(T_e)\right]\right| \tag{5}$$

where n is the number of values, T_m is the transmissivity determined from the pumping test, and T_e is the estimated value of transmissivity. Mean error, $\bar{\varepsilon}$, is defined by

$$\bar{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\left[\log(T_m) - \log(T_e)\right] \tag{6}$$

Of the 217 tests used to define the empirical relationship between transmissivity and specific capacity, 57 tests had the appropriate information (discharge rate, drawdown, pumping time, and well radius) for estimating transmissivity with the analytical solution. Therefore, we were only initially able to use these 57 tests to determine the mean absolute error and mean error between calculated transmissivity (using time-drawdown data) and transmissivity estimated using the two specific capacity methods.

The mean absolute error and mean error for transmissivity estimated using the empirical relationship are 0.33 and 0.17, respectively. A mean absolute error of 0.33 means that, on average, the estimated value of transmissivity is within a factor of 2.1 of the measured value (determined by taking the inverse log of 0.33). The positive mean error indicates a bias toward over predicting transmissivity.

The mean absolute error and mean error for transmissivity estimated using the analytical approach are 0.17 and -0.002, respectively. A mean absolute error of 0.17 means that, on average, the estimated value of transmissivity is within a factor of 1.5 of the measured value (determined by taking the inverse log of 0.17). Because the mean error is close to zero, estimates of transmissivity made with the analytical approach are collectively unbiased and do not have a systematic error toward underestimating or overestimating transmissivity.

Based on the mean absolute errors calculated using data from 57 wells, the analytical approach provides slightly more accurate estimates of transmissivity than does the empirical approach. The limiting variables for analytically estimating transmissivity from specific-capacity data are pumping time and well radius. By using mean values of these variables from all other wells, we were able to increase the number of analytical estimates from 57 to 107. Using this approach slightly increases the mean absolute error and mean error for the analytical approach to 0.173 and -0.02, respectively. Therefore, even with assumed values, the analytical approach is more accurate. The empirical relationship may still be useful for (1) field applications where iterative solutions are unwieldy to solve and (2) where nonideal conditions such as partial penetration of the aquifer, turbulent well losses, or fracture flow conditions need to be considered (Mace, in review). Both methods of estimating transmissivity from specific capacity data can result in errors as much as a factor of 5 (fig. 7).

STATISTICAL DESCRIPTION

We statistically summarized transmissivity, hydraulic conductivity, and storativity data using standard statistics, graphical plots, and geostatistics. Standard statistics include arithmetic and geometric mean (average), median, variance, and standard deviation. A geometric mean is the mean value of log-transformed values. Graphical plots include histograms and cumulative distribution functions. A cumulative distribution function (CDF) is a way to display a probability distribution and represents the probability of observing a value less than or equal to another value. In this study we constructed CDFs using log-transformed values of transmissivity and hydraulic conductivity to more readily compare different categories of the data.

The geostatistical methods we used are semivariograms and kriging. Semivariograms statistically quantify spatial relationships of the data. If the values of a parameter such as hydraulic conductivity depend on spatial position, the values of that parameter measured at two points are more likely similar if the two points are close together than if the points are far apart. This measure of similarity (or semivariance) can be quantified with a semivariogram, which is a plot of semivariance versus separation distance of the points (Clark, 1979; McCuen and Snyder, 1986). For discrete data, the semi-variance, γ, for a given separation distance, λ, is defined as

$$\gamma(\lambda) = \frac{1}{2n} \sum \left\{ X(z_i) - X(z_i + \lambda) \right\}^2 \tag{7}$$

where n is the number of data pairs at a distance λ apart, and $X(z_i)$ and $X(z_i+\lambda)$ are the values of the data for the given pairs.

A range, sill, and nugget generally characterize semivariograms (fig. 8). The range generally represents the distance over which a parameter is spatially correlated. Graphically, this is usually the distance to where the semivariogram plateaus, which is called the sill. The separation distance at which the sill occurs is usually the same as the variance of the entire dataset. Theoretically, the semivariance at a separation distance of zero is zero. However, this may not occur because of measurement error, existence of microstructures (Matheron, 1979), or other characteristics of the data (Villaescusa and Brown, 1990). A nonzero value of semivariance at a separation distance of zero is termed the nugget. If the semivariogram is a flat line, it is termed a pure nugget and the data are not spatially correlated. Experimental semivariograms are simply plots of calculated semivariance versus separation distance using measured datapoints – transmissivity and hydraulic conductivity in this study. Theoretical semivariograms are models of the experimental semivariance and are used for kriging. In this study, spherical theoretical semivariograms were visually fit to the experimental semivariograms. We used Surfer to krige transmissivity and hydraulic conductivity data.

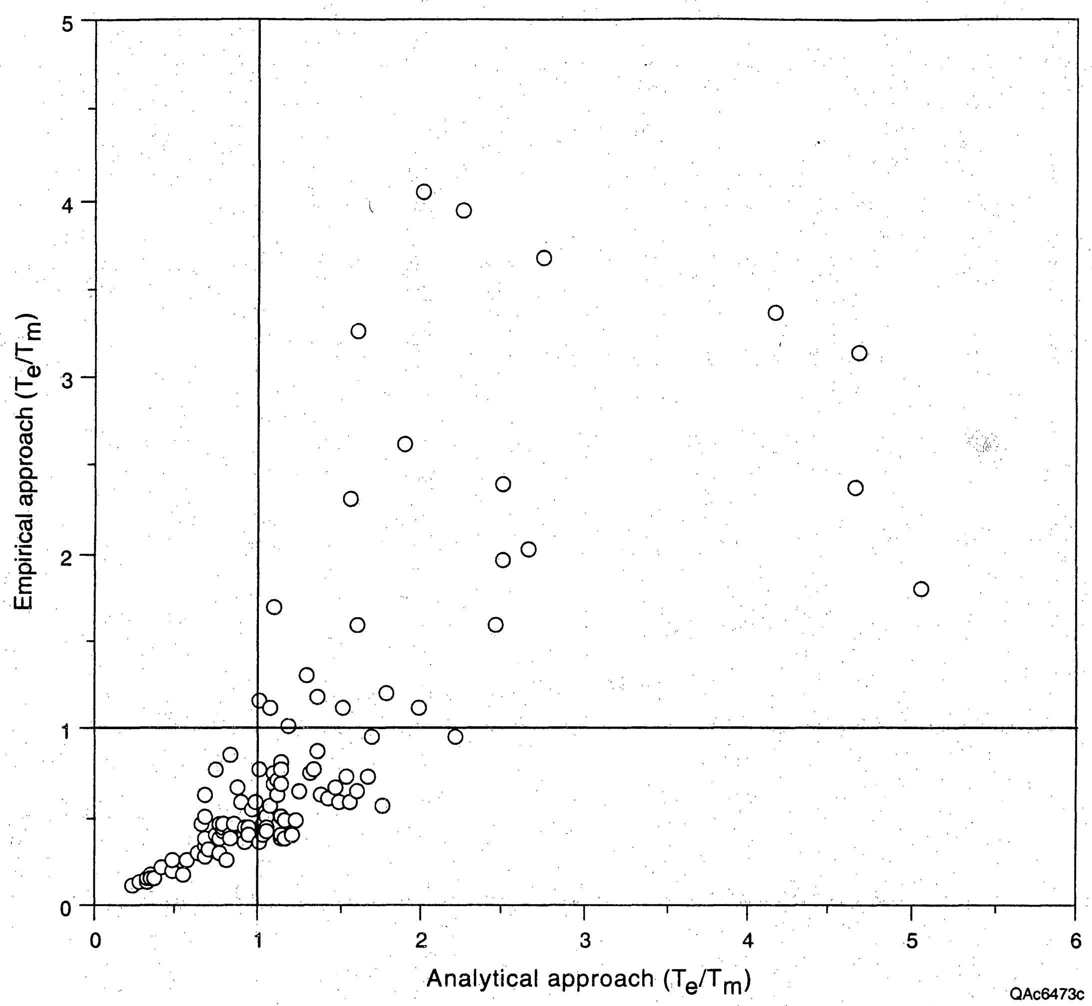

Figure 7. Comparison of the ratios of estimated transmissivity to measured transmissivity for transmissivity estimated by the analytical and empirical approaches.

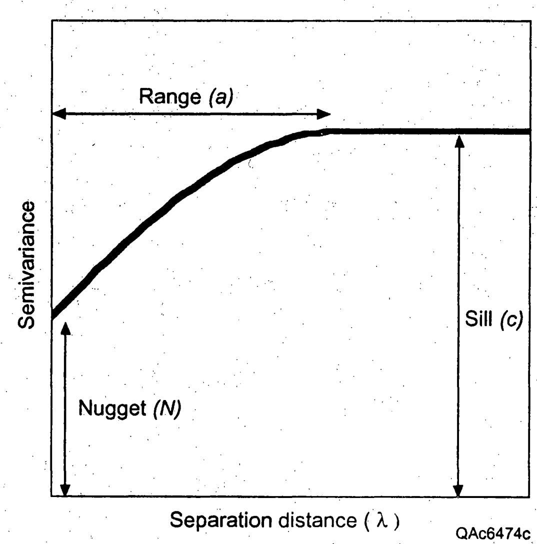

Figure 8. Example semivariogram showing the range, sill, and nugget.

Results and Discussion

This section presents results and discussion on (1) the general characteristics of our compiled database, (2) a statistical description of transmissivity and hydraulic conductivity including analyses of differences between data sources and aquifer testing techniques, (3) the vertical and spatial distribution of transmissivity and hydraulic conductivity, and (4) storativity. Throughout this section we include results of other studies of the Carrizo-Wilcox aquifer for comparison.

GENERAL CHARACTERISTICS OF THE DATABASE

The entire Carrizo-Wilcox database includes 7,402 estimates of hydraulic properties in 4,462 wells. Of the total number of tests, 3,735 were compiled from TNRCC files, 1,671 from an unpublished study by the TWDB on the Carrizo-Wilcox aquifer in Central Texas, 1,394 from the TWDB digital database, 296 from published reports, 179 from TRRC files, and 127 from water utilities. Published reports used in the data compilation include Guyton (1942), Broom and others (1965), Broom (1966), Follett (1966), Tarver (1966), Broom (1968, 1969), Myers (1969), Gaylord and others (1985), Guyton and Associates (1972), Marquardt and Rodriquez (1977), Elder and Duffin (1980), McCoy (1991), and Fisher and others (1996). Test wells from which data are derived are located throughout the outcrop and subcrop of the Carrizo-Wilcox aquifer (fig. 9) and in most counties in the area (fig. 10). Wells become less abundant downdip of the outcrop probably because of drilling costs or because the shallower water-bearing units usually provide adequate yield.

General characteristics of tested wells include: (1) mean diameter of 4.7 inches (fig. 11a, table 2), (2) geometric mean depth of 398 ft (fig. 11b, table 2), and (3) geometric mean screen length of 50 ft (fig. 11c, table 2). Wells in the Carrizo-Wilcox aquifer are generally not screened

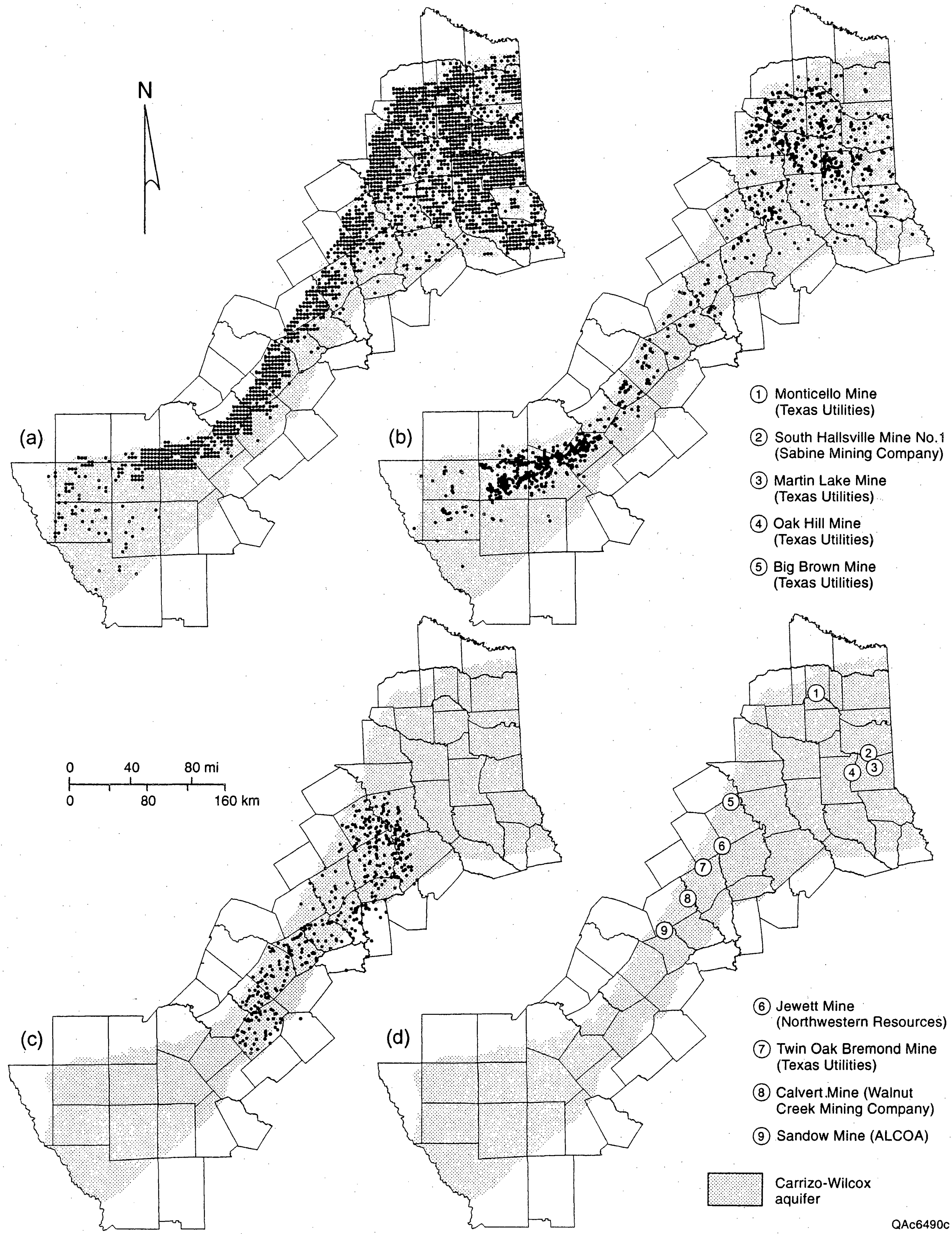

Figure 9. Distribution of aquifer-test wells in the Carrizo-Wilcox aquifer from TNRCC well files, (b) TWDB well database, and (c) well log information from the TWDB.

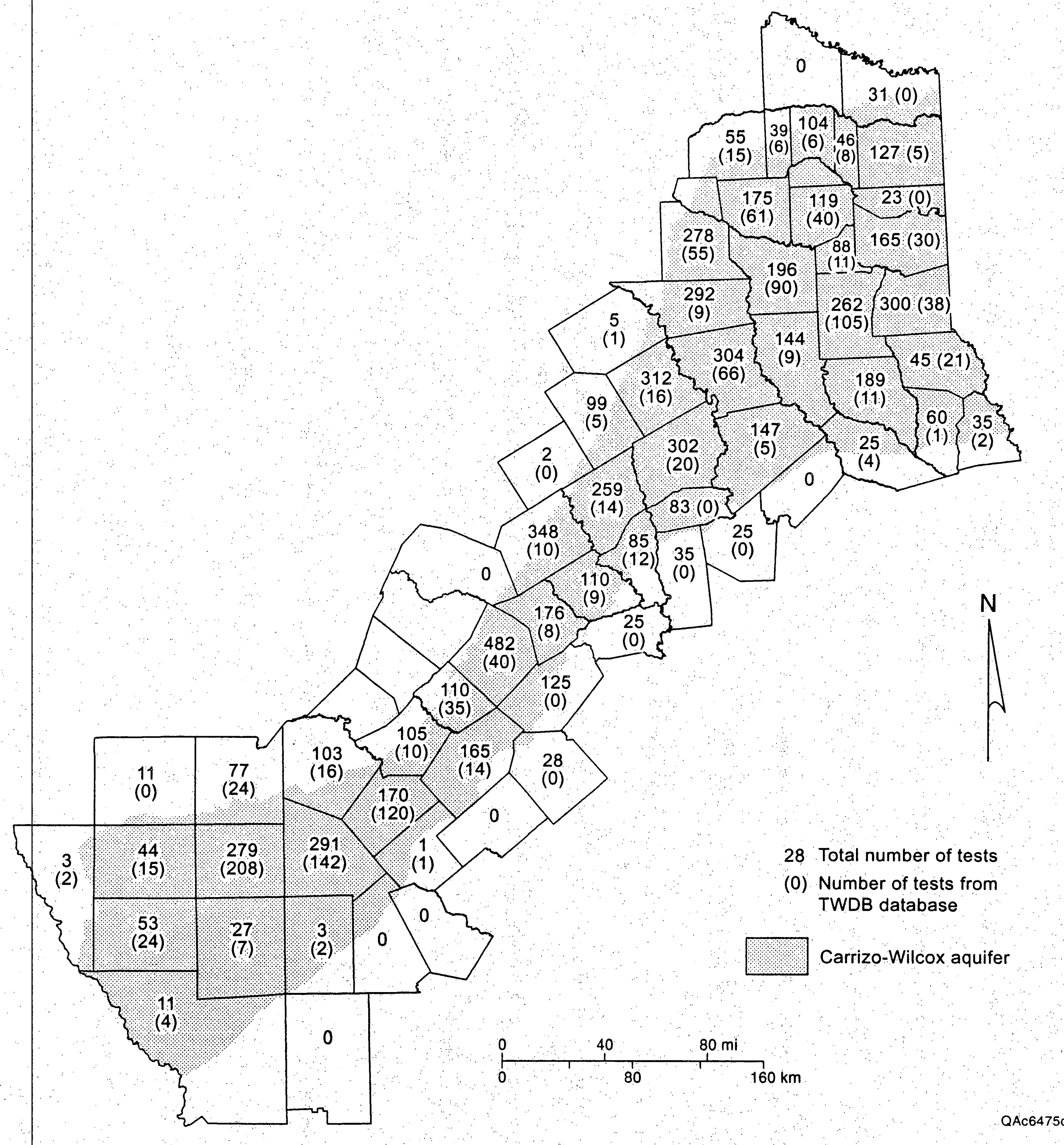

Figure 10. Number of aquifer test wells in each county.

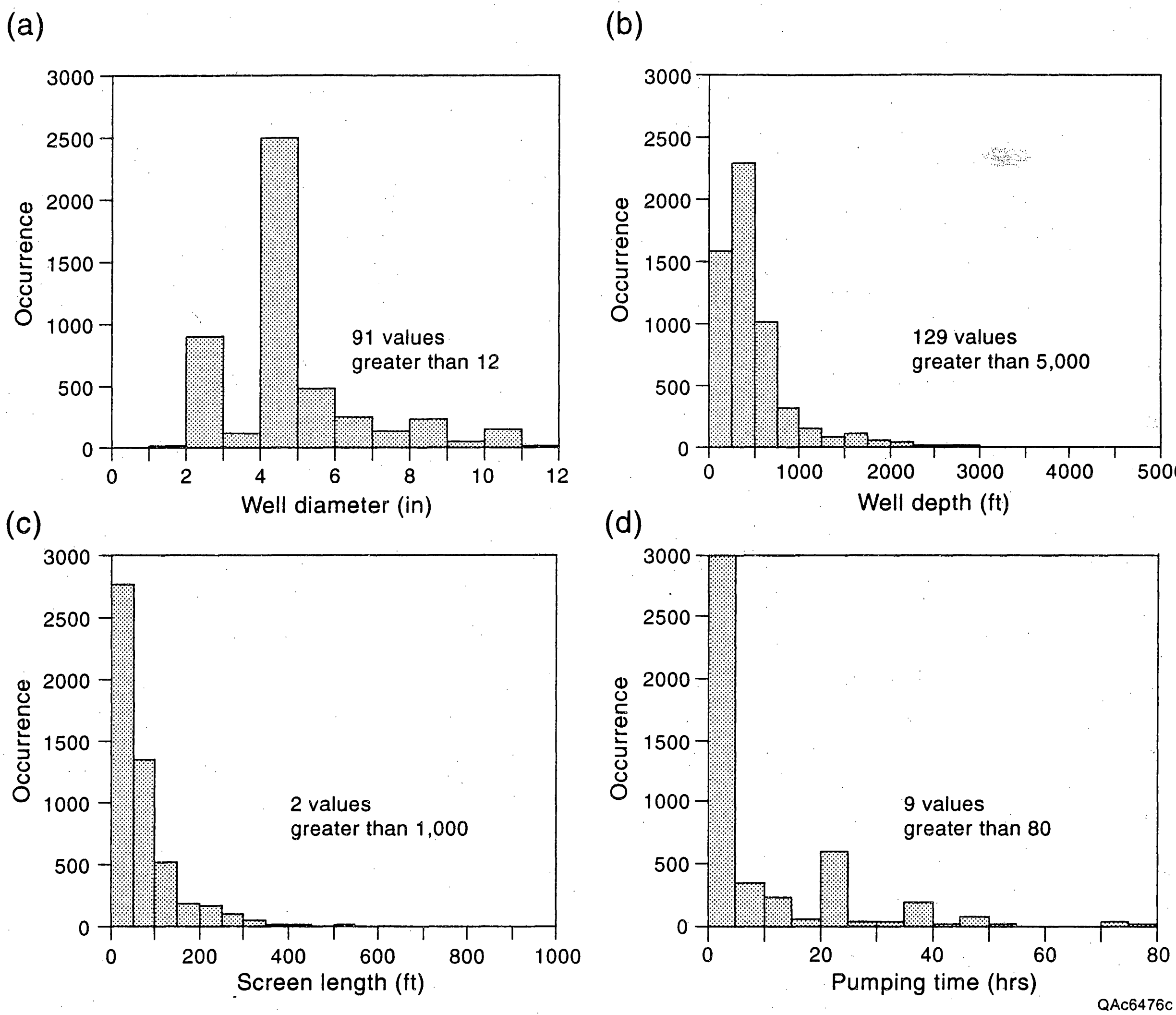

Figure 11. General characteristics of wells and aquifer tests in the database.

throughout the entire thickness of the aquifer. Instead, wells are screened only in the more permeable intervals of the aquifer. Some wells have as many as six discrete screened intervals; however, most (93 percent) have a single screened interval. Mean screen lengths for wells from the TWDB database, water utilities, and published reports (98, 72, and 112 ft, respectively) are three to four times longer than those in wells from TNRCC and TRRC files (38 and 26 ft, respectively). Pumping time of specific-capacity tests in the wells have a geometric mean of 4 hrs (fig 11d, table 2).

Of the 1,404 cases with the tested aquifer reported (1) 726 are in the Carrizo Sand, (2) 227 are in the undivided Wilcox Group, (3) 20 are in the Carrizo-Wilcox aquifer, (4) 138 are in the Calvert Bluff Formation of the Wilcox Group, and (5) 73 are in the Simsboro Formation of the Wilcox Group. An additional 20 tests are reported from wells completed in the Carrizo/Calvert Bluff (5 tests); Carrizo/Reklaw Formation (5 tests); Carizzo/Queen City (3 tests), Hooper Formation of the Wilcox Group (2 tests); Carrizo/Simsboro (2 tests); Calvert Bluff/Simsboro (1 test); Carrizo Sand/Cook Mountain Formation (1 test); and, the Simsboro/alluvium (1 test). In summary, data from 1,394 of the 1,404 wells with aquifer unit identified represent hydraulic properties of the geologic units that compose the Carrizo-Wilcox aquifer. Data from the remaining 10 tests are from wells completed in both Carrizo-Wilcox and overlying stratigraphic units (fig. 2).

TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY VALUES

Transmissivity and hydraulic conductivity for all tests in the Carrizo-Wilcox aquifer appear log-normally distributed (fig. 12). Transmissivity ranges from about 0.1 to 10,000 ft^2d^{-1} and has a geometric mean of about 300 ft^2d^{-1} (fig. 12a, table 3). Hydraulic conductivity ranges from about 0.01 to 4,000 ft d^{-1} and has a geometric mean of about 6 ft d^{-1} (fig. 12b, table 4).

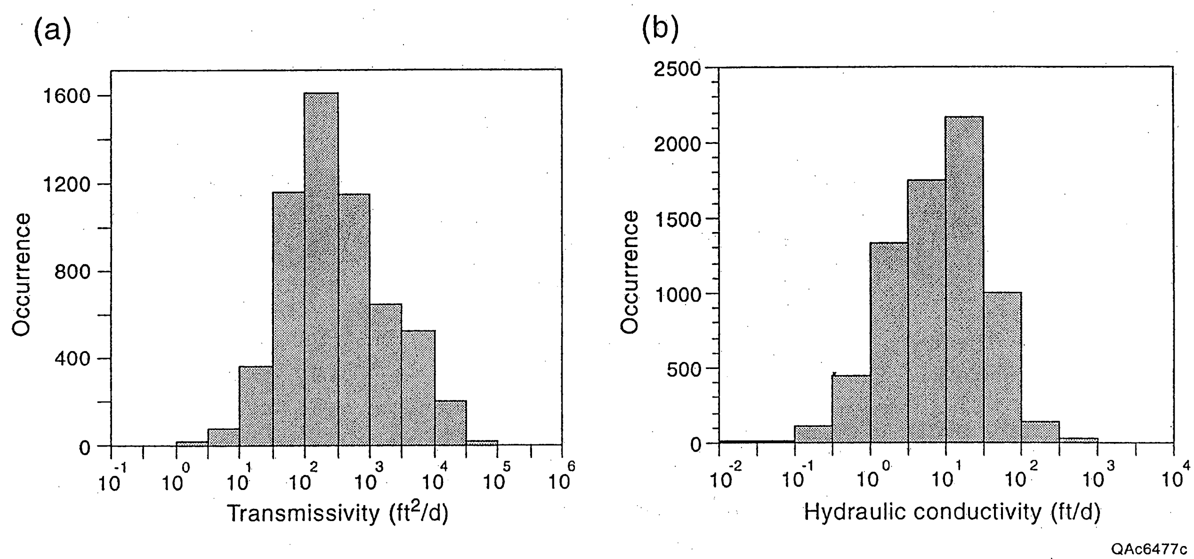

Figure 12. Histograms of all estimates of transmissivity and hydraulic conductivity from the Carrizo-Wilcox aquifer.

Table 2. Characteristics of wells and tests in the database.

Parameter	**units**	**n**	**25th**	**50th**	**75th**	**90th**	$\bar{x}$	s
Diameter	in	5,014	4.0	4.0	5.0	8.0	4.7	2.64
Depth	ft	5,772	240	388	600	1,074	398[a]	0.38[b]
Screen length	ft	5,219	25	41	81	158	50[a]	0.37[b]
Pumping time	hr	4,795	1	2	12	24	4.0[a]	0.56[b]

n number of values
25th 25th percentile
50th 50th percentile (median)
75th 75th percentile
90th 90th percentile
$\bar{x}$ mean
s standard deviation
[a] Geometric mean
[b] Log-transformed standard deviation

Table 3. Transmissivity values (ft^2d^{-1}) estimated from the tests.

	n	25th	50th	75th	90th	$\bar{x}$[a]	s[b]
All tests	5,734	86	240	910	4,600	300	0.79
Source							
TNRCC	3,735	64	150	340	860	150	0.60
TRRC	179	17	130	670	2,700	100	1.09
TWDB	1,397	360	1,400	5,500	11,000	1,300	0.73
Water utilities	127	410	930	2,400	6,900	1,000	0.59
References	296	440	1,600	4,000	9,300	1,300	0.65
Test method							
Pumping test	362	260	950	2,900	5,300	730	0.81
Specific capacity, all	5,300	85	230	810	4,500	290	0.77
Spec. cap., TWDB	1,394	400	1,300	5,000	10,000	1,300	0.73
Spec. cap., bailed	41	28	75	220	470	74	0.69
Spec. cap., jetted	1,481	54	140	370	900	150	0.62
Spec. cap., pumped	2,140	72	150	340	820	170	0.59
Slug tests	72	8	40	150	360	26	0.94
Formation (only TWDB data except where noted)							
Cypress aquifer	18	150	310	550	850	310	0.39
Carrizo	726	1,800	4,900	9,200	15,000	3,500	0.61
Calvert Bluff	13	85	420	800	1,400	310	0.62
Calvert Bluff, w/mine	138	19	110	410	940	79	0.96
Simsboro	56	1,300	2,800	4,500	7,300	2,400	0.42
Simsboro, w/mine	73	1,900	3,200	5,200	7,100	2,700	0.39
Carrizo-Wilcox	220	360	870	2,500	7,500	900	0.67
Wilcox	727	180	440	1,000	2,100	420	0.60

[a] Based on log transformation of original data
[b] Log-transformed standard deviation

n number of values
25th 25th percentile
50th 50th percentile (median)
75th 75th percentile
90th 90th percentile
$\bar{x}$ mean
s standard deviation

Table 4. Hydraulic conductivity values (ft d^{-1}) estimated from the tests.

	n	25th	50th	75th	90th	$\bar{x}$[a]	s[b]
All tests	5,963	2.3	6.6	21.	46.	6.6	0.67
Source							
TNRCC	3,700	1.8	3.8	9.5	25.	4.1	0.61
TRRC	179	1.2	4.9	16.	32.	3.7	0.84
TWDB	1,235	4.6	13.	36.	78.	12.	0.64
TWDB (log)	622	20.	26.	45.	54.	28.	0.21
Water utilities	103	6.1	11.	31.	50.	12.	0.51
References	127	8.0	16.	31.	89.	15.	0.59
Test method							
Pumping test	235	4.6	14.	28.	62.	11.	0.69
Specific capacity, all	5,037	2.1	5.0	15.	39.	5.6	0.65
Spec. cap., TWDB	1,233	5.0	13.	40.	79.	13.	0.64
Spec. cap., bailed	37	0.33	1.9	5.4	16.	1.6	0.79
Spec. cap., jetted	1,463	1.6	3.8	11.	27.	4.0	0.65
Spec. cap., pumped	2,129	1.9	3.8	8.8	23.	4.2	0.58
Slug tests	72	0.53	2.0	5.7	9.7	1.5	0.79
TWDB (log)	622	20.	26.	45.	54.	28.	0.21
Formation (only TWDB data except where noted)							
Cypress aquifer	7	3.0	4.9	9.6	13.	5.6	0.33
Carrizo	602	12.	30.	58.	120.	26.	0.58
Calvert Bluff	11	2.3	4.2	5.1	15.	4.2	0.48
Calvert Bluff, w/mine	136	1.2	4.5	10.	21.	3.2	0.75
Simsboro	56	11.	20.	31.	53.	18.	0.43
Simsboro, w/mine	73	13.	23.	33.	52.	20.	0.39
Carrizo-Wilcox	187	5.2	11.	31.	62.	11.	0.59
Wilcox	615	2.8	6.6	14.	31.	6.0	0.59

[a] Based on log transformation of original data
[b] Log-transformed standard deviation

n number of values
25th 25th percentile
50th 50th percentile (median)
75th 75th percentile
90th 90th percentile
$\bar{x}$ mean
s standard deviation

Variations in Values from Different Sources

There are differences for geometric mean transmissivity and hydraulic-conductivity values between the different data sources. Tests from TNRCC and TRRC files have geometric mean transmissivity values that are about 10 times lower than tests from the TWDB database, water utilities, and reference sources (table 3, fig. 13a). Tests from TNRCC and TRRC files have geometric mean hydraulic-conductivity values that are about three to four times lower than tests from the TWDB database, water utilities, and reference sources (table 4, fig. 13b).

Most of the data from the TNRCC files are for private wells whereas most (at least 70 percent) of the data compiled for the TWDB database are from municipal public supply or industrial wells. Private wells do not require large yields to supply a household and are usually completed when the desired yield is reached during drilling. Consequently, private wells are usually screened in shallower water-bearing zones and rarely penetrate the entire aquifer unit. Municipal public supply and industrial wells are designed and constructed to maximize water yield.

Transmissivity and hydraulic conductivity values from TRRC lignite mine permit reports are lower than TWDB data because the TRRC data are biased toward lower permeability geologic units. This is because most of the TRRC-reported wells are completed in either Calvert Bluff Formation or undivided Wilcox Group deposits. For example, 87 percent of the TRRC wells are completed in Calvert Bluff Formation or undivided Wilcox Group and only 13 percent of the wells are completed in the Carrizo Sand and Simsboro Formation (table 5). The Calvert Bluff Formation and equivalent horizons of the undivided Wilcox Group are the main economically viable, lignite-bearing units in Texas. These heterogeneous units are characterized by higher permeability channel and overbank sands in deposits of low-permeability deltaic-mud and organic-rich swamp deposits (peat that later turned to lignite). The higher permeability

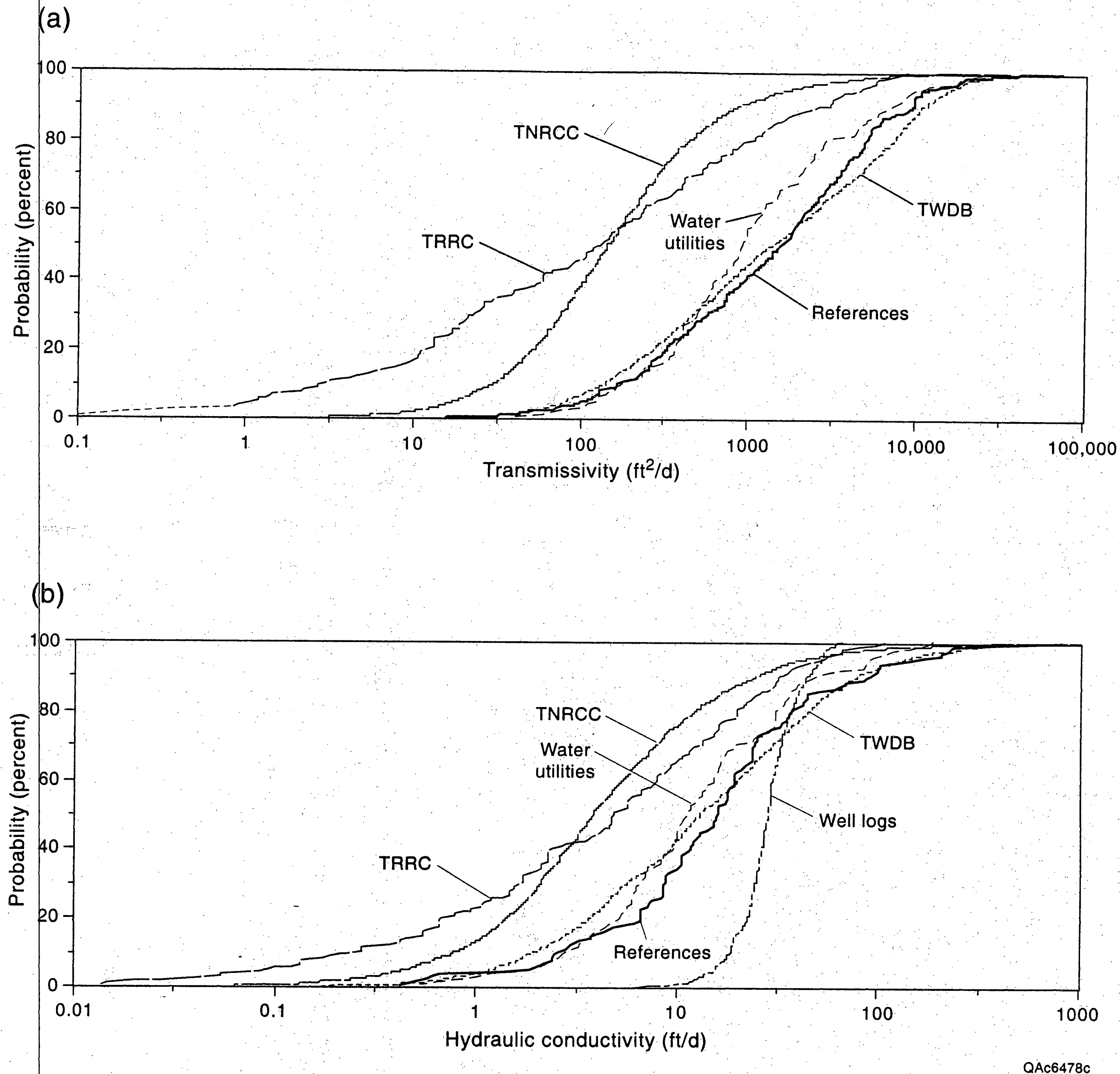

Figure 13. Cumulative distribution functions of transmissivity and hydraulic conductivity for different data sources.

Table 5. Transmissivity and hydraulic conductivity values compiled from lignite mine permit reports on file at the TRRC.

Results of Pumping Tests

	Carrizo Sand			Calvert Bluff Formation		
Mine	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**
Big Brown	-	-	-	14	4.47	89.13
Calvert	-	-	-	-	-	-
Jewett	2	5.37	102.33	20	10.72	288.4
Sandow	-	-	-	7	8.91	97.72
Twin Oak	-	-	-	6	8.51	467.74
Martin Lake	1	64.57	1995.26	-	-	-
Monticello	-	-	-	-	-	-
Oak Hill	-	-	-	-	-	-
South Hallsville	2	15.49	588.84	-	-	-

	Wilcox Group			Simsboro Formation		
Mine	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**
Big Brown	-	-	-	-	-	-
Calvert	-	-	-	7	21.38	3801.89
Jewett	-	-	-	-	-	-
Sandow	-	-	-	10	32.36	4,897.8
Twin Oak	-	-	-	-	-	-
Martin Lake	3	2.14	67.61	-	-	-
Monticello	25	2.14	69.18	-	-	-
Oak Hill	9	13.18	389.05	-	-	-
South Hallsville	1	0.05	2.24	-	-	-

n number of values

$\overline{T_g}$ geometric mean of transmissivity

$\overline{K_g}$ geometric mean of hydraulic conductivity

Table 5. continued

Results of Slug Tests

	Carrizo Sand			Calvert Bluff Formation		
Mine	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**
Big Brown	-	-	-	12	1.05	10.47
Calvert	-	-	-	-	-	-
Jewett	-	-	-	1	57.54	3090.3
Sandow	-	-	-	2	0.62	7.59
Twin Oak	-	-	-	4	6.17	229.1
Martin Lake	1	0.47	15.85	-	-	-
Monticello	-	-	-	-	-	-
Oak Hill	-	-	-	-	-	-
South Hallsville	1	1.11	134.89	-	-	-

	Wilcox Group			Simsboro Formation		
Mine	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**	**n**	$\overline{T_g}$ **(ft²d⁻¹)**	$\overline{K_g}$ **(ft d⁻¹)**
Big Brown	-	-	-	-	-	-
Calvert	-	-	-	-		
Jewett	-	-	-	-	-	-
Sandow	-	-	-	-		
Twin Oak	-	-	-	-	-	-
Martin Lake	6	1.86	40.74	-	-	-
Monticello	27	2	38.02	-	-	-
Oak Hill	7	0.3	3.89	-	-	-
South Hallsville	11	1.59	31.62	-	-	-

n number of values

$\overline{T_g}$ geometric mean of transmissivity

$\overline{K_g}$ geometric mean of hydraulic conductivity

Carrizo Sand and Simsboro Formation were deposited in more fluvially dominant environments. The wide range of depositional environments represented by the TRRC tests also explains the greater variance of tests compiled from TRRC files (tables 2, 3; figure 12; note the wide distribution). Because of the bias toward lower permeability values (table 5), we did not use the TRRC data to analyze spatial statistics.

Hydraulic conductivity estimated by the TWDB on the basis of well logs are two to seven times higher than other values and have a much lower standard deviation (table 4, fig. 13b). Because this method may overestimate actual hydraulic conductivity and not give a realistic representation of the hydraulic properties of the aquifer, we excluded these data from our analysis of spatial statistics.

Variations in Values Due to Different Testing Methods

Values of transmissivity and hydraulic conductivity vary between the different test methods. Values of transmissivity estimated from pumping tests are about twice as high as those estimated from specific-capacity data (only those specific-capacity data compiled from the TNRCC) and almost 30 times higher than those estimated from slug tests (table 3, fig. 14a). Values of hydraulic conductivity estimated from pumping tests are about twice as high as those estimated from specific-capacity data and about seven times higher than those estimated from slug tests (table 4, fig. 14b). The highest estimates of hydraulic conductivity are from the well log interpretation (fig. 14b), which resulted in values 2.5 times higher than values estimated from pumping tests.

The difference is probably due largely to the type and purpose of the well tested. Pumping tests are generally performed in the higher yielding municipal wells. Slug tests are generally performed in formations with low permeability. In this case, the slug test data are

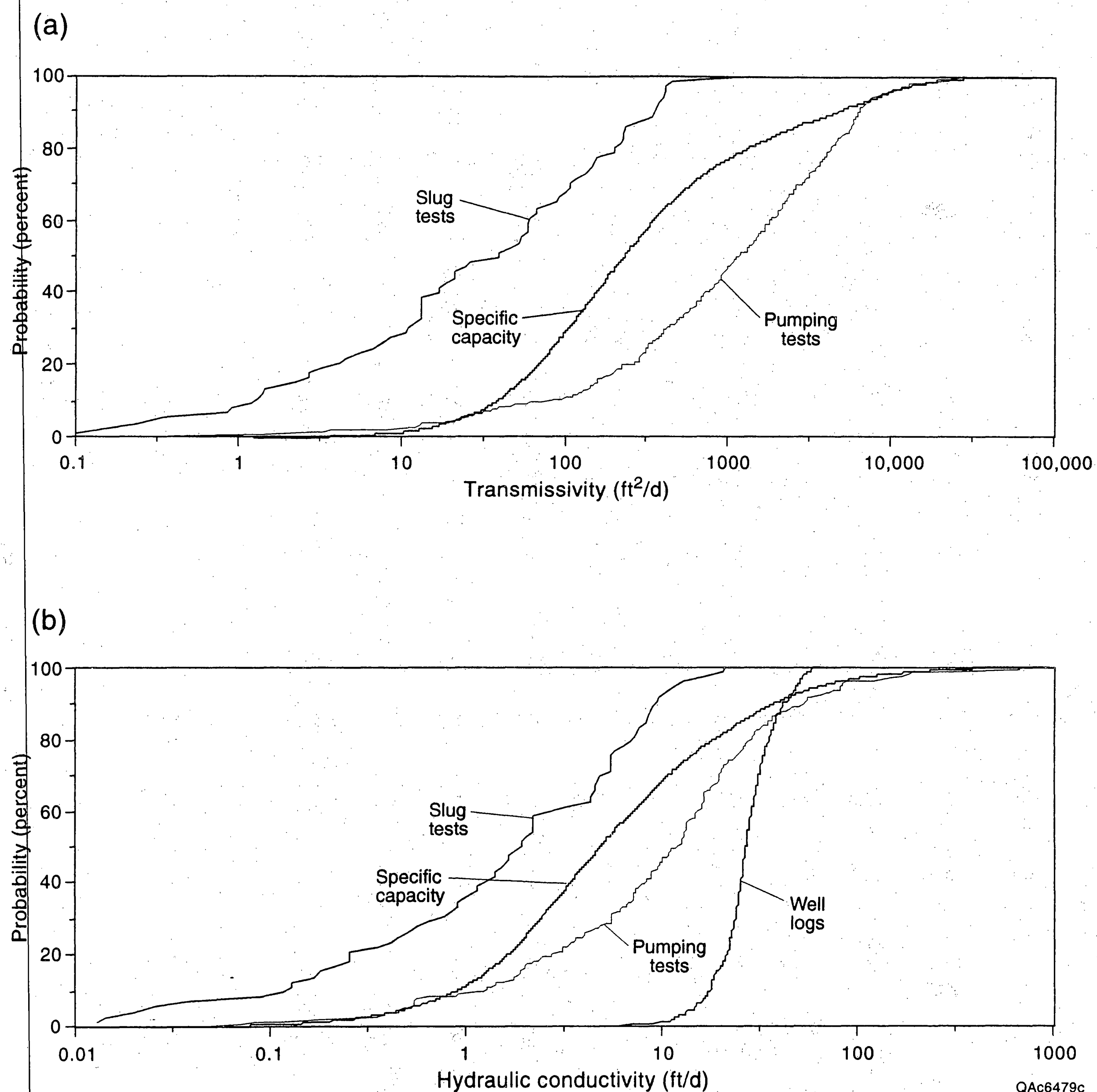

Figure 14. Cumulative distribution functions of transmissivity and hydraulic conductivity for different test types.

exclusively from TRRC-permitted lignite mines where tested wells are most frequently completed in lower permeability Calvert Bluff and Wilcox Group deposits (table 5).

Among tests where we estimated transmissivity from specific-capacity data, wells that were bailed had transmissivity values 100 times lower than wells that were jetted or pumped. Although we compiled substantially fewer specific-capacity data from tests in which wells were bailed, this difference in hydraulic properties supports our decision to forego compiling tests involving bailing. Note that tests for which we were able to determine the method of production used to collect specific capacity data are exclusively from TNRCC files. However, transmissivity values determined from TWDB specific-capacity data are about the same as those determined from pumping tests (table 3). Because of this close correlation, we believe that the method of production for the majority of specific-capacity tests compiled from the TWDB database was pumping.

Another method used to determine hydraulic conductivity is by laboratory analysis of aquifer materials. Klemt and others (1976, p. 12) hydraulically tested core samples from the aquifer and used grain size analysis on drill cuttings to estimate hydraulic conductivity of the Carrizo Sand in the southwestern part of the aquifer. They found county-averaged hydraulic conductivity values that ranged from 5 to 126 ft^2d^{-1} for values estimated from core and 72 to 91 ft^2d^{-1} for values estimated from cuttings. They noted that these values were greater than those determined from pumping tests.

SPATIAL DISTRIBUTION OF TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY

Spatial distribution refers to how transmissivity and hydraulic conductivity vary vertically and laterally within the aquifer. We first investigated how transmissivity and hydraulic conductivity vary between the different formations. Based on that analysis, we then investigated how transmissivity and hydraulic conductivity vary laterally within the aquifer, both regionally and locally, using regional binning and geostatistics. Finally, we investigated if the geology, specifically regional net sand thickness, could help explain some of the lateral variability we observed. Where appropriate, we also include results of other studies that relate to vertical and lateral variability, such as the work of Prudic (1991) on the relationship between depth and hydraulic conductivity. All of the results we present in this section are based on analyses we performed with data sourced from the TWDB well database.

Vertical Variability of Transmissivity and Hydraulic Conductivity

We observe vertical variations in transmissivity and hydraulic conductivity among the different formations and aquifers. The Simsboro Formation and Carrizo Sand portions of the aquifer have transmissivity and hydraulic-conductivity values that are higher (2.5 to eleven times higher for transmissivity and two to six times higher for hydraulic conductivity) than those of the Cypress aquifer, Calvert Bluff Formation, and Wilcox Group as a whole (fig. 15, tables 3 and 4). This is geologically reasonable because the Carrizo Sand and Simsboro Formation tend to have a greater percentage of sand than do other hydrogeologic units within the Carrizo-Wilcox aquifer.

Values of hydraulic conductivity and transmissivity that we compiled are similar to values compiled and summarized by previous researchers (compare to values presented in table 4). Thorkildsen and Price (1991) reported the following hydraulic conductivity values for Carrizo-Wilcox sediments based on the analysis of well logs:

(1) Carrizo Sand ranges from 26 to 140 ft d^{-1}, with an average value of 75 ft d^{-1};

(2) Undifferentiated Wilcox ranges from 2 to 204 ft d^{-1}, with an average of 31 ft d^{-1};

(3) Calvert Bluff ranges from 4 to 18 ft d^{-1}, with an average of 11 ft d^{-1};

(4) Simsboro ranges from 2 to 84 ft d^{-1}, with an average of 24 ft d^{-1} ; and

(5) the Carrizo-Wilcox Aquifer as a whole ranges from 7 to 21 ft d^{-1}, with an average of 12 ft d^{-1}

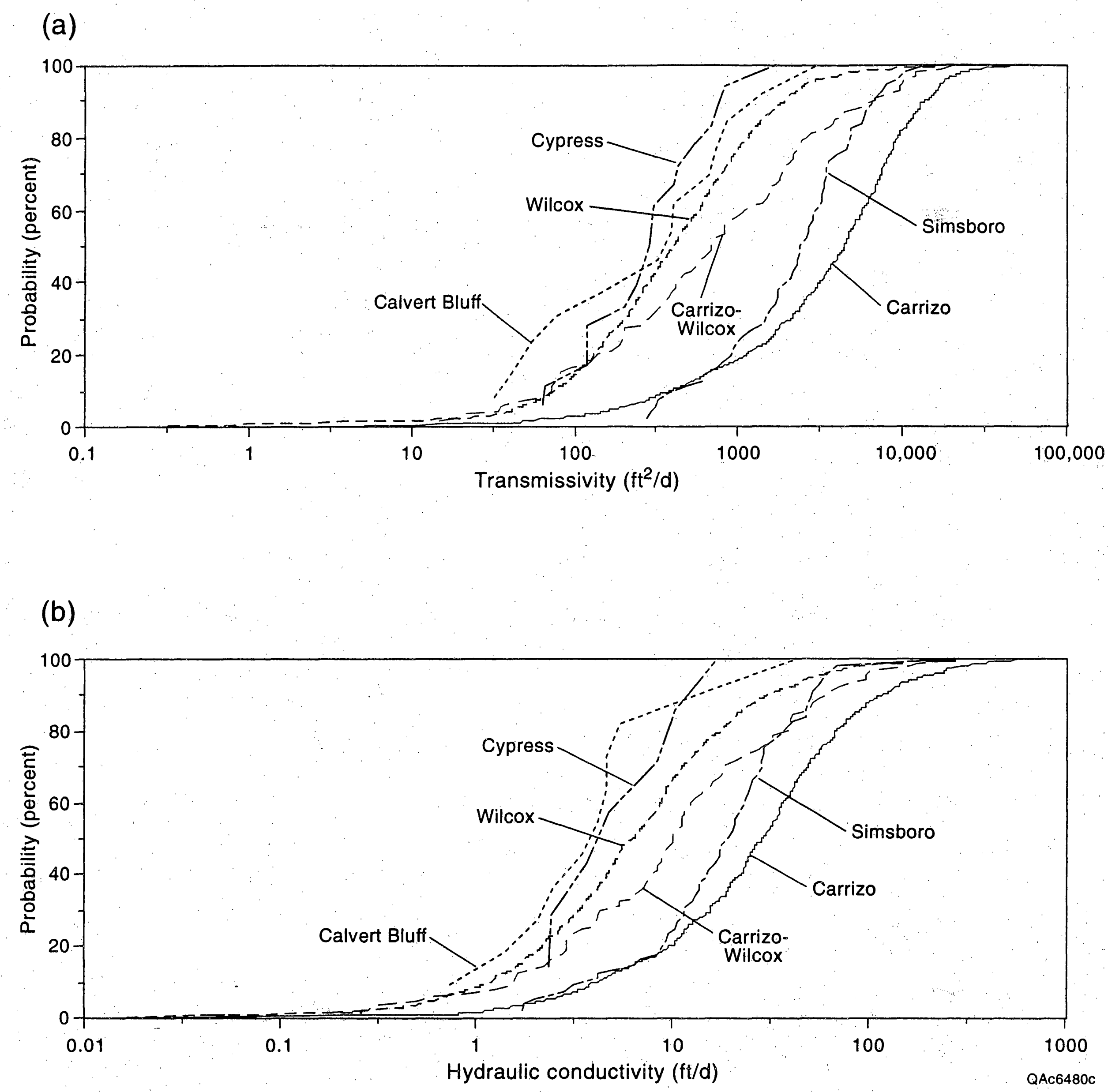

Figure 15. Cumulative distribution functions of transmissivity and hydraulic conductivity for the different geologic units using the data collected from TWDB files.

Thorkildsen and Price (1991) state that the Carrizo Sand is more lithologically uniform than the Wilcox Group. They note that the Carrizo is composed primarily of sand whereas the Wilcox Group is composed of both higher permeability sands and lower permeability clays. The range of hydraulic conductivity they give for Wilcox channel sands is 20 to 60 ft d^{-1}. They also present results from a previous study by Henry and others (1980), which gives hydraulic conductivity values from 3 to 7 ft d^{-1} for Wilcox Group interchannel sands and muds.

Thorkildsen and Price (1991) spoke conceptually on the similarities and differences between the water-bearing units and suggest that the channel sands of the Wilcox Group have hydraulic conductivities similar to the Carrizo Sand. Our analysis of the entire aquifer finds the standard deviations of hydraulic conductivity of the Carrizo Sand and Wilcox Group to be nearly identical (0.58 ft d^{-1} and 0.59 ft d^{-1}, respectively) (table 4). Because water wells in the TWDB database tend to be biased toward sandier intervals of the aquifer, we believe that our results are in agreement with the conceptual ideas presented by Thorkildsen and Price (1991).

Based on aquifer tests, Dutton (1999) finds the Carrizo Sand between the Colorado and Brazos Rivers to have a higher variance than the Simsboro and Calvert Bluff Formations of the Wilcox Group and notes that this observation is in contrast to the findings of Thorkildsen and Price (1991).

Prudic (1991) investigated the relationship between hydraulic conductivity and depth and found that hydraulic conductivity generally decreased with increasing depth. However, due to data scatter and poor regression, his equations, presented below, provide only a general description of the relationship. For the upper Wilcox-lower Claiborne in northeastern Texas, hydraulic conductivity increases slightly with depth.

For the Winter Garden area, the relationship for the middle Wilcox is

$$K = \frac{8.7}{10^{0.00022D}} \tag{7}$$

for a depth range of 34 to 3,536 ft and for the upper Wilcox-lower Claiborne is

$$K = \frac{110}{10^{0.00030D}} \tag{8}$$

for a depth range of 105 to 3,890 where D is depth below land surface in feet and K is in ft d^{-1}. For the northeast area, the relationship for the middle Wilcox is

$$K = \frac{9.1}{10^{0.00010D}} \tag{9}$$

for a depth range of 67 to 2,200 ft and for the upper Wilcox-lower Claiborne is

$$K = 15\left(10^{0.00044D}\right) \tag{10}$$

for a depth range of 91 to 1,370 ft where D is in feet and K is in ft d^{-1}.

Kier and Larkin (1998) questioned whether there is hydraulic connection between the Carrizo Sand and Simsboro Formation in the central part of the aquifer. Ryder (1988) and Hosman and Weiss (1991) separate the Carrizo-Wilcox into two distinct aquifers: the Lower Claiborne-Upper Wilcox Aquifer and the Middle Wilcox Aquifer. Although some workers have used very low vertical hydraulic conductivity values for confining units in ground-water flow models of the Carrizo-Wilcox aquifer (e.g., Dutton, 1999), it is unclear whether there is significant hydraulic connection between these two aquifer units throughout the state. For example, Dutton (1999) assumed the horizontal and vertical hydraulic conductivity of the clays in the Calvert Bluff and Hooper Formations to be $10^{-3.5}$ and $10^{-5.5}$ ft d^{-1}, respectively, for a numerical model in the central part of the aquifer.

Lateral Variability of Transmissivity and Hydraulic Conductivity

Areally, transmissivity and hydraulic conductivity in the Carrizo-Wilcox aquifer increases from north to south (tables 6 through 9). Counties north of and including Henderson, Anderson, and Houston have geometric mean transmissivity and hydraulic-conductivity values of 450 ft^2d^{-1} and 6.7 ft d^{-1}, respectively (table 9; fig. 16). In comparison, counties south of and including Caldwell and Gonzales have geometric mean transmissivity and hydraulic-conductivity values of 4,200 ft^2d^{-1} and 29 ft d^{-1}, respectively (table 9; fig. 16). This difference is partially due to geology because more water is produced solely from the sandier Carrizo Sand (fig. 4) in the south part of the aquifer (85 percent of the wells) than in the north part (15 percent of the wells).

Prudic (1991) noted greater values of hydraulic conductivity in the southwestern part of the aquifer than in the northeastern part (table 6). As part of a greater study of the Gulf Coast aquifers, he noted values of 43 ft d^{-1} for hydraulic conductivity of the aquifer in all the states in the coastal region, 14 ft d^{-1} for the northeastern part of the Carrizo-Wilcox aquifer in Texas, and 22 ft d^{-1} for the southwestern part of the Carrizo-Wilcox aquifer in Texas (Prudic, 1991)

Carrizo Sand and Wilcox Group transmissivity and hydraulic conductivity values from the TWDB database are spatially correlated (fig. 17). Semivariograms show a decrease in semivariance for smaller separation distances indicating spatial continuity. However, the semivariograms also have relatively large nuggets, especially the semivariograms for transmissivity and hydraulic conductivity in the Wilcox Group, suggesting a large amount of randomness due to local-scale heterogeneity and/or measurement errors.

The range, or the distance within which a parameter is spatially correlated, is about 80,000 to 100,000 ft for transmissivity and hydraulic conductivity in the Carrizo Sand and about 130,000 for transmissivity and hydraulic conductivity in the Wilcox Group (table 10, fig. 17). This means that transmissivity and hydraulic conductivity values measured in the Carrizo Sand

Table 6. Hydraulic conductivity values (ft d^{-1}) reported by Prudic (1991).

Test	*#*	*s*	$\bar{x}_a$	$\bar{x}_h$	$\bar{x}_g$	$P_{0.01}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.99}$
upper Wilcox-lower Clairborne (all states)										
AQ	104	67	70	16	39	0.69	20	43	83	390
SC	151	82	112	16	46	.69	26	47	88	800
COMB	255	76	97	16	43	.84	23	45	84	580
middle Wilcox (all states)										
AQ	213	43	94	5.2	14	.52	5.6	13	40	710
SC	569	48	75	7.4	22	.47	9.9	24	54	430
COMB	782	47	81	6.6	20	.50	8.5	20	51	440
lower Wilcox (all states)										
AQ	58	158	181	32	95	1.0	60	91	170	720
SC	78	129	149	4.2	65	.06	34	77	190	710
COMB	136	141	164	6.6	76	.43	44	84	180	720
Texas Coastal Uplands Aquifer (Texas, Winter Garden area)										
AQ	23	46	59	5.6	18	.61	7.8	17	84	220
SC	43	47	49	7.2	25	.39	13	33	50	180
COMB	66	47	52	6.5	22	.39	9.8	28	54	220
Texas Coastal Uplands Aquifer (Northeast Texas area)										
AQ	185	19	25	5.0	10	.57	5.3	10	23	170
SC	177	27	27	10	18	.79	9.6	17	37	140
COMB	362	23	26	6.6	14	.58	6.9	14	29	140

AQ = T from aquifer tests
SC = T from specific capacity datas
COMB = both together

#	number of tests
s	standard deviation
$\bar{x}_a$	arithmetic mean
$\bar{x}_h$	harmonic mean
$\bar{x}_g$	geometric mean
$P_{0.01}$	1st percentile
$P_{0.25}$	25th percentile
$P_{0.5}$	50th percentile (median)
$P_{0.75}$	75th percentile
$P_{0.99}$	99th percentile

Statistical analysis excludes values above 1,000 ft d^{-1}

Table 7. Transmissivity values (ft^2d^{-1}) from the TWDB database for the different counties in the study area.

	n	25th	50th	75th	90th	$\bar{x}^a$	s^b
Anderson	66	360	860	2,300	3,900	850	0.54
Angelina	4	2,400	2,600	2,900	3,200	2,700	0.09
Atascosa	140	3,500	6,300	9,300	15,000	5,200	0.42
Bastrop	40	670	1,800	3,300	5,500	1,300	0.59
Bexar	16	430	980	2,700	10,000	1,200	0.74
Brazos	12	3,900	6,600	8,400	10,000	4,600	0.40
Burleson	9	930	1,100	2,300	2,400	1,200	0.25
Caldwell	35	140	910	1,700	3,000	560	0.63
Camp	25	210	340	680	980	330	0.45
Cass	5	190	510	610	650	230	0.68
Cherokee	9	220	300	1,300	3,200	410	0.75
Dimmit	24	940	1,200	2,500	3,600	1,400	0.34
Franklin	6	140	650	1,800	3,000	550	0.72
Freestone	16	170	180	260	410	210	0.29
Frio	208	5,400	8,700	13,000	19,000	8,100	0.33
Gonzales	14	820	4,600	6,800	7,900	2,400	0.71
Gregg	11	190	220	370	790	270	0.31
Guadalupe	10	450	1,400	2,700	31,000	1,700	0.79
Harrison	30	150	320	710	1,300	310	0.52
Henderson	9	100	350	370	420	170	0.46
Hopkins	15	150	330	590	680	270	0.40
Houston	5	830	1,400	2,500	3,800	1,500	0.42
Karnes	1	-	-	-	-	-	-
La Salle	7	1,600	2,400	3,100	4,200	2,400	0.23
Lee	8	140	790	2,700	3,700	620	0.73
Leon	20	300	510	1,000	2,500	550	0.46
Limestone	5	650	860	1,100	1,100	620	0.37
Maverick	2	-	-	-	-	120	-
McMullen	2	-	-	-	-	1,400	-
Medina	24	400	1,700	4,600	13,000	1,600	0.66
Milam	10	420	2,100	3,100	3,800	950	0.76
Morris	8	100	180	330	640	210	0.51
Nacogdoches	11	200	450	660	810	380	0.30
Navarro	1	-	-	-	-	1,300	-
Panola	38	160	600	1,000	1,400	440	0.51
Rains	12	160	210	300	640	240	0.28
Robertson	14	440	1,400	2,000	3,500	1,000	0.52
Rusk	105	280	570	1,100	1,900	530	0.45
Sabine	2	-	-	-	-	21	-
San Augustine	1	-	-	-	-	980	-

Table 7. continued

Parameter	**n**	**25th**	**50th**	**75th**	**90th**	$\bar{x}$ [a]	s [b]
Shelby	21	170	460	760	1,500	390	0.42
Smith	90	240	990	3,000	5,000	900	0.64
Titus	6	180	330	830	1,000	310	0.52
Upshur	40	78	170	360	710	190	0.46
Van Zandt	55	150	290	510	690	280	0.39
Webb	4	19	33	120	920	69	1.20
Wilson	120	2,600	5,400	10,000	15,000	4,800	0.47
Wood	61	170	460	1,000	2,700	460	0.55
Zavala	15	4,500	7,500	9,300	12,000	6,000	0.31

[a] Based on log transformation of original data
[b] Log-transformed standard deviation

n number of values
25th 25th percentile
50th 50th percentile (median)
75th 75th percentile
90th 90th percentile
$\bar{x}$ mean
s standard deviation

Table 8. Hydraulic conductivity values (ft d^{-1}) from the TWDB database for the different counties in the study area.

	n	25th	50th	75th	90th	$\bar{x}$[a]	s[b]
Anderson	66	5.1	11.	21.	47.	11.	0.54
Angelina	4	25.	26.	30.	34.	28.	0.10
Atascosa	123	16.	34.	58.	94.	27.	0.49
Bastrop	35	5.6	18.	28.	79.	15.	0.60
Bexar	12	8.7	14.	45.	57.	13.	0.83
Brazos	12	9.1	15.	26.	30.	12.	0.44
Burleson	9	8.0	13.	23.	28.	13.	0.35
Caldwell	30	4.3	14.	48.	80.	12.	0.68
Camp	25	2.8	5.4	9.0	11.	4.7	0.47
Cass	5	0.50	3.4	3.6	4.5	1.4	0.66
Cherokee	8	3.0	5.1	8.6	64.	7.7	0.74
Dimmit	12	3.6	4.0	12.	20.	6.3	0.35
Franklin	6	2.6	12.	28.	45.	8.5	0.76
Freestone	16	2.8	3.5	5.0	6.3	3.5	0.27
Frio	180	23.	37.	85.	170.	43.	0.41
Gonzales	14	24.	55.	230.	390.	60.	0.73
Gregg	11	3.0	4.2	8.4	11.	3.2	0.62
Guadalupe	8	20.	24.	49.	200.	32.	0.58
Harrison	30	2.3	4.3	10.	23.	4.6	0.51
Henderson	5	3.5	4.5	5.8	7.2	4.0	0.31
Hopkins	15	3.9	7.2	11.	15.	6.3	0.32
Houston	5	4.8	7.3	13.	26.	8.9	0.43
Karnes	1	-	-	-	-	9.4	-
La Salle	5	6.1	6.6	9.8	11.	7.5	0.14
Lee	6	1.8	4.7	170.	1300.	21.	1.47
Leon	20	3.5	6.9	10.	27.	6.7	0.44
Limestone	5	4.4	14.	23.	38.	11.	0.59
Maverick	1	-	-	-	-	0.62	-
McMullen	2	-	-	-	-	4.2	-
Medina	10	9.6	17.	44.	70.	14.	0.75
Milam	8	5.5	12.	22.	51.	12.	0.50
Morris	8	1.2	2.2	5.1	13.	2.9	0.62
Nacogdoches	11	3.9	4.8	7.7	9.3	4.9	0.23
Panola	36	2.6	11.	20.	27.	8.1	0.59
Rains	12	3.4	3.9	6.2	11.	5.0	0.26
Robertson	9	4.3	7.0	12.	33.	8.1	0.47
Rusk	93	4.0	7.0	11.	24.	6.8	0.44
Sabine	2	-	-	-	-	0.85	-
San Augustine	1	-	-	-	-	19.	-
Shelby	17	2.9	9.5	24.	36.	9.2	0.52

Table 8. continued

	n	25th	50th	75th	90th	$\bar{x}$[a]	s[b]
Smith	79	4.7	11.	29.	51.	11.	0.56
Titus	6	4.3	9.5	13.	13.	5.9	0.49
Upshur	40	1.2	3.1	7.6	14.	3.1	0.51
Van Zandt	51	2.3	4.8	8.8	13.	4.5	0.45
Webb	3	0.13	1.6	1.7	1.8	0.31	1.28
Wilson	108	19.	37.	69.	150.	33.	0.54
Wood	60	3.0	9.0	19.	55.	8.6	0.60
Zavala	8	22.	48.	89.	150.	42.	0.56

[a] Based on log transformation of original data
[b] Log-transformed standard deviation

n	number of values
25th	25th percentile
50th	50th percentile (median)
75th	75th percentile
90th	90th percentile
$\bar{x}$	mean
s	standard deviation

Table 9. General areal distribution of transmissivity and hydraulic conductivity values.

	n	25th	50th	75th	90th	$\bar{x}$[a]	s[b]
Transmissivity (ft^2d^{-1})							
Northeastern area	635	190.	450.	1,000.	2,600.	450.	0.55
Central area	135	330.	1,000.	2,600.	5,300.	920.	0.61
Southwestern area	624	2,200.	5,800.	10,000.	17,000.	4,200.	0.58
Hydraulic conductivity ($ft\ d^{-1}$)							
Northeastern area	596	3.0	7.0	15.	33.	6.7	0.54
Central area	120	4.1	9.2	22.	44.	9.8	0.59
Southwestern area	517	15.	33.	68.	130.	29.	0.57

Counties north of and including Henderson, Anderson, and Houston Counties define the northeastern area. Counties south of and including Caldwell and Gonzales Counties define the southwestern area. The central area includes counties between the northeastern and southwestern areas.

[a] Based on log transformation of original data
[b] Log-transformed standard deviation.

n number of values
25th 25th percentile
50th 50th percentile (median)
75th 75th percentile
90th 90th percentile
$\bar{x}$ mean
s standard deviation

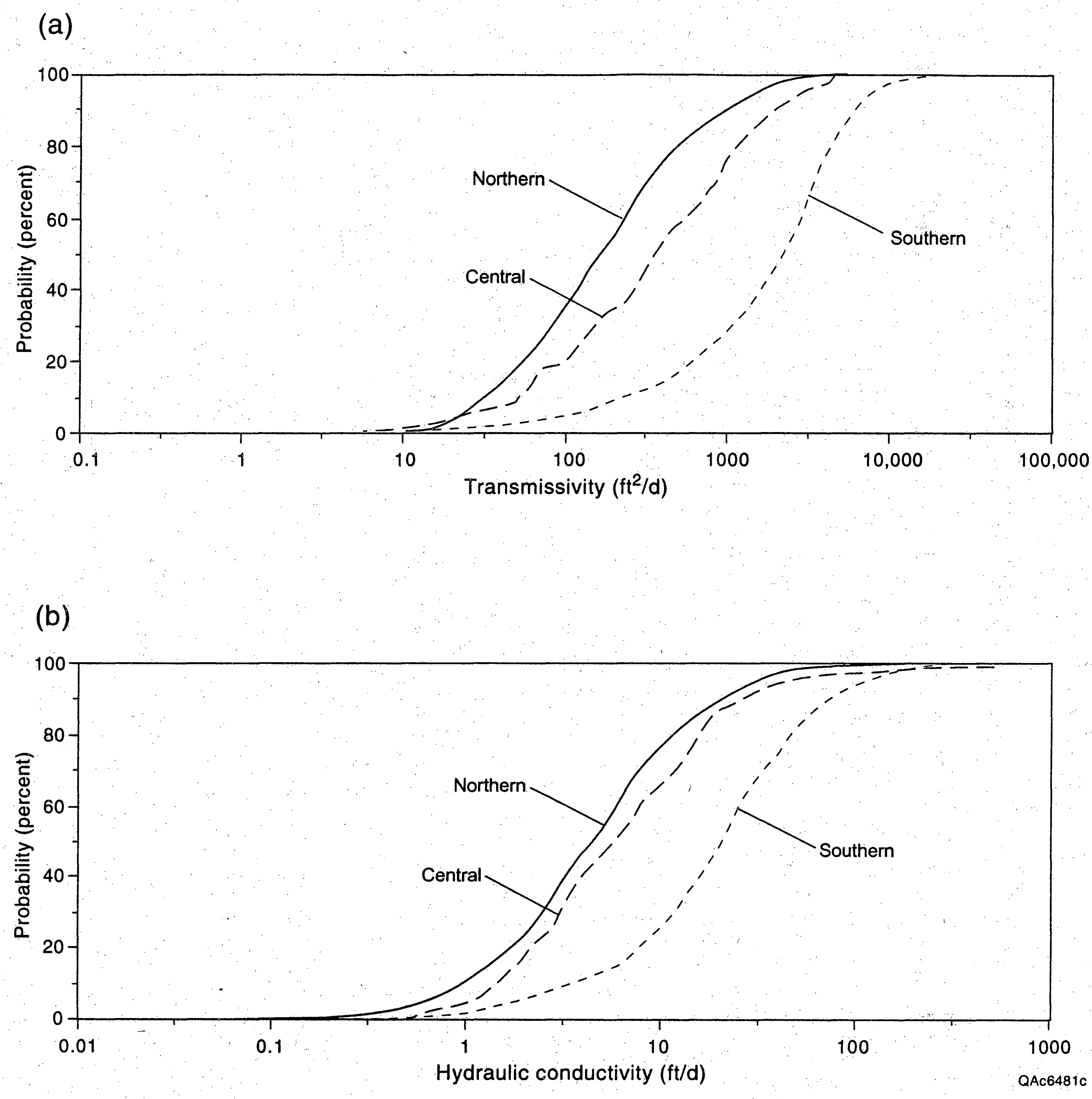

Figure 16. Cumulative distribution functions of transmissivity and hydraulic conductivity for the northern, central, and southern areas of the aquifer.

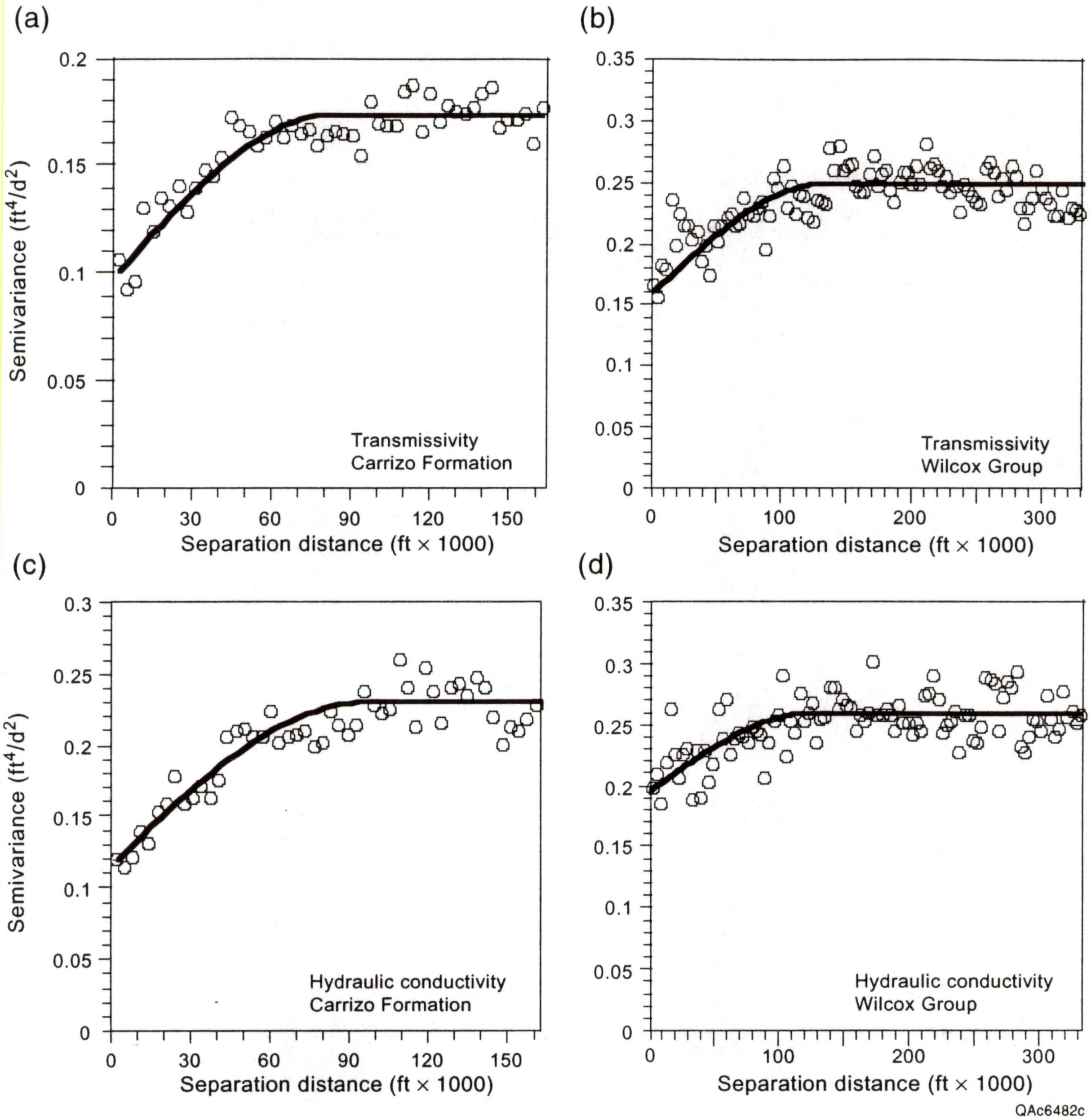

Figure 17. Experimental (dots) and theoretical (lines) semivariograms of transmissivity and hydraulic conductivity in the Carrizo Formation and Wilcox Group.

Table 10. Fitting parameters for the theoretical semivariograms.

	N	*C*	*a*
Transmissivity in Carrizo Sand	0.1	~~0.075~~ .175	82,000
Transmissivity in Wilcox Group	0.16	~~0.09~~ .25	130,000
Hydraulic conductivity in Carrizo Sand	0.11	~~0.12~~ .23	98,000
Hydraulic conductivity in Wilcox Group	0.19	~~0.07~~ .26	130,000

for semivariograms of transmissivity, *N* and *C* have units of ft^4d^{-2}
for semivariograms of hydraulic conductivity, and have units of ft^2d^{-2}
a has units of ft

and the Wilcox Group are similar to other values within about 17 and 25 mi, respectively. Although the range is larger for the Wilcox Group than for the Carrizo Sand, the autocorrelation of transmissivity and hydraulic conductivity in the Carrizo Sand is stronger because there is less of a nugget effect (80 percent of the variance is represented by the nugget for hydraulic conductivity for the Wilcox Group compared with 50 percent for the Carrizo Sand). In other words, we quantify the more homogeneous nature of the Carrizo Sand relative to the Wilcox Group.

Theoretical semivariograms, spherical semivariograms with a nugget effect, were visually fit to the experimental data. The spherical semivariogram, γ is described by

$$\gamma(h) = N + C\left[\frac{3h}{3a} - \frac{h^3}{2a^3}\right] \tag{7}$$

where h is the separation distance, N is the nugget, C is the sill, and a is the range (see fig. 8). Parameters, N, C, and a for the four semivariograms shown in figure 17 are listed in table 10.

Using parameters for the fitted theoretical semivariograms, we used the kriging function in Surfer (GSI, 1995) to contour transmissivity and hydraulic conductivity of the Carrizo Sand and Wilcox Group for tests from the TWDB database. Note that although transmissivity and hydraulic conductivity are contoured for the entire extent of the aquifer, interpolated and extrapolated values are only valid near control points (figs. 18 through 21).

Transmissivity and hydraulic conductivity values for the Carrizo Sand are abundant in (1) the Winter Garden irrigation district area in the southwest part of the aquifer (south of the Nueces River) and (2) in the west part (Sabine Uplift) of the north part of the aquifer (north of the Trinity River) (figs. 18, 19). The Carrizo Sand has higher values of transmissivity and hydraulic conductivity in the southwest part of the aquifer than in the northeast and central parts (figs. 18, 19). The greatest transmissivities and hydraulic conductivities in the Carrizo Sand are

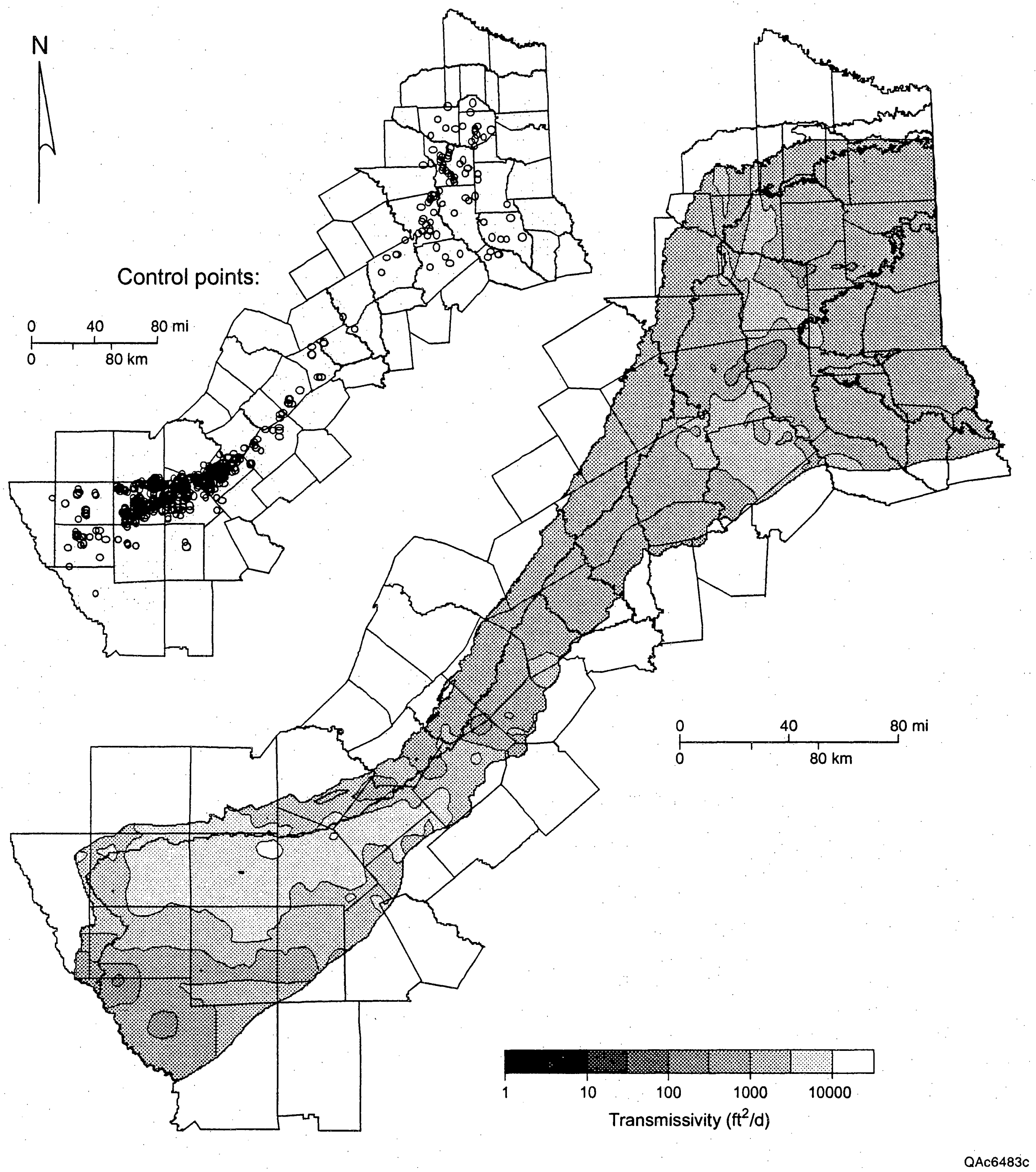

Figure 18. Spatial distribution of transmissivity in the Carrizo Formation using kriging values from the TWDB database. Location of control points shown in upper left-hand corner.

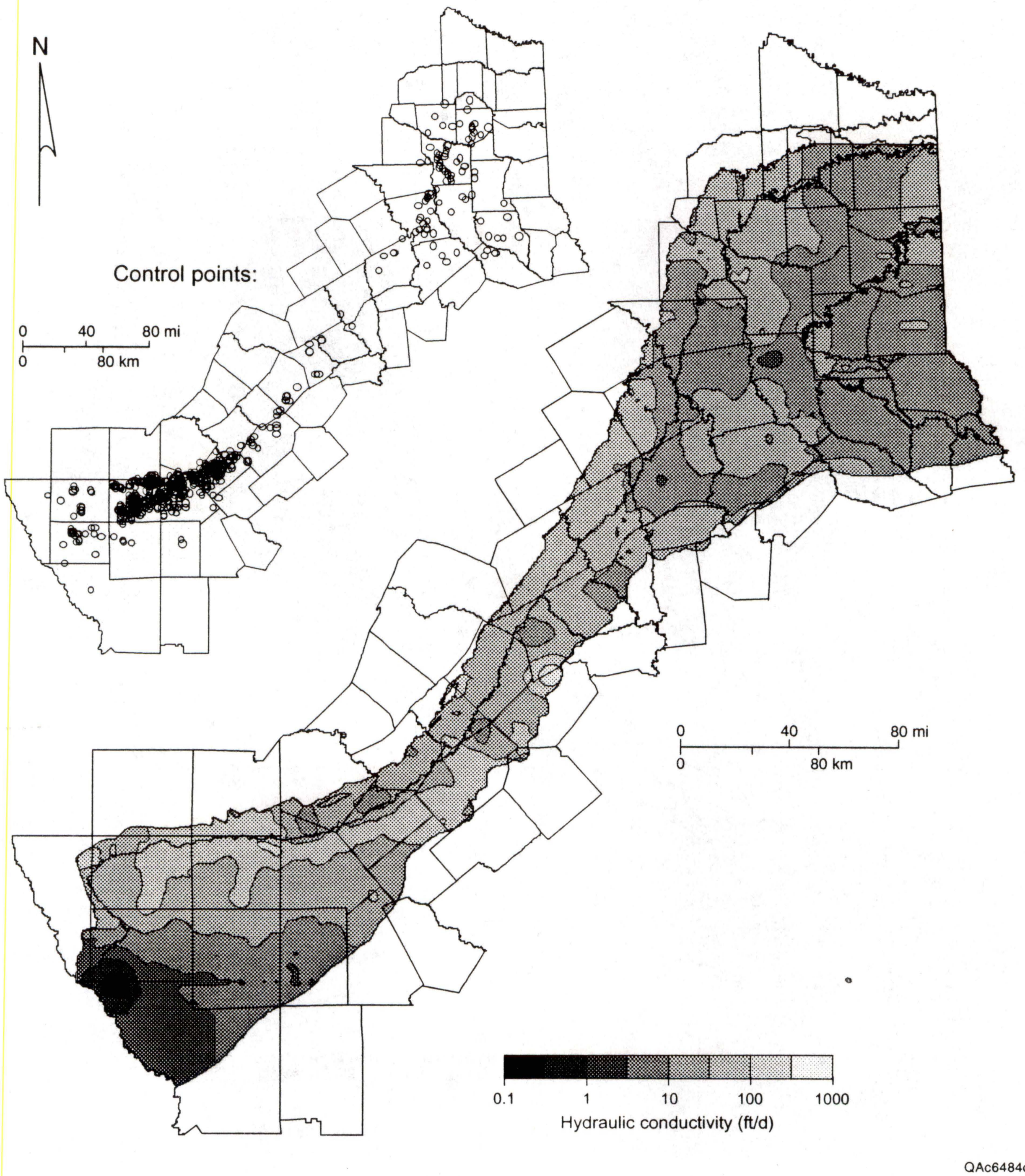

Figure 19. Spatial distribution of hydraulic conductivity in the Carrizo Formation using kriging values from the TWDB database. Location of control points shown in upper left-hand corner.

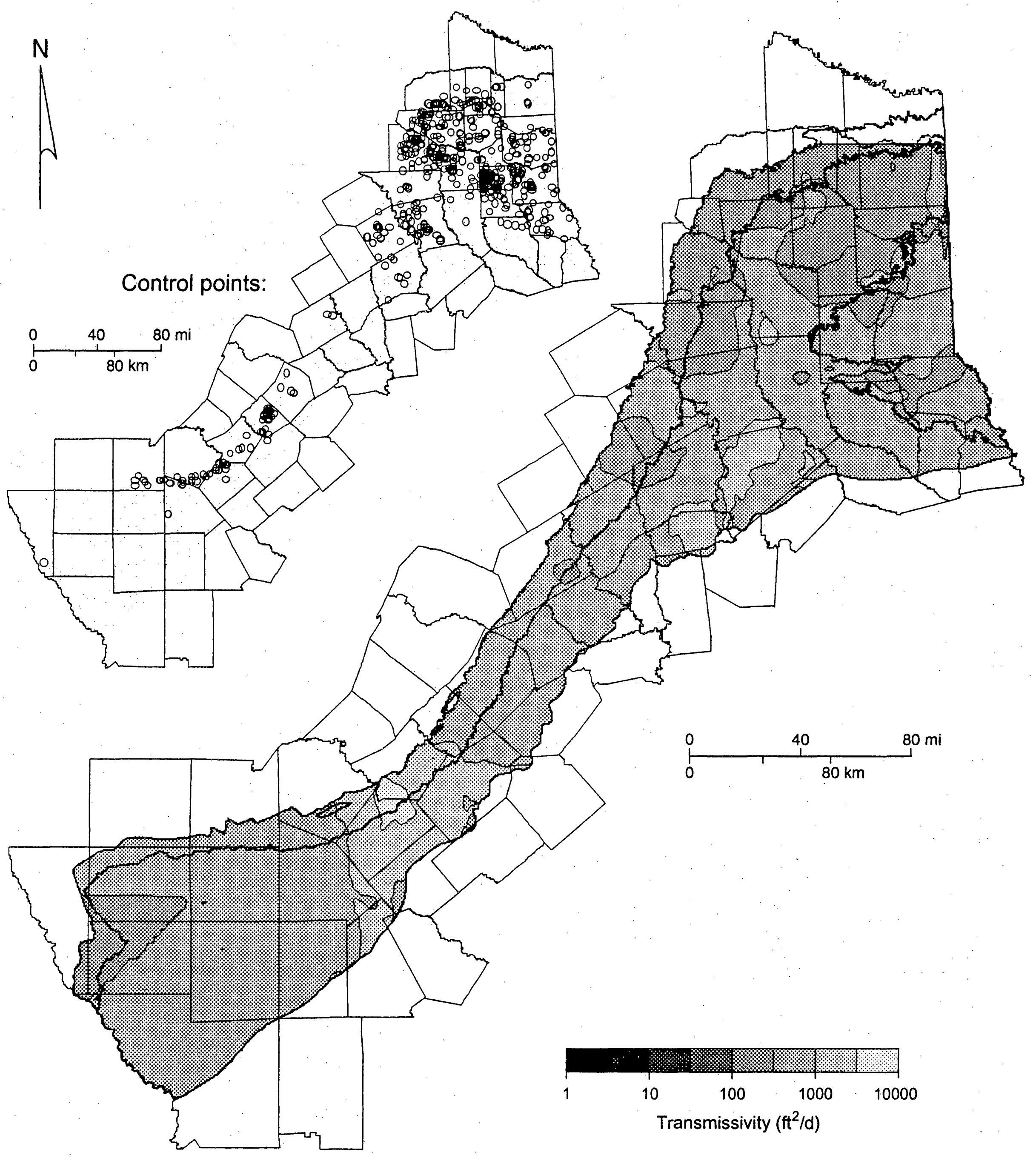

Figure 20. Spatial distribution of transmissivity in the Wilcox Group using kriging values from the TWDB database. Location of control points shown in upper left-hand corner.

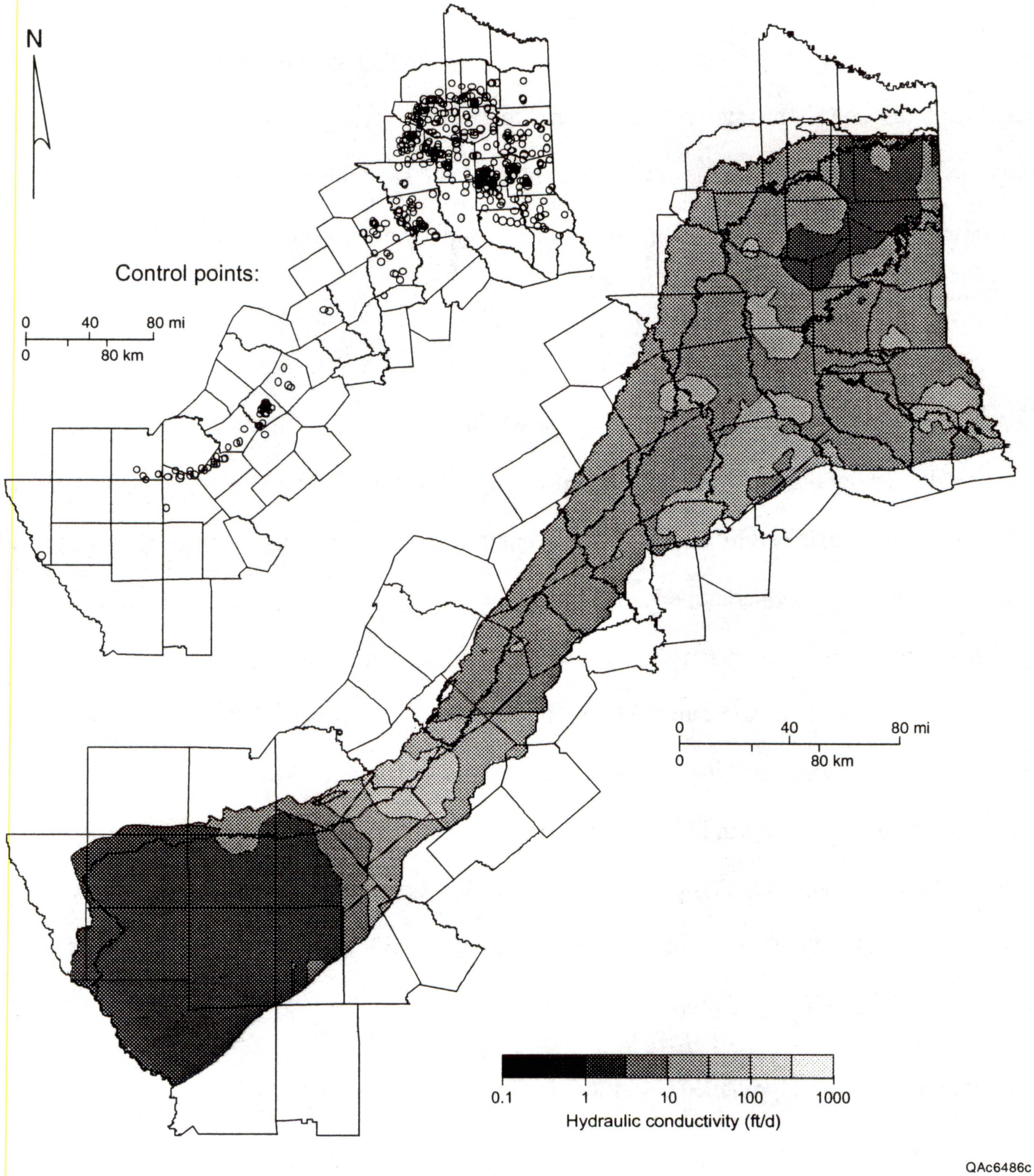

Figure 21. Spatial distribution of hydraulic conductivity in the Wilcox Group using kriging values from the TWDB database. Location of control points shown in upper left-hand corner.

found in Atascosa, Frio, Gonzales, Wilson, and Zavala Counties (figs. 18, 19). This finding is consistent with the observation by Ashworth and Hopkins (1995) that some of the greatest yields are produced in the Carrizo sand in the south, or Winter Garden, area of the aquifer. This localization of higher transmissivity and hydraulic conductivity in the Winter Garden area is also consistent with observed increases in (1) percent sand and sand thickness of the Lower Claiborne-Upper Wilcox aquifer (fig. 4 and table 1) and (2) presence of a very high permeability beach sand deposit (table 1).

Transmissivity and hydraulic conductivity values for the Wilcox Group are abundant in the northeast part of the aquifer (Sabine Uplift) and in the outcrop of the Winter Garden irrigation district area in the southwest part of the aquifer (figs. 20, 21). The Wilcox Group has higher values of transmissivity and hydraulic conductivity in (1) the south-central part of the aquifer just south of the Guadalupe River and (2) the south part of the northeast part of the aquifer, adjacent to the Trinity River (figs. 20, 21). The greatest transmissivities and hydraulic conductivities in the Wilcox Group are found in Caldwell, Guadalupe, Wilson, and parts of Anderson, Leon, and Smith Counties (figs. 20, 21). We expected the Wilcox Group hydraulic values to be higher to the north of the Colorado and south of the Trinity Rivers because this is where the Simsboro Formation is present. The scarcity of control point wells in this area is probably influencing the lower than expected values of transmissivity and hydraulic conductivities of the Wilcox Group kriged data.

Relationship between Hydraulic Conductivity and Sand Thickness

To investigate the possible relationship between hydraulic conductivity and sand thickness, we digitized generalized net sand maps for the upper and lower Wilcox Group published in Bebout and others (1982). We then used the geographic information system to query the net sand map for the net sand in each well test from the TWDB database and tested for a relationship between net sand thickness and hydraulic conductivity. However, of the 642 transmissivity values available for analysis, 41 percent of the well locations were in the outcrop where net-sand values are not available, and 58 percent of the remaining well locations had the same value for net sand. Therefore, we were not able to assess the relationship between regional net-sand thickness and hydraulic properties.

More detailed, local-scale analyses of the relationship between hydraulic conductivity and sand thickness were conducted by several other workers. Payne (1975) investigated the relationship between hydraulic conductivity and sand thickness. He found that for sands deposited in stream channels, the hydraulic conductivity varied directly with the sand thickness. Henry and others (1979, 1980) reported hydraulic conductivities of 20 to 66 ft d^{-1} (6 to 20 m d^{-1}) for the Simsboro and Calvert Bluff sands and 3 to 6 ft d^{-1} (1 to 2 m d^{-1}) for interchannel muds in East Texas. Fogg (1986) found that thicker channel-fill sands in the Wilcox Group were more permeable and continuous than sands deposited in the adjacent floodplain and interchannel basins. Thorkildsen and Price (1991) reported hydraulic conductivities ranging from 20 to 60 ft d^{-1} in the channel sand deposits and 3 to 7 ft d^{-1} in the interchannel muds. Prudic (1991) did not find a conclusive relationship between hydraulic conductivity and sand thickness for the entire region.

STORATIVITY

We were able to compile 107 values of storativity and calculate 68 values of specific storage (storativity divided by the screen length) for the Carrizo-Wilcox aquifer. Of the storativity values, we compiled 64 percent from TRRC files of pumping and slug tests at lignite mines. Eleven of the values compiled from TRRC files were determined from slug tests.

Storativity and specific storage both approximate log-normal distributions (fig. 22). Storativity ranges from about 10^{-6} to 10^{-1}, with a geometric mean of 3.0×10^{-4} (fig. 22a; table 11). These results cover the range of expected unconfined, semiconfined, and confined values of storativity. Specific storage ranges from about 10^{-7} to 10^{-3} with a geometric mean of 4.5×10^{-6} (fig. 22b; table 11). Lower values of storativity and specific storage tend to occur at shallow depths, as would be expected with unconfined conditions (fig. 23). However, semiconfined to confined storativities (values less than 0.01) also occur at shallow depths (fig. 23). We did not see patterns in differences of geometric mean storage values for different data sources, test methods, or formations.

Several researchers have reported on the storage properties of the Carrizo-Wilcox aquifer. Follett (1970) reported storativities in the Carrizo-Wilcox aquifer that range from 0.0003 to 0.0006. Klemt and others (1976) reported an average unconfined storativity (specific yield) of 0.25 and an average confined storativity of 0.0005 for the Carrizo aquifer. Duffin and Elder (1979) used seismic refraction along 20 profiles to estimate specific yield in the Carrizo Sand in South Texas (west of Gonzales County) and found values that range between 0.05 and 0.35. They found higher values (0.26 to 0.32) east of the Frio River and lower values (0.16 to 0.24) west of the Frio River. Thorkildsen and others (1989) estimated confined storativity to range between 10^{-5} and 10^{-3} and unconfined storativity (specific yield) to range between 0.05 and 0.3. Prudic (1991) assumed that (1) the storativity was 0.15 for well depths or top of screened interval shallower than 150 ft, and (2) the specific storage was 4×10^{-6} ft^{-1} for well depths greater than 150 ft. Thorkildsen and Price (1991) reported confined storativities to range between 10^{-2} and 10^{-5} and unconfined storativity to range from 0.1 to 0.3. Ryder (1996) estimated that the unconfined storativity ranges between 0.1 and 0.3 and the confined storativity ranges between 1.0×10^{-4} and 1.5×10^{-3}.

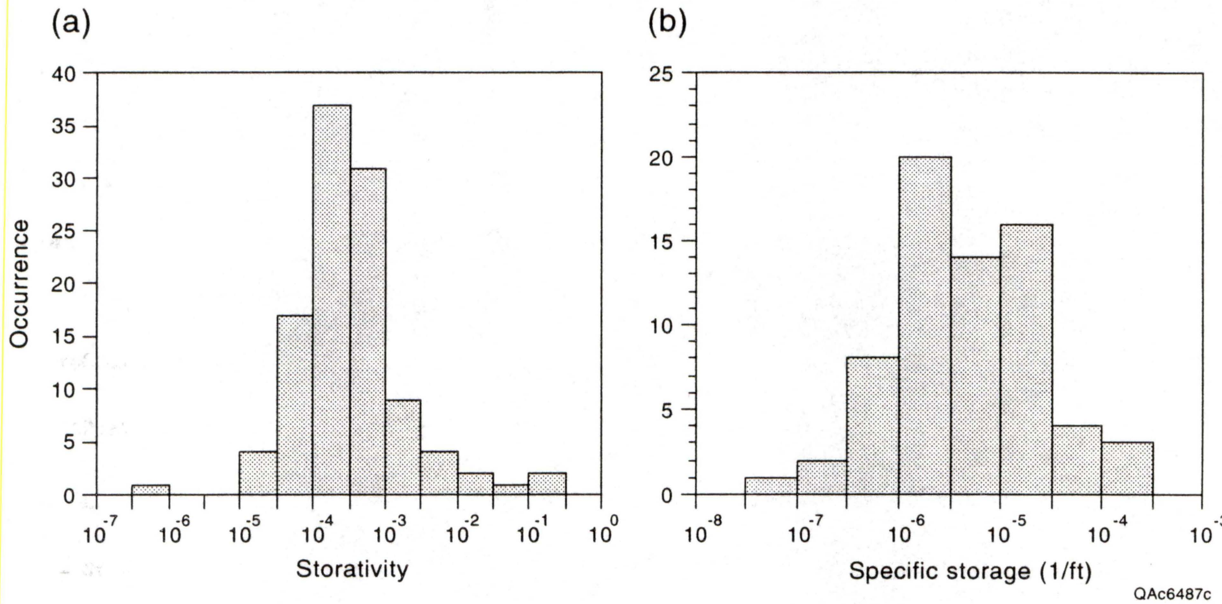

Figure 22. Histograms of storativity and specific storage for the Carrizo-Wilcox aquifer.

Table 11. Storativity and specific storage (ft^{-1}) values for the Carrizo-Wilcox aquifer.

	n	25th	50th	75th	90th	$\bar{x}$ [a]	s [b]
Storativity (-)	108	$10^{-4.00}$	$10^{-3.52}$	$10^{-3.22}$	$10^{-2.60}$	$10^{-3.52}$	0.78
Specific storage	68	$10^{-5.83}$	$10^{-5.35}$	$10^{-4.81}$	$10^{-4.49}$	$10^{-5.34}$	0.69

[a] Based on log transformation of original data
[b] Log-transformed standard deviation.

n number of values
25th 25th percentile
50th 50th percentile (median)
75th 75th percentile
90th 90th percentile
$\bar{x}$ mean
s standard deviation

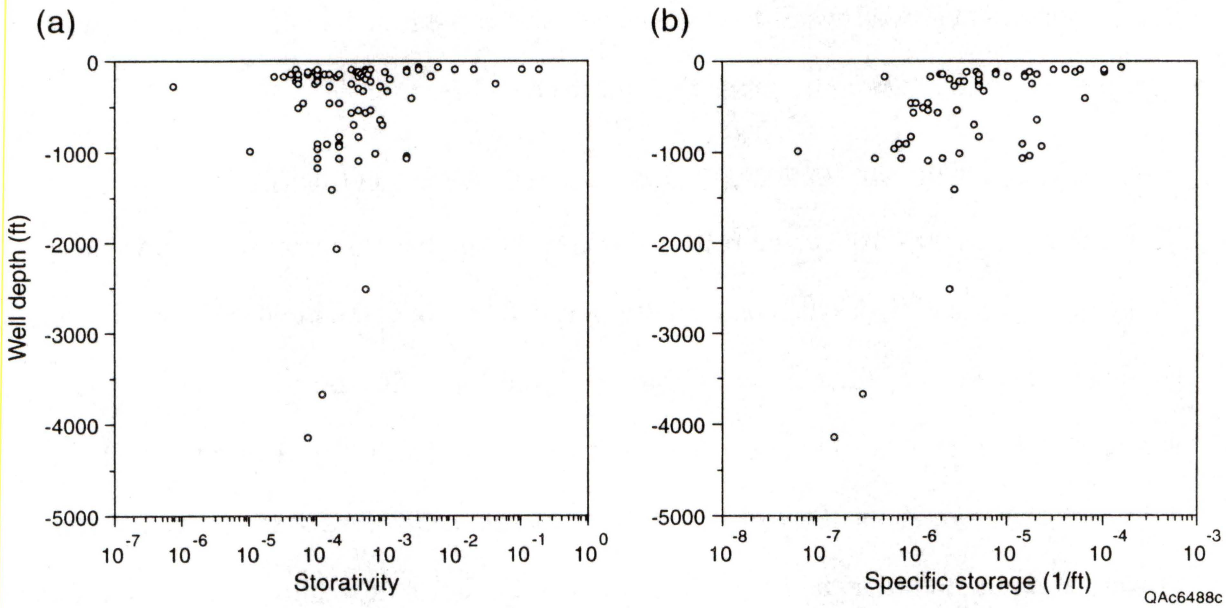

Figure 23. Variation of storativity and specific storage with depth.

Conclusions

In addition to compiling a large data base of hydraulic properties, this study quantifies the variability and spatial distribution of transmissivitity, hydraulic conductivity, and storativity and reviews previous hydrogeologic studies of the units that compose the Carrizo-Wilcox aquifer. We think the results of this study will be useful for developing local and regional water plans and developing numerical ground-water-flow models to predict the future availability of the water resource. The main conclusions of our analysis of the data base are:

1. Transmissivity, hydraulic conductivity, and storativity are log-normally distributed. Transmissivity ranges from about 0.1 to 10,000 ft^2d^{-1} and has a geometric mean value of about 300 ft^2d^{-1}, and hydraulic conductivity ranges from about 0.01 to 4,000 ft d^{-1} and has a geometric mean value of about 6 ft d^{-1}. Storativity and specific storage both approximate log-normal distributions and range from about 10^{-6} to 10^{-1} with a geometric mean of 3.0×10^{-4} and from about 10^{-7} to 10^{-3} with a geometric mean of 4.5×10^{-6}, respectively. Lower values of storativity and specific storage tend to occur at shallow depths, as would be expected with unconfined conditions. We did not see differences of geometric mean storage values for different data sources, test methods, or geologic formations.

2. Different data sources and testing procedures may be biased and result in different statistical distributions of transmissivity and hydraulic conductivity. Tests from TNRCC and TRRC files have geometric mean transmissivity and hydraulic conductivity values that are about 10 and 4 times lower, respectively, than tests from the TWDB data base, water utilities, and reference sources. This difference is due in part to the wide range in geologic environments tested and the types of wells (municipal versus private) tested.

3. Transmissivity and hydraulic conductivity vary vertically among formations and laterally within formations. The Simsboro and Carrizo Sands have transmissivity and hydraulic-conductivity values that are 2.5 to 11 times higher and 2 to 6 times higher, respectively, than does the Cypress aquifer (Wilcox Group, Carrizo Sand, Reklaw Formation, and Queen City Sand in northeast Texas), Calvert Bluff Formation, and Wilcox Group.

4. Lateral variations of transmissivity and hydraulic conductivity have spatial continuity. Semivariograms show that transmissivity and hydraulic-conductivity values in the Carrizo Sand and Wilcox Group are spatially correlated over about 17 and 25 mi, respectively. However, the semivariograms also have relatively large nuggets, especially for tests from the Wilcox Group, suggesting a large amount of randomness due to local-scale heterogeneity and measurement errors. Kriged maps of transmissivity and hydraulic conductivity show the greatest values for the Carrizo Sand in the Winter Garden area and the greatest values for the Wilcox Group in the south-central and northeast parts of the study area.

Acknowledgments

The work described in this report was sponsored by the Texas Water Development Board. We thank the municipal and industrial ground-water users and water-supply companies that shared their data and thoughts with us. We thank Mr. David Thorkildsen of the TWDB for sharing the hydraulic-conductivity data estimated from well logs for the TWDB models of the Carrizo-Wilcox aquifer. We also thank the friendly staff at the TWDB, TRRC, and the TNRCC for their help in retrieving data from their files. Report illustrations were prepared by Jana Robinson under the direction of Joel L. Lardon, Graphics Manager. Word processing was done by Susan Lloyd, and Lana Dieterich edited the report under the supervision of Susan Doenges.

Acronyms

BEG	Bureau of Economic Geology
TNRCC	Texas Natural Resource Conservation Commission
TRRC	Texas Railroad Commission
TWDB	Texas Water Development Board
USGS	U.S. Geological Survey

References

Ashworth, J. B., and Hopkins, Janie, 1995, Aquifers of Texas: Texas Water Development Board Report 345, 69 p.

Ayers, W. B. and Lewis, A. H., 1985, The Wilcox Group and Carrizo Sand (Paleogene) in east-central Texas: depositional systems and deep-basin lignite: University of Texas at Austin, Bureau of Economic Geology Special Publication, 19 p., 30 pl.

Barnes, V. E., 1970, Waco sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

________ 1974, Austin sheet: University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Bebout, D. G., Weise, B. R., Gregory, A. R., and Edwards, M. B., 1982, Wilcox Sandstone reservoirs in the deep subsurface along the Texas Gulf Coast; their potential for production of geopressured geothermal energy: University of Texas at Austin, Bureau of Economic Geology Report of Investigations No.117, 125 p.

Broom, M. E., Alexander, W. H., and Myers, B. N., 1965, Ground-water resources of Camp, Franklin, Morris, and Titus Counties, Texas: Texas Water Commission Bulletin 6517, 153 p.

Broom, M. E., 1966, Ground-water resources of Harrison County, Texas: Texas Water Development Board Report 27, 75 p.

________ 1968, Ground-water resources of Wood County, Texas: Texas Water Development Board Report 79, 89 p.

________ 1969, Ground-water resources of Gregg and Upshur Counties, Texas: Texas Water Development Board Report 101, 83 p.

Brown, R. H., 1963, Estimating the transmissivity of an artesian aquifer from the specific capacity of a well: U.S. Geological Survey Water Supply Paper 1536-I, p. 336-338.

Clark, Isobel, 1979, Practical geostatistics: Applied Science Publishers, Limited, London, 129 p.

Cooper, H. H., Jr., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history: American Geophysical Union Transactions, v. 27, p. 526-534.

Duffin, G. L., and Elder, G. R., 1979, Variations in specific yield in the outcrop of the Carrizo Sand in South Texas as estimated by seismic refraction: Texas Department of Water Resources Report 229, 56 p.

Dutton, A. R., 1999, Groundwater availability in the Carrizo-Wilcox aquifer in Central Texas- numerical simulations of 2000 through 2050 withdrawal projections: University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 256, 53 p.

Elder, G. R., and Duffin, G. L., 1980, Records of wells, water levels, pumpage, and chemical analysis of water from the Carrizo aquifer in the Winter Garden area, Texas: Texas Department of Water Resources Report 254, 127 p.

El-Naqa, A., 1994, Estimation of transmissivity from specific capacity data in fractured carbonate rock aquifer, central Jordan: Environmental Geology, v. 23, no. 1, p. 73-80.

Fisher, R. S., Mace, R. E., and Boghici, Erika, 1996, Ground-water and surface-water hydrology of Camp Swift, Bastrop County, Texas: The University of Texas at Austin, Bureau of Economic Geology, final report for the Adjutant General's Department of Texas, Texas Army National Guard and the Nature Conservancy of Texas, 53 p.

Fogg, G. E., 1986, Groundwater flow and sand body interconnectedness in a thick, multiple-aquifer system: Water Resources Research, v. 22, no. 5, p. 679-694.

________ 1980, Aquifer modeling of the Oakwood salt dome area, *in* Geology and geohydrology of the East Texas Basin; a report on the progress of nuclear waste isolation feasibility studies: University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-7, p. 139-149.

Follett, C. R., 1966, Ground-water resources of Caldwell County, Texas: Texas Water Development Board Report 12, 138 p. + 3 pl.

________ 1970, Ground-water resources of Bastrop County, Texas: Texas Water Development Board Report 109, 138 p.

Galloway, W. E., Liu, Xijin, Travis-Neuberger, Deborah, and Xue, Liangqing, 1994, Reference high-resolution correlation cross sections, Paleogene section, Texas Coastal Plain: University of Texas at Austin, Bureau of Economic Geology, 19 p., 4 pl.

Gaylord, J. L., Slade, R. M., Jr., Ruiz, L. M., Welborn, C. T., and Baker, E. T., Jr., 1985, Water resources appraisal of the Camp Swift lignite area, Central Texas: U.S. Geological Survey, Water-Resources Investigations Report 84-4333, 164 p.

Grubb, H. F., and Carillo, J. J., 1988, Region 23, Gulf of Mexico coastal plain, *in* Back, W., Rosenshein, J. S., and Seaber, P. R., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America v. O-2, p. 219-228.

GSI, 1995, Surfer (Win32) Version 6.01, Surface Mapping System: Golden, Colorado, Golden Software, Inc., software.

Guyton, W. E., 1942, Results of pump tests in wells at Camp Swift, Texas: U.S. Geological Survey, Open File Report, 27 p.

Guyton, W. F. & Associates, 1972, Ground-Water conditions in Andson, Cherokee, Freestone, and Henderson Counties, Texas: Texas Water Development Board Report 150, 250 p.

Guyton and Associates, 1998, Interaction between ground water and surface water in the Carrizo-Wilcox aquifer: Final contract report prepared for the Texas Water Development Board by LBG-Guyton and Associates in association with HDR Engineering, Inc., variously paginated.

Hamlin, H. S., 1988, Depositional and ground-water flow systems of the Carrizo-Upper Wilcox, South Texas: University of Texas at Austin, Bureau of Economic Geology Report of Investigations, No. 175, 61 p.

Henry, C. D., Basciano, J. M., and Duex, T. W., 1979, Hydrology and water quality of the Eocene Wilcox Group; significance for lignite development in East Texas: Transactions - Gulf Coast Association of Geological Societies, v. 29, p. 127-135.

________ 1980, Hydrology and water quality of the Eocene Group- significance for lignite development in east Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-3, 9 p.

Hosman, R. L. and Weiss, J. S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416-B, variously paginated, 19 pl.

Hovorka, S. D., Mace, R. E., and Collins, E. W., 1995, Regional distribution of permeability in the Edwards Aquifer: University of Texas at Austin, Bureau of Economic Geology, Final contract report to the Edwards Underground Water District under contract no. 93-17-FO, 126 p

________ 1998, Permeability structure of the Edwards aquifer, south Texas- Implications for aquifer management: University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 250, 55 p.

Huntley, David, Nommensen, Roger, and Steffey, Duane, 1992, The use of specific capacity to assess transmissivity in fractured-rock aquifers: Ground Water, v. 30, no. 3, p. 396-402.

Jackson, M. P. A., 1982, Fault tectonics of the East Texas Basin: University of Texas at Austin, Bureau of Economic Geology Circular 82-4, 31p.

Kaiser, W. R., 1974, Texas lignite: near-surface and deep basin resources: University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 79, 70 p.

Kier, R. S., and Larkin, R. G., 1998, Hydrogeology of the Carrizo-Wilcox aquifer system- Bastrop, Caldwell, Fayette, Lee, Travis, and Williamson Counties: preliminary report prepared for the Aqua Water Supply Company, Bastrop, Texas: Robert S. Kier Consulting, variously paginated.

Klemt, W. B., Duffin, G. L., and Elder, G. R., 1976, Ground-water resources of the Carrizo aquifer in the Winter Garden area of Texas, volume 1: Texas Water Development Board report 210, 30 p.

Kruseman, G. P. and de Ridder, N. A., 1990, Analysis and evaluation of pumping test data, 2nd edition: Wageningen, The Netherlands, International Institute for Land Reclamation and Improvement, 377 p.

Mace, R. E., 1995, Geostatistical description of hydraulic properties in karst aquifers, a case study in the Edwards Aquifer: in Charbeneau, R. J., ed., *Groundwater Management*, Proceedings of the International Symposium: Water Resources Engineering Division, American Society of Civil Engineers, American Society of Civil Engineers, p. 193-198.

Mace, R. E., 1997, Determination of transmissivity from specific capacity data in a karst aquifer, Ground Water, v. 35 no. 5, p. 738-742.

Mace, R. E., in review, Using specific-capacity data in hydrogeologic investigations: UT BEG.

Mace, R. E., Nance, H. S., and Dutton, A. R., 1994, Geologic and hydrogeologic framework of regional aquifers in the Twin Mountains, Paluxy, and Woodbine Formations near the SSC site, North-Central Texas: Draft topical report submitted to the TNRLC under contract no. IAC(92-93)-0301 and no. IAC 94-0108, 48 p.

Marquardt, G., and Rodriguez, E. Jr., 1977, Ground water resources of the Carrizo Aquifer in the Winter Garden area of Texas: Texas Water Development Board Report 210, 466 p.

Matheron, G., 1979, Principles of geostatistics: Economic Geology, v. 58, p. 1246-1266.

McCoy, T. W, 1991, Evaluation of the ground-water resources of the Western Portion of the Winter Garden area, Texas: Texas Water Development Board, Report 334, 64 p.

McCuen, R. H., and Snyder, W. M., 1986, Hydrologic modeling: statistical methods and applications: Englewood Cliffs, New Jersey, Prentice Hall, 568 p.

Mullican, W. F., III, Johns, N. D., and Fryar, A. E., 1997, Playas and recharge of the Ogallala aquifer on the southern High Plains of Texas- an examination using numerical techniques: University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 242, 72 p.

Myers, B. N., 1969, Compilation of results of aquifer tests in Texas: Texas Water Development Board Report 98, 532 p.

Payne, J. N., 1975, Geohydrologic significance of lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas and the Meridian Sand of Mississippi: U.S. Geological Survey Professional Paper, P 0569-D, 11 p.

Prudic, D. E., 1991, Estimates of hydraulic conductivity from aquifer-test analyses and specific-capacity data, Gulf Coast regional aquifer systems, south-central United States: U. S. Geological Survey, Water-Resources Investigations, WRI 90-4121, 38 p.

Razack, M., and Huntley, David, 1991, Assessing transmissivity from specific capacity in a large and heterogeneous alluvial aquifer: Ground Water, v. 29, no. 6, p. 856-861.

Ryder, Paul, 1996, Ground water atlas of the United States- Oklahoma, Texas: - U.S. Geological Survey, HA 730-E, variously paginated.

Ryder, P. D., 1988, Hydrogeology and predevelopment flow in the Texas Gulf Coast Aquifer System, U.S. Geological Survey Water Resource Investigations Report 87-4248, 109 p.

Tarver, G. E., 1966, Ground-water resources of Houston county, Texas: Texas Water Development Board Report 18, 86 p. + 2 pl.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, v. 16, p. 519–524.

________ 1963, Estimating the transmissivity of a water-table aquifer from the specific capacity of a well: U.S. Geological Survey Water Supply Paper 1536-I, p. 332-336.

Theis, C. V., Brown, R. H., and Myers, R. R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells. Methods of determining permeability, transmissivity, and drawdown: U.S. Geological Survey Water Supply Paper, 1536-I.

Thomasson, H. J., Olmstead, F. H., and LeRoux, E. R., 1960, Geology, water resources, and usable ground water storage capacity of part of Solano County, CA: U.S. Geological Survey Water Supply Paper 1464, 693 p.

Thorkildsen, D., and Price, R. D., 1991, Ground-water resources of the Carrizo-Wilcox aquifer in the Central Texas Region: Texas Water Development Board Report 332, variously paginated.

Thorkildsen, D., Quincy, R., and Preston, R., 1989, A digital model of the Carrizo-Wilcox aquifer within the Colorado River basin of Texas: Texas Water Development Board Report LP-208, 59 p.

Villaescusa, E., and Brown, E. T., 1990, Characterizing joint spatial correlation using geostatistical methods *in* Barton, Nick, and Stephansson, Ove, Rock joints, Brookfield, Vermont, Proceedings of the International Symposium on Rock Joints, Loen, Norway: A. A. Balkema Publishers, p. 115-122.

Walton, W. C., 1970, Groundwater resource evaluation: New York, McGraw-Hill.

Appendix A:

List of Cities and water utilities responding to the survey

No.	City	Utility
1	College Station	City of College Station
2	Hallsville	City of Hallsville
3	Seguin	Springs Hill Water Supply Corporation
4	Caldwell	City of Caldwell
5	Carrizo Springs	City of Carrizo Springs
6	Hemphill	South Sabine Water Supply Corporation
7	Mt. Vernon	Cypress Springs Water Supply Corporation
8	Cauton	Crooked Creek Water Supply Corporation
9	Stockdale	Sunko Water Supply Corporation
10	Alba	Bright Star-Salem Water Supply Corporation
11	Kilgore	Liberty City Water Supply Corporation
12	Carrizo Springs	Carrizo Hill Water Supply Corporation
13	Marshall	Cypress Valley Water Supply Corporation
14	Cotulla	City of Cotulla
15	Teague	City of Teague
16	Brownsboro	Edom Water Supply Corporation
17	Stockdale	City of Stockdale
18	Eustace	Purtis Creek State Park
19	Waskom	City of Waskom
20	Waskom	Waskom Rural Water Supply Corporation
21	Carrison	City of Carrison
22	Nacogdoches	Lilly Grove Water Supply Corporation
23	Wills Point	MacBee Water Supply Corporation
24	Dale	Dale Water Supply Corporation
25	McDade	Bastrop County W.C.I.D
26	Yantis	City of Yantis
27	Gladewater	Union Grove Water Supply Corporation
28	New Summerfield	City of New Summerfield
29	San Antonio	Texas Department of Transportation
30	Mineola	City of Mineola
31	Centerville	Southeast Water Supply Corporation
32	Catarina	Catarina Water Supply Corporation
33	Henderson	Chalk Hill Special Utility District
34	Grapeland	City of Grapeland
35	-	TRI-County Supply Corporation
36	Lufkin	City of Lufkin Water Utilities Department
37	Lufkin	M & M Water Supply Corporation
38	Etoile	Etoile Water Supply Corporation

Appendix A (cont.)

No.	City	Utility
39	Athens	City of Athens
40	Jacksonville	City of Jacksonville
41	Huntsville	Texas Department of Criminal Justice Office of Environmental
42	Marlin	TRI-County SUDAppendix A: