ABSTRACT

This report documents one of three overlapping, quasi-three-dimensional, numerical models of the occurrence and movement of groundwater in the Carrizo–Wilcox aquifer in Texas. The model was developed as part of a Texas Groundwater Availability Modeling (GAM) program to assist in evaluating groundwater availability and water levels in response to potential droughts and future pumping, including new well fields. Formations of the Paleocene-Eocene-age Wilcox Group, along with the overlying Carrizo Formation, make up a major aquifer system in Texas. This model covers the central section of the Carrizo–Wilcox aquifer as defined by the surface-water divide between the San Antonio and Guadalupe Rivers to the southwest and the surface-water divide between the Trinity and Neches Rivers to the northeast. Groundwater withdrawal from the central part of the Carrizo–Wilcox aquifer accounted for approximately 36 percent of all pumping from the aquifer in 2000.

The model is based on data on geological structure and depositional setting of the aquifer, hydrological properties, water-use survey estimates of historical groundwater withdrawals, and base flow of rivers and streams. New insights into how the downdip circulation of freshwater is affected by fault zones and a deep-basin geopressured zone are based on maps of total dissolved solids and equivalent water levels from the outcrop to depths of more than 10,000 ft. In addition, results of field studies using "environmental" tracers yielded regional estimates of recharge rates that broadly match estimates from previous models.

The six-layer model was developed using MODFLOW-96 and includes four layers representing groundwater in the Simsboro and Carrizo Formations, the main flow units of the

Carrizo–Wilcox aquifer system, and in the Hooper and Calvert Bluff Formations, which locally act as confining layers or aquitards within the Carrizo–Wilcox aquifer. During the past 2 decades, about 90 percent of the water pumped from the aquifer was from the Simsboro and Carrizo Formations. Another confining unit, representing the overlying Reklaw Formation, was included as a bounding layer in which water levels in the Queen City aquifer were applied. We also included a layer representing alluvium along the Colorado, Brazos, and Trinity Rivers in the outcrop of the Carrizo–Wilcox aquifer. The Simsboro and Carrizo Formations contribute base flow to these rivers, but discharge is indirect, through the alluvium, rather than directly to stream beds.

A steady-state model representing "predevelopment" (no pumping) conditions was calibrated against water levels measured prior to 1950 and historical low-flow measurements in streams. A transient version of the model with 1-yr-long stress periods was calibrated against water-level hydrographs and stream-flow data for the period from 1950 through 1990, with an emphasis on 1990 data. The calibrated model was verified by comparison with water levels recorded during the 1990s, with an emphasis on 2000 data. During the 1980s and 1990s the years with the smallest rainfall were 1988 and 1996 in the study area. Model runs were made with monthly stress periods for the 36 months from 1987 through 1989 and from 1995 through 1997 to check how simulated water level responds to short-term variation in recharge and pumping rates. Recharge rates, vertical hydraulic conductivity, specific storage, specific yield, and boundary-flux properties were calibrated using the model. We considered horizontal hydraulic conductivity to be one of the more well-known attributes of the aquifer, given the number of pumping- and specific-capacity tests and the quality of regional mapping of the distribution and thickness of sandstones that make up the permeable architecture of the aquifer. Uncertainty in calibrated water levels is less than or equal to 10 percent of the range of water-level measurements.

To demonstrate the use of the groundwater model as an evaluative and predictive tool, several simulations were made of future water-level changes with assumed periods of normal and drought-of-record precipitation. Future rates of groundwater withdrawal were assigned on the basis of demand numbers from eight Regional Water Planning Groups.

Groundwater pumpage is expected to continue to increase between 2000 and 2050, but at a slower rate than that of the past decade. Pumping rates will continue to increase from the Bryan-College Station well field but will be fairly steady from the Lufkin-Angelina County well field. Additional well fields, including municipal well fields, will be established or grow. Many municipalities and industries will meet future needs by drilling new wells and increasing their withdrawal from the Carrizo–Wilcox aquifer. Mining operations will continue to extract a significant volume of groundwater, but after increasing in withdrawal rate during the period from 1990 through 2010, pumping rates related to mining are expected to remain steady or decrease. Overall, total pumping from the Carrizo–Wilcox aquifer in the study area is expected to increase from 194,000 acre-feet per year in 2000 to over 360,000 acre-feet per year in 2050.

The simulated decline of water level related to groundwater pumping will occur mainly through a decrease in artesian storage. The pressure head of groundwater is simulated to remain above the top of aquifer layers except where the confined aquifer is at shallow depths near the outcrop. The model also suggests that the major rivers will continue to receive groundwater discharge even with increased pumping and under drought conditions. Model predictions for 2050 using average recharge versus drought-of-record recharge result in only a few feet of simulated water-level differences in the outcrop.

1.0 INTRODUCTION

The Carrizo–Wilcox aquifer is one of nine major aquifers in Texas and extends across the state from the Rio Grande in the south, northeastward into Arkansas and Louisiana, parallel to the Gulf Coast aquifer (Ashworth and Hopkins, 1995). This aquifer supplies water to approximately 60 counties. Groundwater production is predominantly for municipal public-water supply, manufacturing, and rural domestic use. The largest areas of municipal use are in the Bryan-College Station, Lufkin-Nacogdoches, and Tyler areas, all of which use groundwater from the Carrizo–Wilcox aquifer. A significant volume of groundwater in the central part of the aquifer is extracted as part of lignite mining operations. Irrigation pumping from the Carrizo–Wilcox aquifer is greatest in the Wintergarden region in South Texas. Water use in 1997 amounted to 430,000 acre-feet/yr, exceeded only by the Gulf Coast and Ogallala aquifers (Texas Water Development Board [TWDB], 2002).

Planning for water needs for the period from 2000 through 2050 is critical for the State of Texas because of the frequency of droughts. The State Water Plan (TWDB, 2002) describes the development, management, and conservation of water resources and preparation for potential droughts (TWDB, 2002). The most recently published State Water Plan differs from previous Texas water plans in that it is a result of a bottom-up rather than top-down approach and represents the management strategies adopted by the 16 Regional Water Planning Groups in Texas. Estimating groundwater availability for the 50-yr planning period in Texas involves aquifer management goals, environmental issues, rules and regulations, and scientific understanding of how an aquifer works (Mace and others, 2000b).

Groundwater availability assessment is important for the Carrizo–Wilcox aquifer. Pumping from the aquifer in the area between the Neches and San Antonio Rivers, for example, increased 170 percent between 1980 and 2000. In the area between the Colorado and Brazos Rivers, pumpage increased from 10,600 to 37,900 acre-feet/yr between 1951 and 1996, primarily as a result of mining needs (Dutton, 1999).

Numerical modeling is a useful tool for assessing groundwater availability during the next 50 yr under proposed pumpage scenarios and potential future drought conditions. The Groundwater Availability Model (GAM) program involves development of GAM models for each of the major and minor aquifers in the state. Three separate numerical models (Northern, Central, and Southern) were developed for the Carrizo–Wilcox aquifer in Texas, with large overlap regions between the models (fig. 1). This report documents the development of the GAM model for the central part of the Carrizo–Wilcox aquifer.

The format for the models developed under the GAM program has been standardized. Each model includes the development of a conceptual model of groundwater flow in the model area, which forms the basis for the numerical model of the region. The numerical model requires information on the initial and boundary conditions and the hydraulic properties in the aquifer. A steady-state model is developed that represents predevelopment conditions. In addition, a transient model is developed and simulated results are compared with measured water levels in 1990, as well as water-level changes through time. The model is verified by simulating the period from 1990 through 2000 and comparing the simulated water levels with measured values in 2000, as well as with water-level changes for that period. Comparison of simulated and estimated base flow of streams is also part of model calibration. Sensitivity analyses are performed in the steady-state and transient models and help determine important controls on groundwater flow and assess uncertainties in model parameters. The calibrated model is then used to predict aquifer conditions during the 50-yr planning cycle (2000 to 2050). Groundwater withdrawal for the 50-yr period was derived from a TWDB analysis of the demands and supplies of surface water and groundwater,

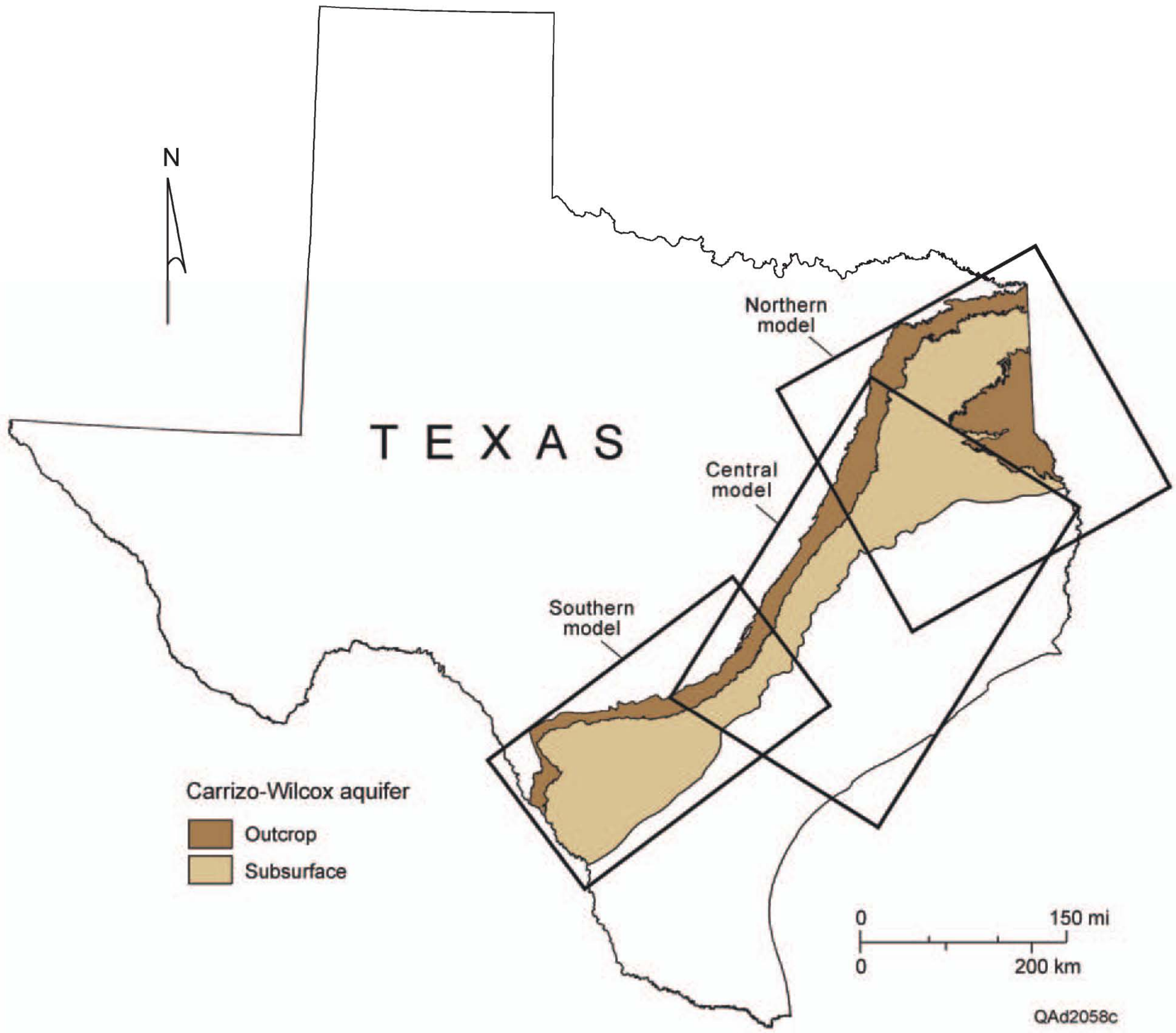

Figure 1. Location of the Carrizo–Wilcox aquifer in Texas showing the overlapping position of the three regional models.

along with possible water-management strategies, projected by the Regional Water Planning Groups. Input from stakeholders was incorporated into the modeling process through quarterly stakeholder advisory forums. The model developed for the Central Carrizo–Wilcox aquifer is described in this report according to the requirements of the GAM program. The model developed in this study is available for Groundwater Conservation Districts, Regional Water Planning Groups, River Authorities, and others to assess the groundwater availability in the Central Carrizo–Wilcox aquifer. The report and model are posted on the GAM web page at http://www.twdb.state.tx.us/GAM.

2.0 STUDY AREA

The study area overlaps with the areas of the southern and northern models of the Carrizo–Wilcox aquifer developed concurrently with the model of the central part of the aquifer in Texas (fig. 1). This report focuses on the central part of the Carrizo–Wilcox aquifer in Texas. The southwestern boundary of the study area falls along the course of the San Antonio River (fig. 2). The boundary to the northwest is at the limit of the outcrop of the formations that make up the Carrizo–Wilcox aquifer. The northeastern boundary of the study area runs from the aquifer outcrop in Van Zandt County, across part of the East Texas Basin and the Sabine Uplift, and then continues into the deep part of the Carrizo–Wilcox aquifer. The southeastern boundary of the study area was placed approximately 10 to 40 mi downdip of the base of freshwater in the aquifer and coincides with a major fault zone, as discussed in Section 4.2. Application of the southern or northern Carrizo–Wilcox aquifer models may provide more representative results than this central model near the southwestern and northeastern lateral boundaries (fig. 3).

Parts of more than 30 counties are included in the study area (fig. 2). The study area includes all or parts of 18 groundwater conservation districts (fig. 4), several of which have pending confirmation. Parts of eight regional water planning areas are within the study area (fig. 5): Region C, North East Texas D, Brazos G, Region H, East Texas I, Lower Colorado K, South Central Texas L, and Lavaca P regions. Information on the water plans of these regions may be found at www.state.tx.us/assistance/rwpg/main-docs/regional-plans-index.htm. The study area also includes parts of eight River Authority jurisdictions: the Angelina and Neches River Authority, Brazos River Authority, Guadalupe-Blanco

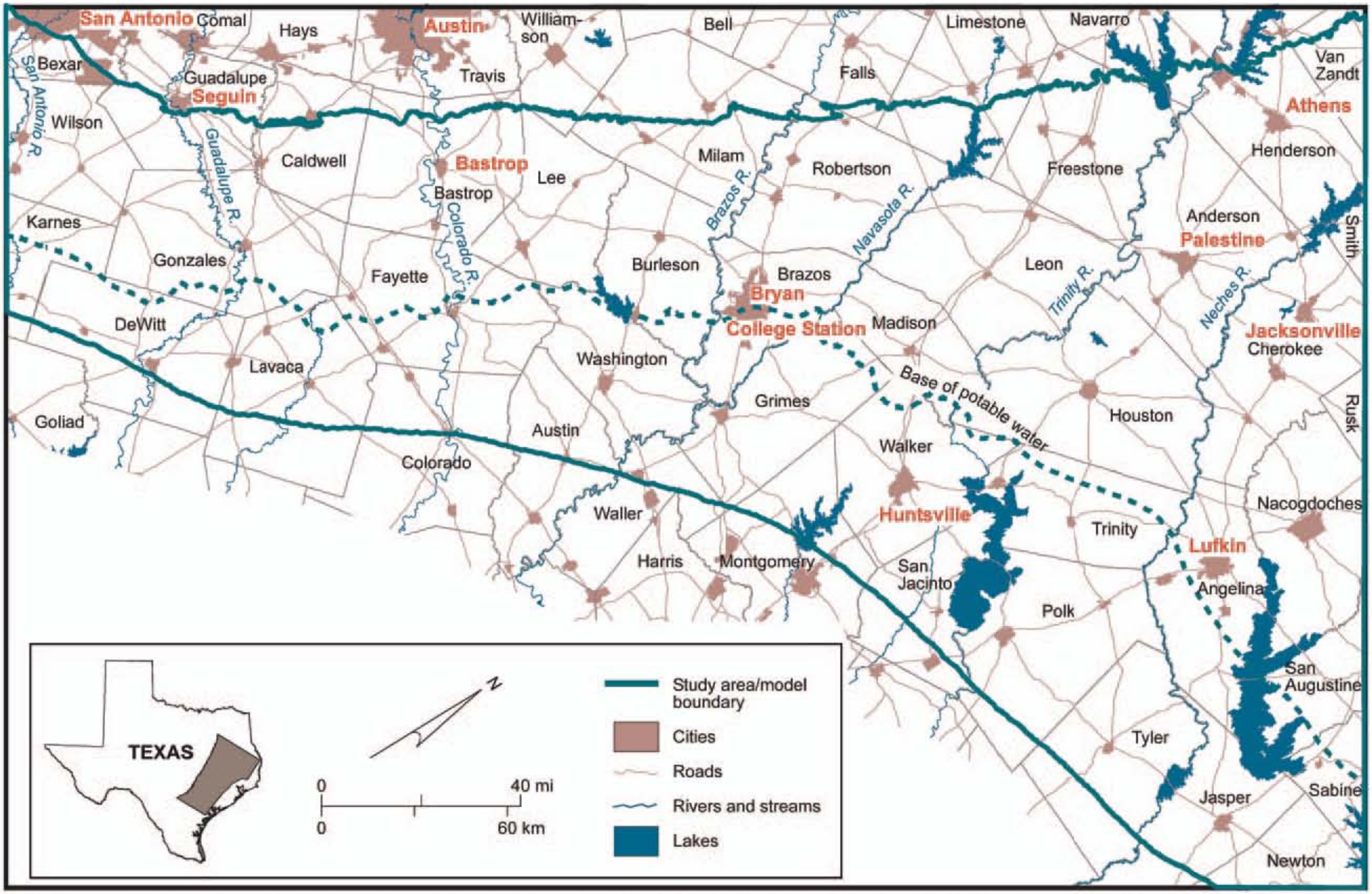

Figure 2. Location of the study area relative to roads, major cities and towns, lakes, and rivers. The study area extends beyond the limit of potable water in the Carrizo–Wilcox aquifer.

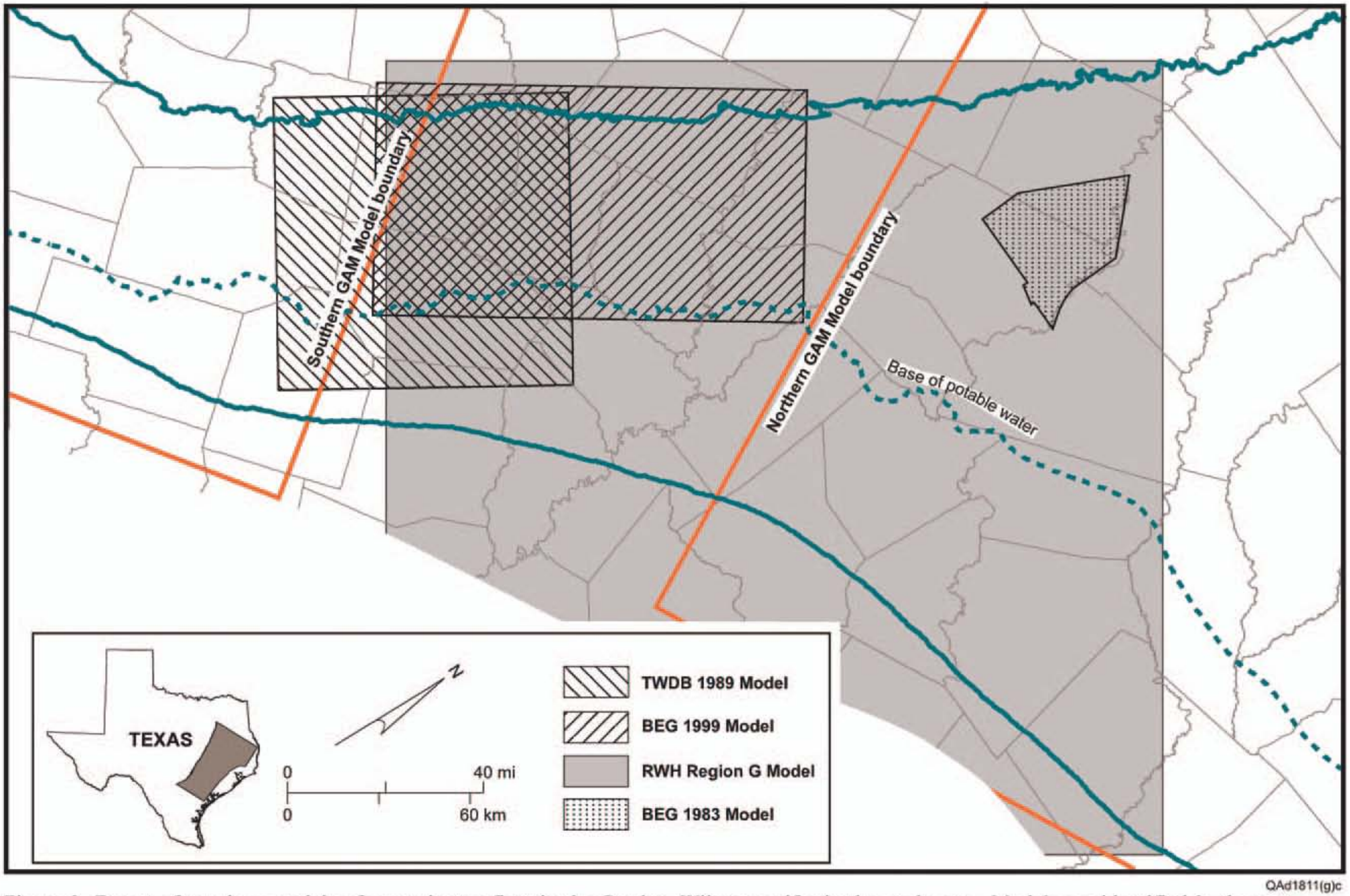

Figure 3. Extent of previous models of groundwater flow in the Carrizo–Wilcox aquifer in the study area. Models are identified in the text.

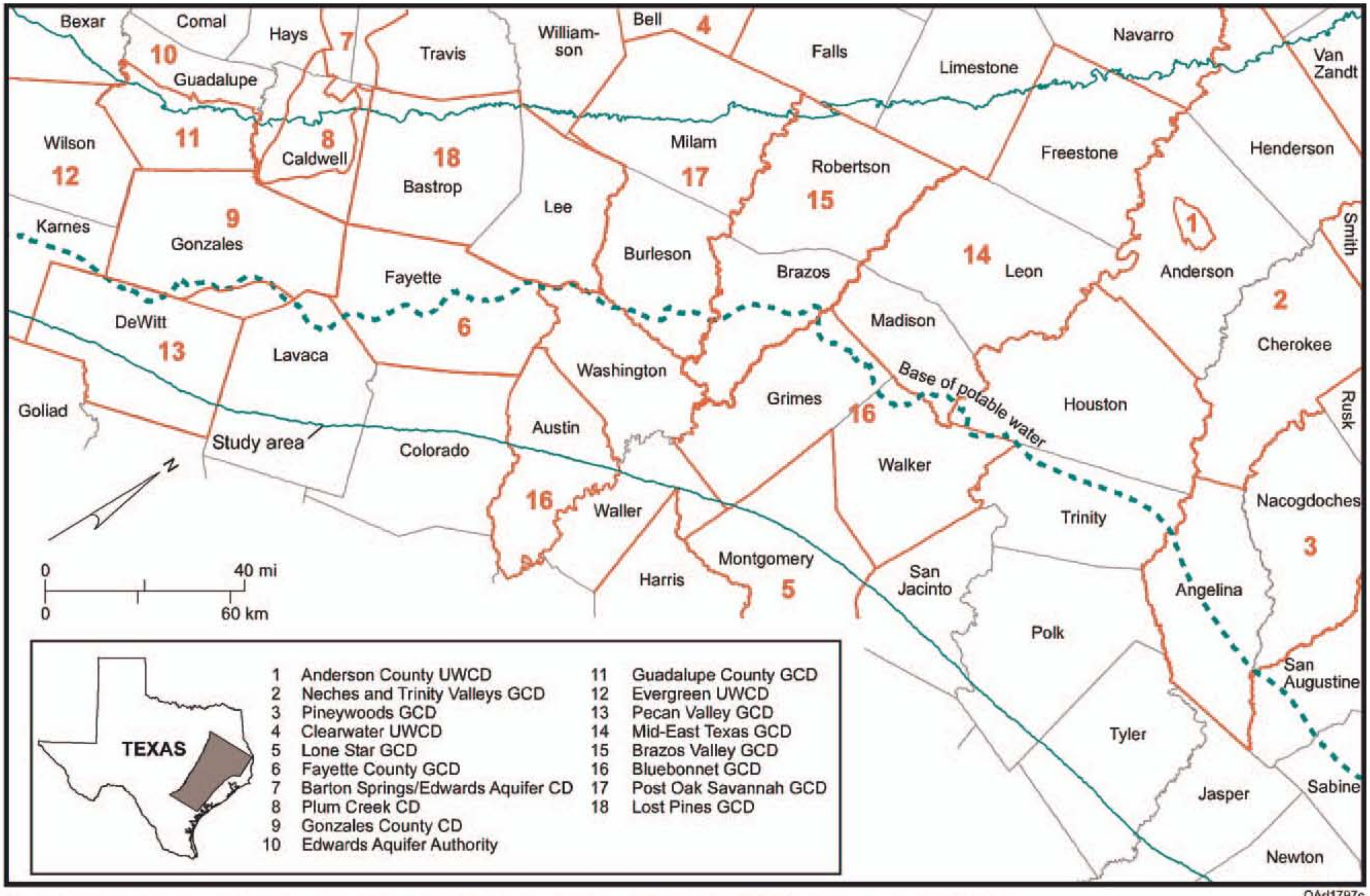

Figure 4. Location of groundwater conservation districts in the study area (November 2002). Taken and modified from http://www.twdb.state.tx.us/mapping/index.htm.

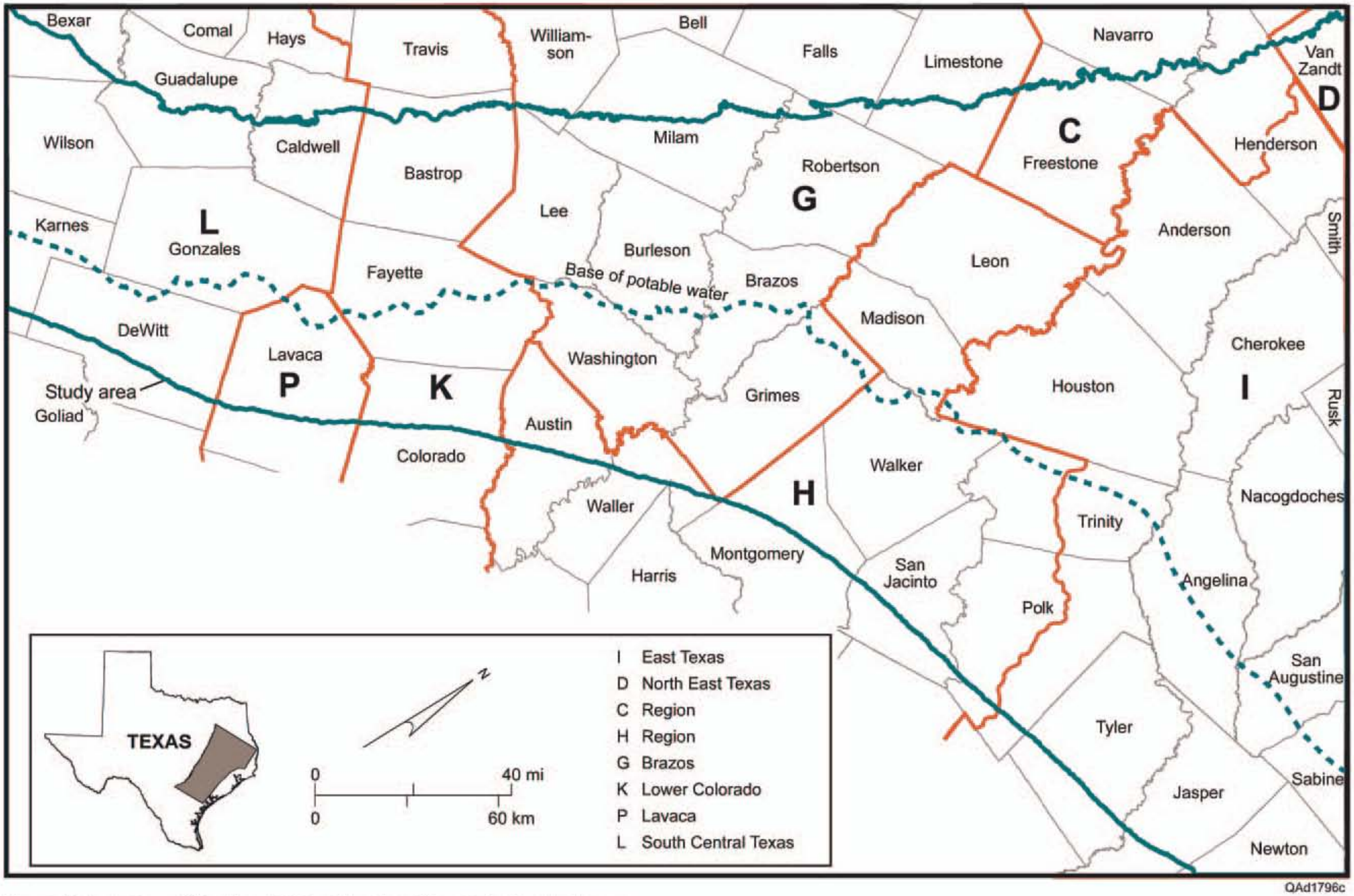

Figure 5. Location of Regional Water Planning Groups in the study area.

River Authority, Lavaca-Navidad River Authority, Lower Colorado River Authority, Lower Neches River Authority, San Antonio River Authority, and Trinity River Authority.

2.1 Physiography and Climate

The study area lies entirely within the Interior Coastal Plains, part of the Gulf Coastal Plain (Wermund, 1996a). To the west is the Blackland Prairies and farther west is the limestone escarpment at the eastern edge of the Hill Country. To the southeast are the Coastal Prairies. Land-surface elevations across the study area range from almost 750 ft (all elevations in this report are given relative to mean sea level [msl]) in the southwest, closer to the Balcones Escarpment, to less than 150 ft in river bottomlands (fig. 6). The valleys of the Brazos, Colorado, and Trinity Rivers are deeper and broader than those of the San Antonio, Guadalupe, Navasota, and Neches Rivers. Ground-surface elevation overlying the Carrizo–Wilcox aquifer is highest in the study area in the upland areas between Trinity and Neches Rivers and between Neches and Angelina Rivers (fig. 6).

The Interior Coastal Plains is underlain at the surface mostly by deposits of poorly consolidated sandstone, mudstone, and shale. Although the sandstones are friable and poorly cemented, they are somewhat resistant to erosion and form hills of low relief with slopes of 3 to 10 percent that may rise as much as 100 ft above the adjacent areas (Henry and Basciano, 1979). The sandstone hills are the outcrop of fluvial and deltaic channel deposits that make up the aquifer in the subsurface. The strike of the sandstone hills within the Simsboro, Carrizo, and Queen City Formations forms long sandy ridges separated by topographic trends of areas with slightly lower elevation, which are underlain by the

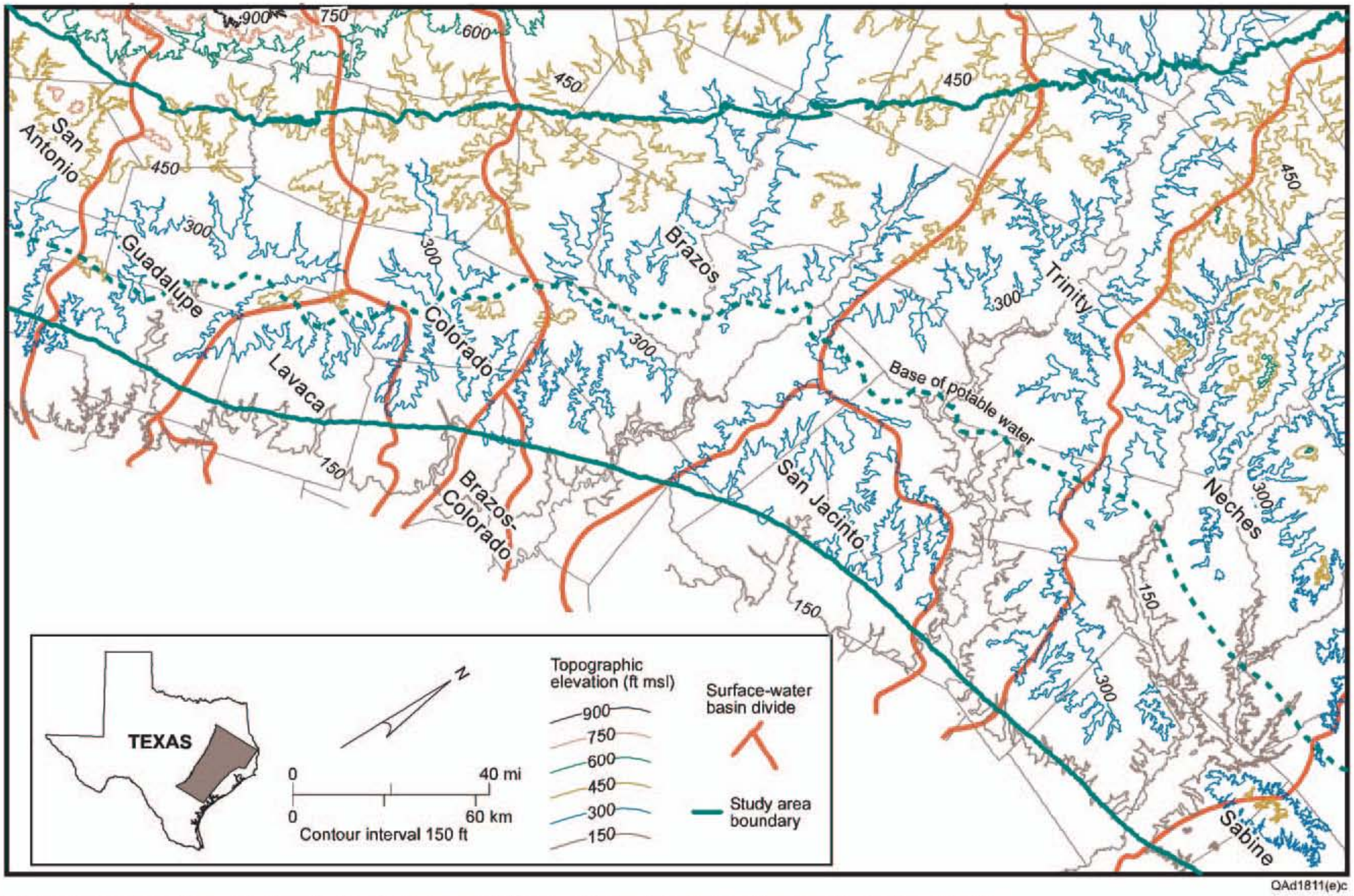

Figure 6. Land-surface elevation in the study area relative to divides between surface-water drainage basins. The study area is within the Interior Coastal Plains physiographic province. River basins from Wermund (1996b).

muddy substrates of the Hooper, Calvert Bluff, and Reklaw Formations. Relief between the upland divides and river bottomlands of about 100 ft is typical across the study area.

Climate of the study area is subhumid (Larkin and Bomar, 1983). Precipitation gradually decreases from east to west from more than 52 inches/yr to less than 28 inches/yr (fig. 7), following the regional trend across the Gulf Coastal Plain. Annual precipitation for the period from 1940 through 1997 across the study area averaged about 41.7 inches/yr. Average annual precipitation during the period from 1900 through 1997 ranged from 14 inches/yr in 1917 to 60.4 inches/yr in 1973. The period from 1954 through 1956 included 3 of the 10 driest years since 1940 and can be defined as the drought of record for the area (fig. 8). The driest years during the decades of the 1980s and 1990s were 1988 (average of 29.4 inches/yr) and 1996 (average of 38.1 inches/yr). Mean annual air temperature ranges from 65º F in the north to 70º F in the south (Larkin and Bomar, 1983). Evaporation increases from east to west across the study area. Average annual (1950–1979) gross lake evaporation is about 1.5 times average annual precipitation and ranges from 46 inches in the east to 63 inches in the west. Net lake-surface evaporation (gross lake evaporation minus precipitation) is less than zero (negative) in the eastern third of the study area (fig. 9), where precipitation rate is high; there is more precipitation than evaporation. The positive value of net lake evaporation in the western part of the study area means there is a potential on average each year for more evaporation than precipitation. Precipitation between October and May, however, is subject to less evaporation.

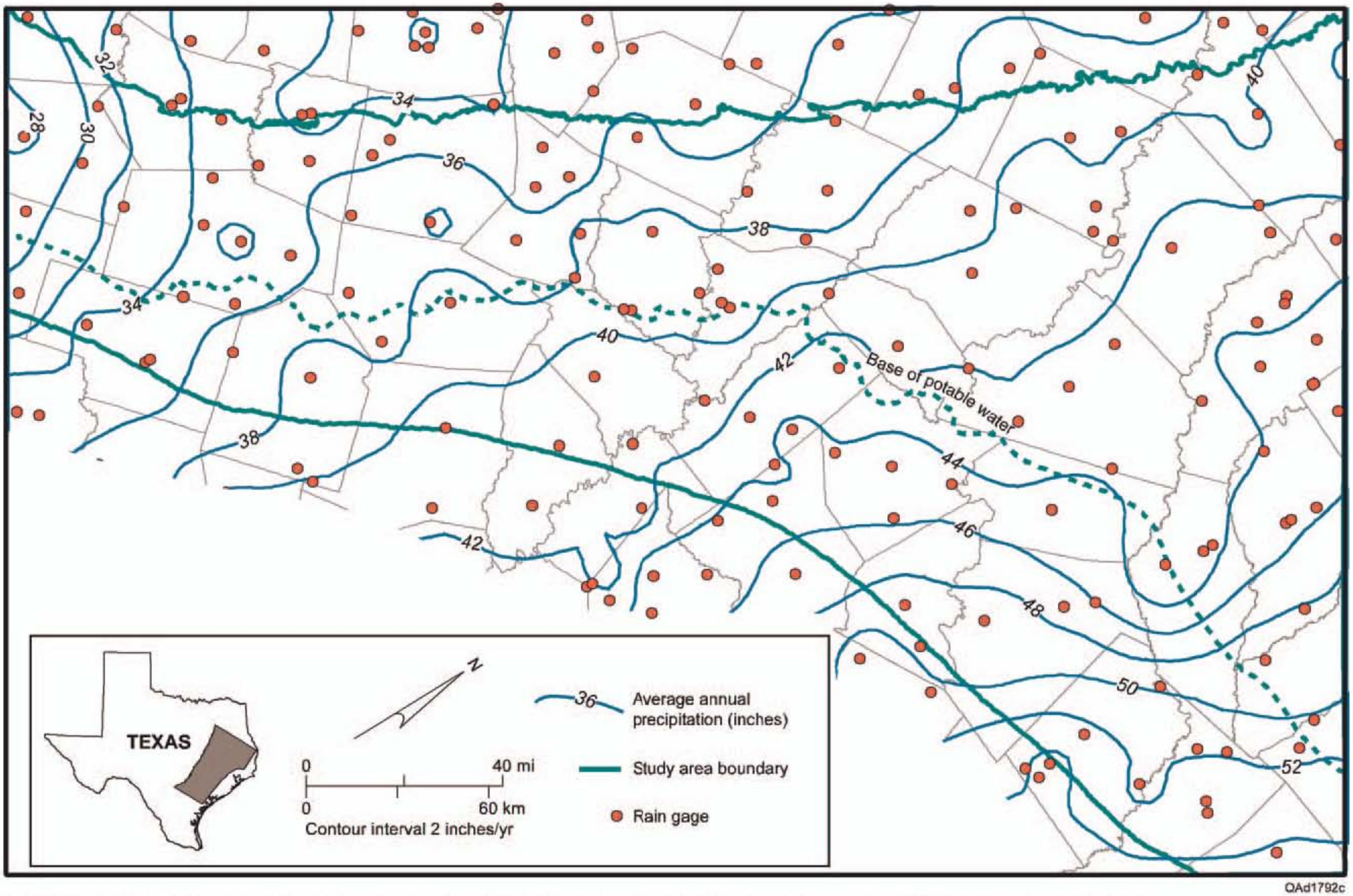

Figure 7. Average annual precipitation (1940 through 1997) in the study area. Data from www.twdb.state.tx.us/mapping/gisdata.htm.

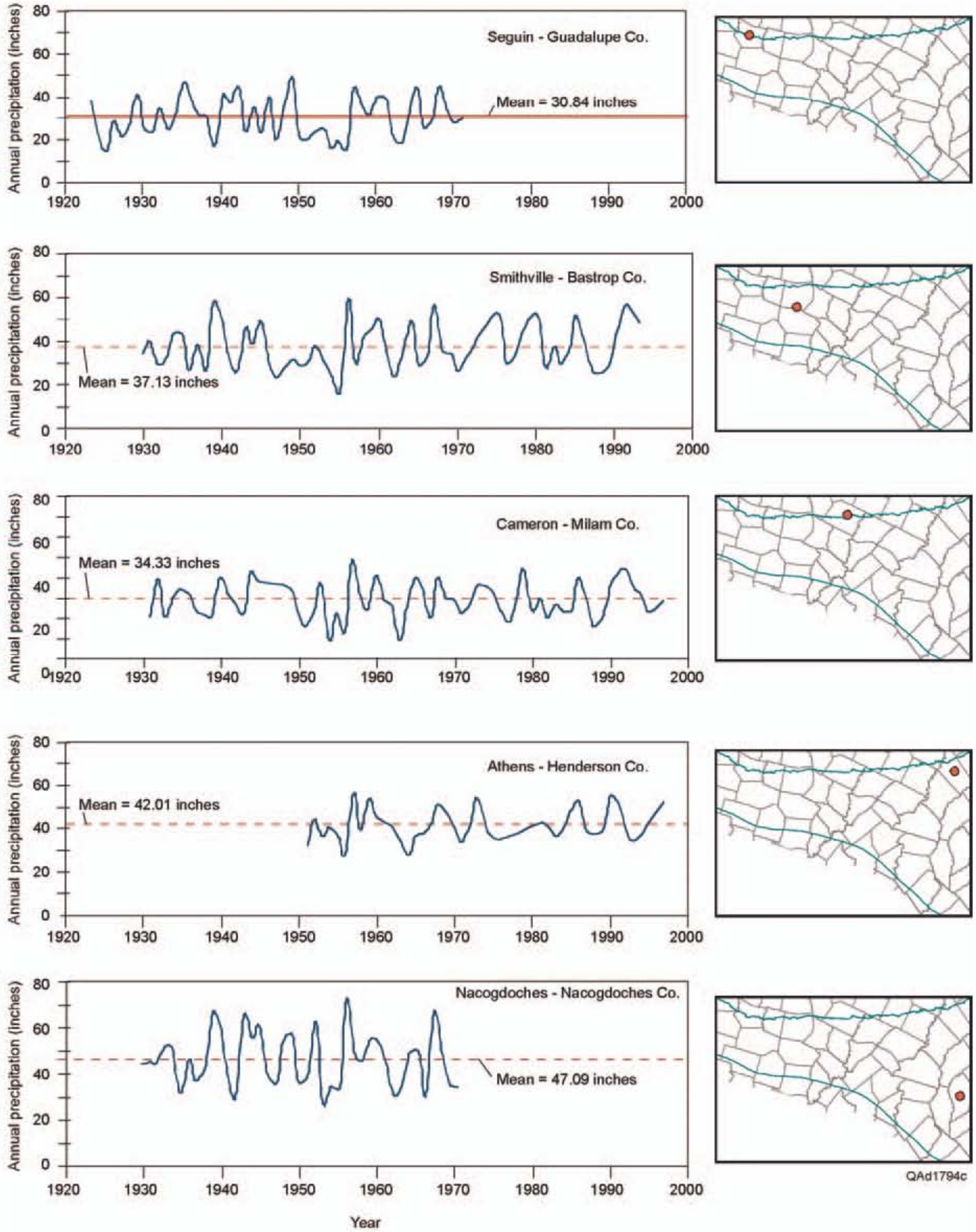

Figure 8. Historical annual precipitation measured at rain gages at Seguin, Smithville, Cameron, Athens, and Nacogdoches. Data from http://lwf.ncdc.noaa.gov/oa/climate/online/coop-precip.html.

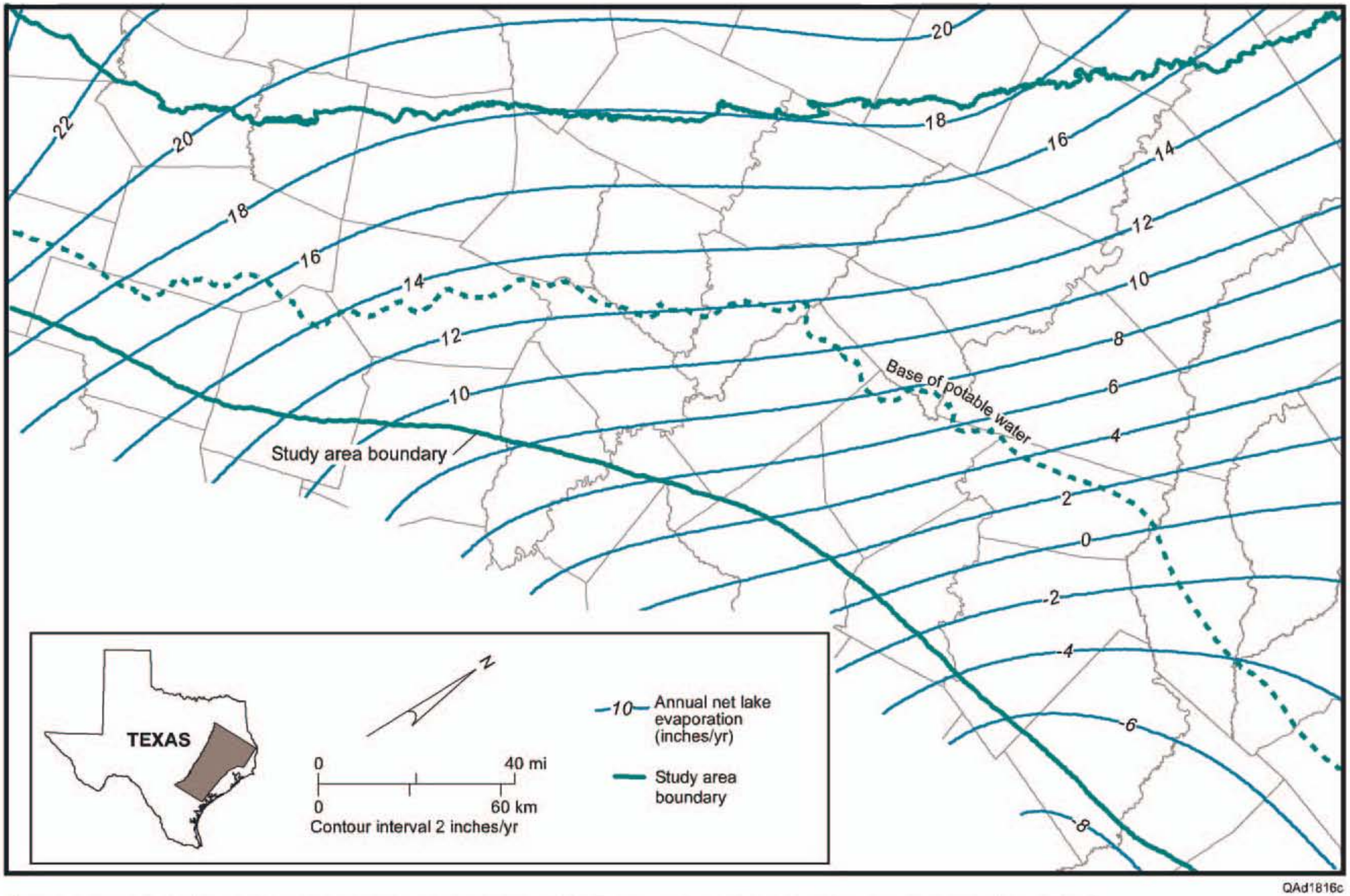

Figure 9. Average net lake evaporation rate in the study area. Data from http://hyper20.twdb.state.tx.us/Evaporation/evap.html.

2.2 Geology

The Carrizo–Wilcox aquifer is made up of the Wilcox Group and the overlying Carrizo Formation of the Claiborne Group (figs. 10, 11). The Carrizo Formation is included in the Wilcox Group in the deep subsurface (Bebout and others, 1982; Hamlin, 1988; Xue and Galloway, 1995). Between the Trinity and Colorado Rivers the Wilcox Group is formally subdivided into three formations, which are, from oldest to youngest, the Hooper, Simsboro, and Calvert Bluff Formations (Kaiser, 1978; Ayers and Lewis, 1985; Xue and Galloway, 1995). The Carrizo and Simsboro Formations make up the main aquifer units. More than 80 percent of the Carrizo and Simsboro Formations in the study area consist of porous and permeable sandstone (Ayers and Lewis, 1985).

The outcrop of each formation that makes up the Carrizo–Wilcox aquifer (the Hooper, Simsboro, Calvert Bluff, and Carrizo Formations) between the Trinity and Colorado Rivers is generally 1 to 3 mi in width except for the thicker Calvert Bluff Formation that has an outcrop typically 4 to 6 mi in width (fig. 11). This reflects cumulative formation thicknesses near the outcrop that are less than 500 ft and a coastward formational dip of 0.25° to 2° (20 to 180 ft/mi) (Henry and Basciano, 1979). The width of the undifferentiated Wilcox Group outcrop south of the Colorado River and north of the Trinity River is approximately 10 to 15 mi wide.

The Hooper Formation represents the initial progradation of the Wilcox Group fluvial-deltaic systems into the Houston Embayment of the Gulf of Mexico basin and consists of interbedded shale and sandstones in subequal amounts, with minor amounts of lignite. It coarsens upward from shale-dominated prodelta deposits of the Rockdale delta to sand-dominated upper delta plain and fluvial deposits in the outcrop area (Ayers and Lewis, 1985) and delta-front/prodelta facies in the downdip part of the study area.

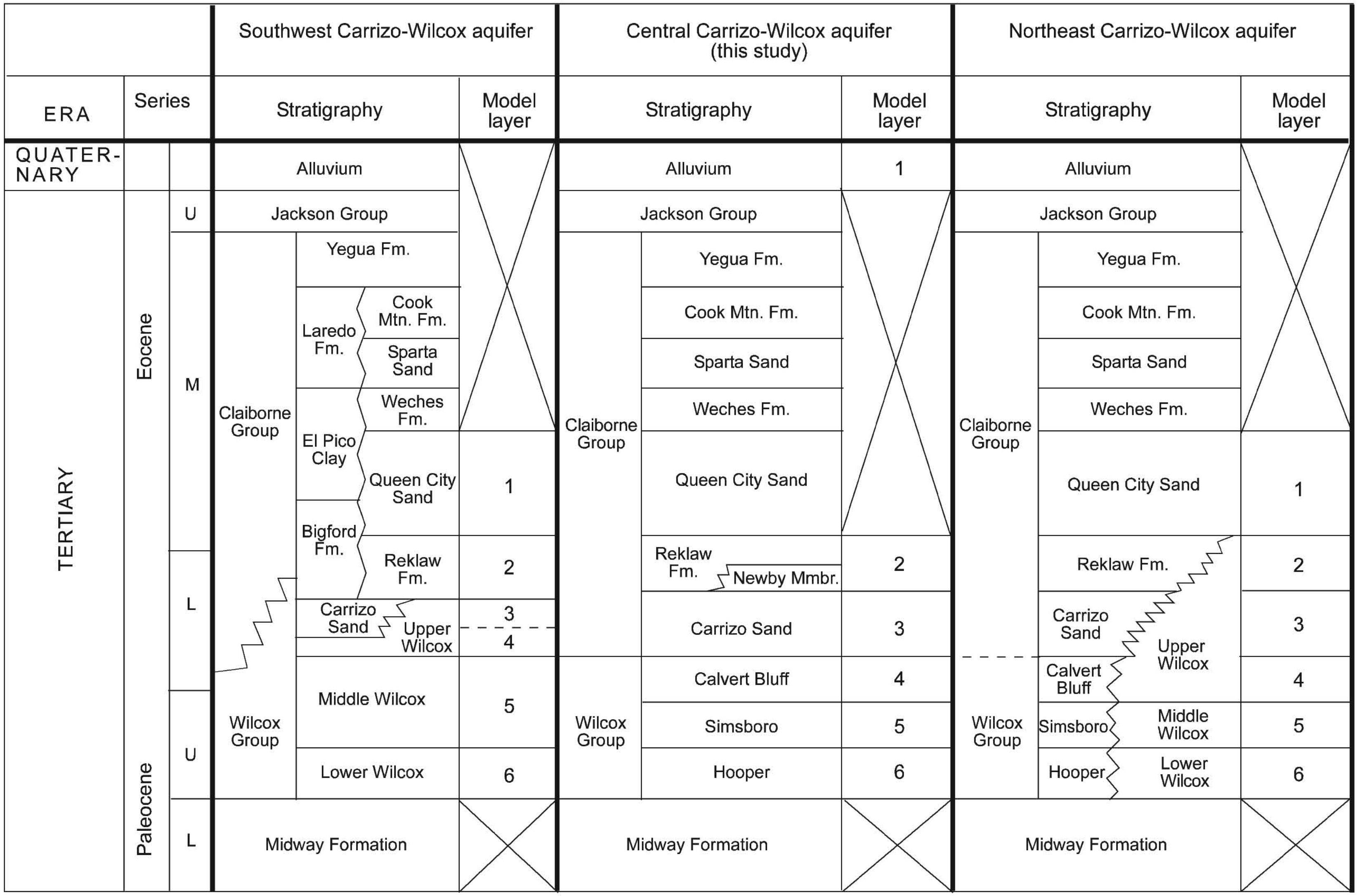

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Figure 10. Generalized stratigraphic chart for the study area (after Ayers and Lewis, 1985; Hamlin, 1988; Kaiser, 1978; Intera and Parsons Engineering Science, 2002a, b).

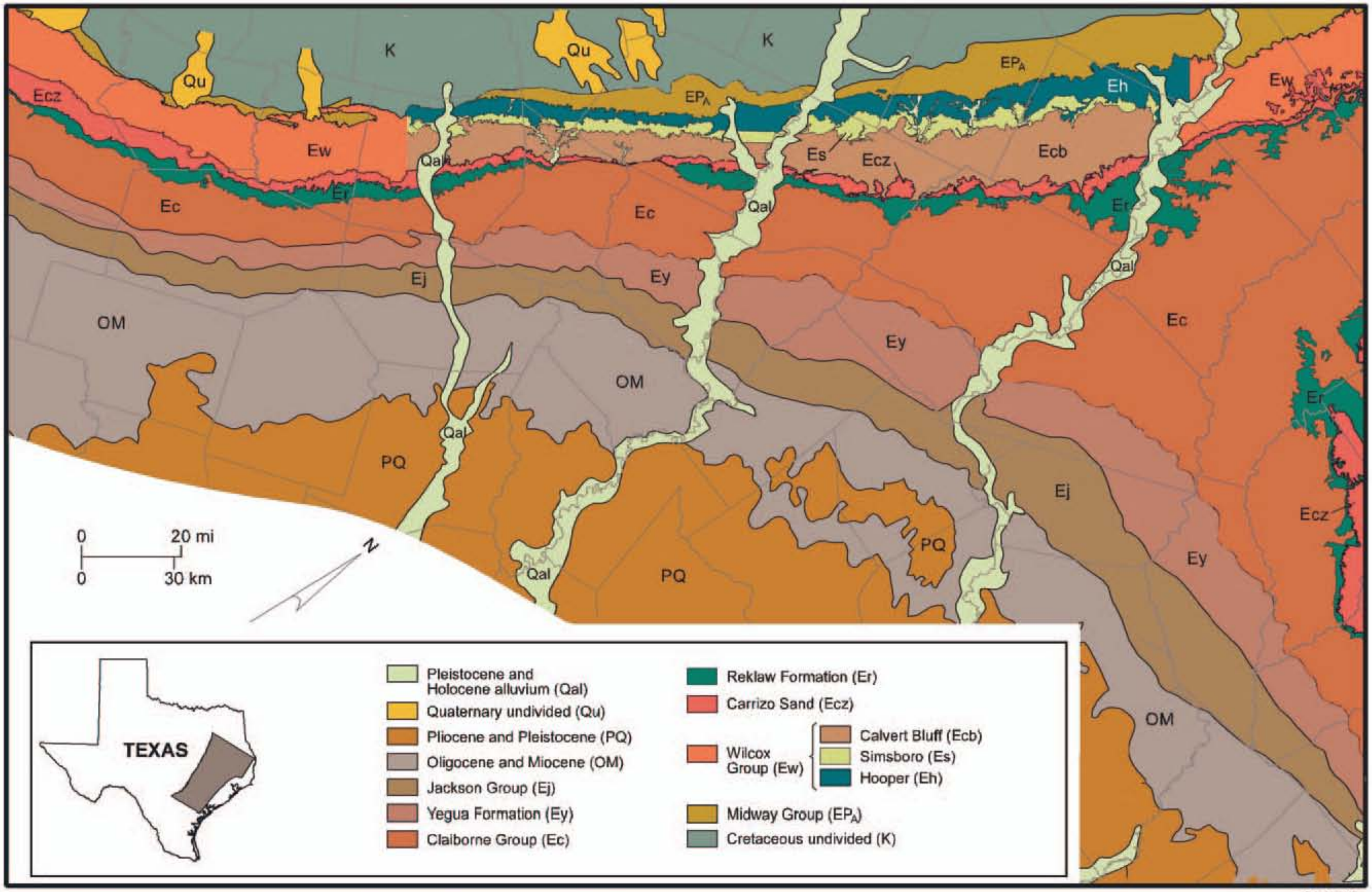

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Figure 11. Generalized map of surface geology in the study area. The Wilcox Group is not subdivided into formations south of the Colorado River or north of the Trinity River. Claiborne Group shown on map does not include Yegua Formation, Reklaw Formation, and Carrizo Sand. Modified from Bureau of Economic Geology (1992).

Sandstone thickness trends are dominantly dip elongate, being northwest-southeast oriented in the central and northern parts of the study area and more southerly in the southern part of the model area. Thickness of “major sands” ranges from 40 ft to narrow bands of more than 200 ft in the shallow subsurface, with these narrow bands widening and thickening to more than 300 ft, broadly, in the middip region of the model area, and then thinning to near zero in most of the downdip model area (Ayers and Lewis, 1985). Sandstone percent ranges from less than 20 percent adjacent to major axes of deposition to 50 percent at axes. Thick sandstone bodies do not extend downdip beyond the base of freshwater except in the areas of Lavaca, Austin, and Waller Counties.

The Simsboro Formation is predominantly a sand-rich formation (fig. 12) composed of a multistory, multilateral sand deposit (Henry and others, 1979). The Simsboro Formation was deposited in environments ranging from fluvial and upper delta floodplain near the outcrop (Fisher and McGowen, 1967; Ayers and Lewis, 1985) to delta front and prodelta at the downdip margins of the study area. Its deposits have been referred to as making up the Rockdale Delta System (Fisher and McGowen, 1967). The Rockdale Delta, which lies between the Colorado and Trinity Rivers, has more than 500 ft of sandstone in the Simsboro Formation (fig. 12). Thick sandstones extend well past the base of freshwater. Sandstone thickness patterns consist of narrow, dip-oriented trends of more than 500 ft alternating with areas of less than 100 ft in the updip and middip regions, thinning to less than 100 ft in the downdip part of the study area. More north- to south-oriented sandstone trends of generally less than 200 ft exist in the northern part of the model area, composing the Mt. Pleasant Fluvial System of Fisher and McGowen (1967). Thick Simsboro sandstones between the Colorado and Trinity Rivers separate the more muddy and thin-bedded sands of the lower and upper Wilcox Group (fig. 10). Whereas sandstone generally makes up 80 percent of

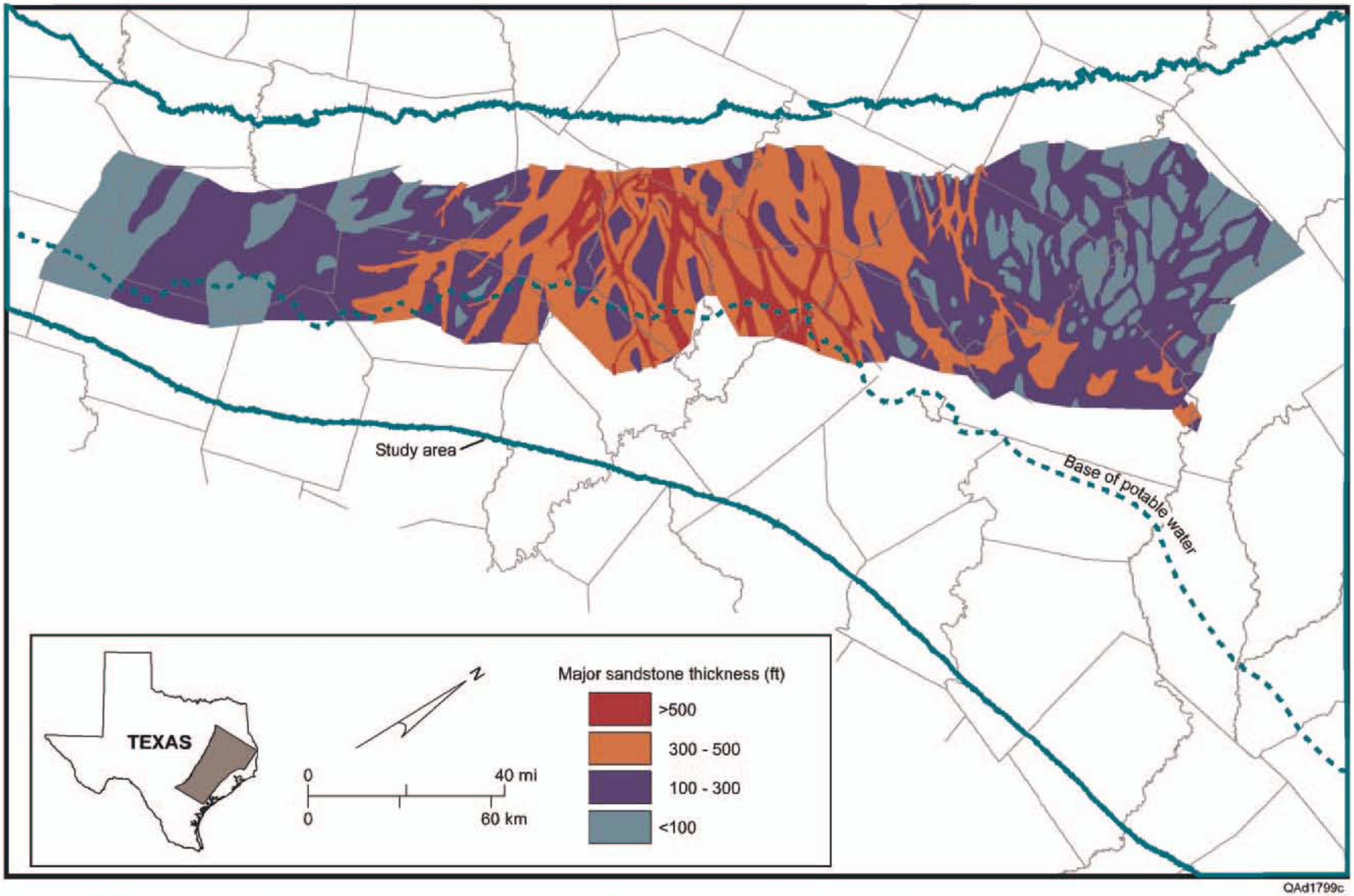

Figure 12. Thickness of major sandstones in the Simsboro Formation in the study area. Modified from Ayers and Lewis (1985).

the Simsboro Formation, it is generally only 20 to 40 percent of the underlying Hooper Formation and overlying Calvert Bluff Formations. Hooper and Calvert Bluff Formations, however, have as much as 50 percent sandstone locally and are locally important groundwater-bearing units.

Multilateral sands are less abundant, and the Wilcox Group is not formally subdivided where the Rockdale Delta System dies out to the south and north (fig. 12). South of the Colorado River, Simsboro-equivalent deposits change to strike-oriented, nearshore, marine-dominated facies (the San Marcos Strandplain Bay system of Fisher and McGowen, 1967), which do not make up a major sand system and are not differentiated from the rest of the Wilcox Group (Barnes, 1992; Henry and others, 1979). The geological map (fig. 11) breaks out the Hooper, Simsboro, and Calvert Bluff Formations of the Wilcox Group between the Colorado and Trinity Rivers. Mapping does not formally define separate formations of the Wilcox Group south of the Colorado River or north of the Trinity River.

The Calvert Bluff, like the Hooper Formation, consists mainly of low-permeability claystone and lignite deposits (Ayers and Lewis, 1985), which function like confining layers that retard the vertical movement of water within the Carrizo–Wilcox aquifer across the study area. Where present in sufficient thickness, however, sandstones can yield appreciable quantities of water in the Calvert Bluff. The communities of Bastrop, Elgin, and Milano, for example, have had public water-supply wells in the Calvert Bluff or Hooper Formations. Sandstone and shale are interbedded in subequal parts, with intermixed lignite beds, a significant resource in Central and East Texas (Kaiser, 1978). Multistory sandstone bodies that are 50 to 100 ft thick in the updip area reflect fluvial to upper delta-plain deposition. By 10 to 15 mi downdip of the outcrop, these have changed to distributary facies, which terminate in delta-front and prodelta facies in the downdip part of the model area. Narrow axes where sandstone thickness of greater than 200 ft near the outcrop give way to broader axes of more than 400 ft of sandstone in the middip region, change to a broad, strike-oriented thickness trend near the downdip limit of freshwater that finally thins to less than 100 ft in the downdip part of the model area (Ayers and Lewis, 1985). Greatest sandstone thickness occurs in the southern part of the study area and in central Leon, eastern Madison, and eastern Walker Counties, reflecting diversion of Rockdale Delta deposition around former loci of deposition in the underlying Simsboro Formation.

The Carrizo Formation is hydrologically connected to the underlying Wilcox Group; the two units collectively are referred to as the Carrizo–Wilcox aquifer, the subject of this study. The Carrizo Formation is the oldest part of the Claiborne Group in the Central Texas study area (fig. 10) and is considered part of the Wilcox Group in the subsurface (Bebout and others, 1982). By the time of Carrizo Formation deposition, the center of sand deposition had shifted to the south of the San Marcos Arch, feeding the Rosita Delta System (Ayers and Lewis, 1985). Within the central and northeastern parts of the study area, sand thickness is strongly dip oriented (northwest to southeast). Total thickness of sandstone in the Carrizo Formation is typically between 100 and 200 ft, typically less than in the Simsboro Formation. Sandstone thickness in the Carrizo Formation, however, increases to several hundreds of feet to the southwest in Gonzales, Wilson, DeWitt, and Karnes Counties (fig. 13) (Hamlin, 1988), where the remaining activity of the Rockdale Delta was focused. Ayers and Lewis (1985, p. 7) mapped the top of the Carrizo Sand at the top of an upward-fining sequence called the Newby Member of the Reklaw Formation.

Framework mineralogy in the Carrizo–Wilcox aquifer was characterized by Loucks and others (1986), who documented an increase in feldspar content in Wilcox sandstone from South Texas through East Texas. Under the classification of Folk (1968), Carrizo–Wilcox

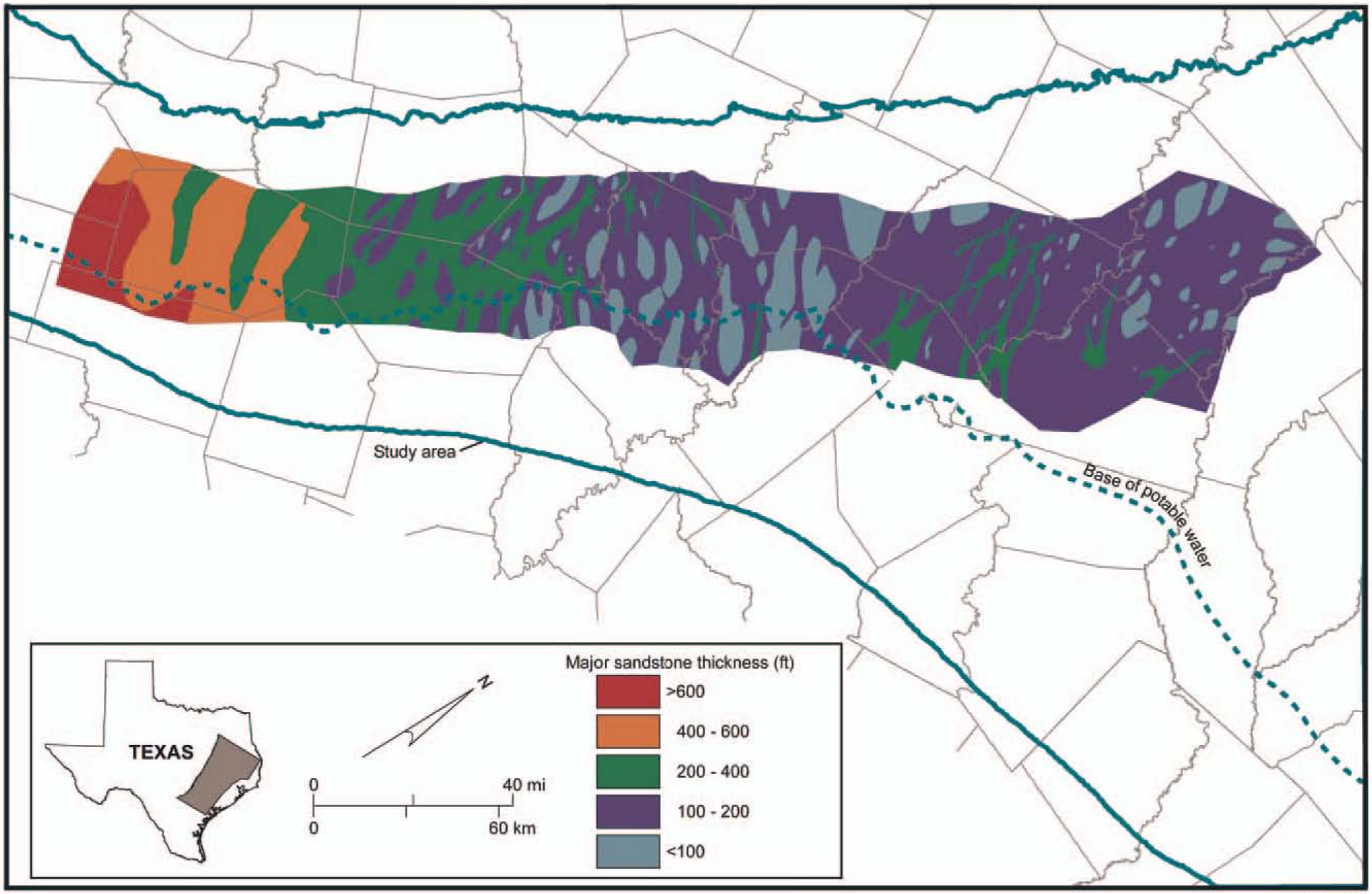

Figure 13. Thickness of major sandstones in the Carrizo Formation in the study area. Modified from Ayers and Lewis (1985).

sandstones vary from subarkose, arkose, and lithic arkose in the lower coast (quartz ~60 to 85 percent and feldspar-to-rock fragments ratios of >3:1 to <1:1) to subarkose, arkose, lithic arkose, and feldspathic litharenite in the upper coast (quartz ~40 to 80 percent and feldspar:rock fragment ratios of 3:1 to slightly greater than 1:3). Authigenic clay grain coatings, feldspar, kaolinite, and minor carbonate cements dominate digenetic events at depths of less than 5,000 ft. Quartz cement is a dominant diagenetic phase at depths of between about 5,000 and 8,000 ft, and iron-rich carbonate cement is dominant at depths below 8,000 ft. Feldspar corrosion and dissolution are common soil-forming processes in the unsaturated zone, with formation of kaolinitic and smectitic clay coats on other framework grains (Dutton, 1990).

Underlying the Carrizo–Wilcox aquifer is the marine shale of the Paleocene Midway Formation (figs. 10, 11). The Midway is transitional between the fully marine deposits of the Upper Cretaceous and the foredelta and lower delta floodplain deposits of the Hooper Formation (Fisher and McGowen, 1967; Ayers and Lewis, 1985).

Deposits of the Claiborne Group that overlies the Wilcox Group also reflect several episodes of fluvial and deltaic progradation, marked by thick sandstones of the Queen City and Sparta Formations, interspersed with relative marine advances marked by the marine shale of the Reklaw, Weches, and Cook Mountain Formations. Low-permeability marine shale of the Reklaw Formation restricts groundwater movement between the Carrizo Formation and the overlying aquifer in the Queen City Formation in the Claiborne Group (fig. 10). The Carrizo and Reklaw Formations are broken out of the Claiborne Group in the geological map (fig. 11) because they are included as separate hydrological layers in the model.

Pleistocene and Holocene (Quaternary) alluvium floors the valleys of the Colorado, Brazos, and Trinity Rivers. Alluvial deposits contain highly permeable sands and gravels, as well as low-permeability silts and clays. Various terrace levels record the history of floodplain evolution in the coastal plain over the past several million years (Hall, 1990).

3.0 PREVIOUS WORK

This study has built on previous hydrogeologic investigations and regional computer models of the Carrizo–Wilcox aquifer (fig. 3). The scale of previous models ranges from the local to regional. All models have treated the base of the Wilcox Group (base of Hooper Formation) as a no-flow boundary, making the assumption that there is negligible exchange of groundwater with the underlying Midway Group. Other boundary conditions varied between models.

Fogg and others (1983) developed a model of the Carrizo–Wilcox aquifer in the Trinity River Basin (Leon and Freestone Counties) using the TERZAGI code (BEG 1983 Model, fig. 3). The main purpose of this study was to evaluate how to represent hydraulic conductivities of highly heterogeneous aquifers.

Thorkildsen and others (1989) simulated groundwater flow in the Carrizo–Wilcox aquifer in the Colorado River basin (TWDB 1989 Model, fig. 3). This study compiled well data, geologic information, and hydraulic parameters, developed a groundwater model, and evaluated aquifer response to various future pumpage scenarios. The model of Thorkildsen and others (1989) subdivided the Carrizo–Wilcox aquifer into four layers, and the model was bounded by a no-flow boundary at the outcrop limit and a constant-head boundary at the downdip limit. Steady-state calibration was based on 1985 water levels. Transient simulations were run for 1985 through 2029 to evaluate aquifer response to future pumpage. Thorkildsen and Price (1991, unpublished simulations) used models to evaluate groundwater availability in the Carrizo–Wilcox aquifer between the Colorado and Trinity Rivers; however, there is little documentation of these models. The models of the Carrizo–Wilcox aquifer by Thorkildsen and others (1989) and Thorkildsen and Price (1991; unpublished simulations) have model blocks that represent areas of 4 and 16 mi^2, respectively.

The U.S. Geological Survey's RASA (Regional Aquifer System Analysis) program includes the development of large-scale regional models of aquifers along the coastal plain rimming the Gulf of Mexico, including the Carrizo–Wilcox aquifer in Texas (Ryder, 1988; Williamson and others, 1990; Ryder and Ardis, 1991). The Carrizo–Wilcox aquifer is represented as two layers. The code used for these models was developed by Kuiper (1985). The primary objective of these models was to evaluate the regional groundwater flow system, including the hydrogeologic framework and hydraulic attributes of the units. The model developed by Ryder (1988) was restricted to steady-state simulations representing predevelopment conditions. The model developed by Williamson and others (1990) included steady-state and transient simulations (1935 through 1980). In addition to steady-state and transient (1910 through 1982), Ryder and Ardis (1991) also conducted predictive simulations to evaluate aquifer response to potential future pumpage scenarios. This model used a constant-head, updip boundary condition, which probably results in overestimation of recharge rate under future pumpage conditions because the constant-head boundary condition provides an inexhaustible supply of water. The models by Ryder (Ryder, 1988; Ryder and Ardis, 1991) have model blocks that represent an area of 25 mi^2.

Dutton (1999) prepared a predictive model of the groundwater in Hooper, Simsboro, Calvert Bluff, and Carrizo Formations between the Colorado and Brazos Rivers (BEG 1999 Model, fig. 3). No-flow boundaries to the north and south were located beyond the Colorado and Brazos Rivers, assumed to be hydrologic boundaries. The model excluded pumping in the area of the well field of the cities of Bryan and College Station and did not take into account the effect of this well field on the model area. The downdip boundary was set 10 to

20 mi beyond the limit of freshwater; a vertical gradient in hydraulic head was prescribed along the downdip boundary. Hydraulic conductivity was assigned on the basis of the distribution of sand deposits (Ayers and Lewis, 1985). Various assumed water-development projects were simulated for the period from 2000 through 2050. Model results suggested that lateral and downdip boundaries had some effect on model results.

R. W. Harden and Associates, Inc., developed a model of the aquifer between the Colorado and Neches Rivers for the Brazos Region G Regional Water Planning Group (RWH Region G Model, fig. 3). The MODFLOW code was used for the simulations and the Carrizo–Wilcox aquifer was subdivided into five layers, representing the Hooper, Simsboro, Calvert Bluff, and Carrizo Formations and the Newby Member of the Reklaw Formation. A downdip model boundary was set very far away from the area of interest so as not to affect model results directly. Hydraulic conductivity was assigned on the basis of the distribution of sand deposits (Ayers and Lewis, 1985). The model included steady-state simulations (1950, 1985) and predictive simulations (2000 through 2050).

While the present model has been in development, simultaneous efforts were under way to construct parallel models of the Carrizo–Wilcox aquifers in northern and southern parts of the aquifer in Texas (fig. 3) (Intera and Parsons Engineering Science, 2002a, b). Geology, hydrology, climate, and history of groundwater use differ somewhat between the northern, central, and southern parts of the Carrizo–Wilcox aquifer in Texas. The models overlap large areas (figs. 1, 3), and model development was coordinated to make the results as consistent as possible.

4.0 HYDROLOGIC SETTING

In this section on hydrogeologic setting, we discuss information on the aquifer and its properties that has been compiled and analyzed for building the groundwater model. Groundwater conditions in counties included in the study area have been previously documented (for example, Anders, 1957, 1960; Arnow, 1959; Dillard, 1963; Peckham, 1965; Shafer, 1965, 1966, 1974; Follett, 1966, 1970, 1974; Tarver, 1966, 1968; Thompson, 1966, 1972; Cronin and Wilson, 1967; Rogers, 1967; Wilson, 1967; Guyton and Associates, 1970, 1972; White, 1973; Henry and Basciano, 1979; Henry and others, 1979; Ayers and Lewis, 1985; Dutton, 1985, 1990; Rettman, 1987; Sandeen, 1987; Thorkildsen and others, 1989; Baker and others 1990; Duffin, 1991; Thorkildsen and Price, 1991). We developed the hydrogeologic setting on the basis of these and additional studies we conducted in support of this modeling effort. Additional studies include remapping structural elevations of the aquifer layers, developing water-level hydrographs and maps of the potentiometric surface, estimating base flow to rivers and streams, investigating recharge rates, and mapping total dissolved solids.

4.1 Hydrostratigraphy

The Carrizo–Wilcox aquifer system in the Central Texas study area is composed of four hydrostratigraphic units with distinct hydraulic properties: the Hooper, Simsboro, and Calvert Bluff Formations of the Wilcox Group and the Carrizo Sand of the Claiborne Group (fig. 10). In general, the Simsboro and Carrizo Formations contain thicker, more laterally continuous and more permeable sands (figs. 12, 13) and, therefore, are more important hydrostratigraphic units when determining groundwater availability. Calvert Bluff and

Hooper Formations typically are made up of clay, silt, and sand mixtures, as well as lignite deposits. Because of their relatively low vertical permeability, the Hooper and Calvert Bluff Formations act as leaky aquitards that confine fluid pressures in the Simsboro and Carrizo aquifers and restrict groundwater movement between the layers. Although the Hooper and Calvert Bluff Formations contain sand units, they are generally finer and less continuous than the sands of the Simsboro and Carrizo Formations. The four units of the Carrizo–Wilcox aquifer system in the Central Texas study area were modeled as individual layers (fig. 10).

Deposits of the Claiborne Group that overlies the Wilcox Group also reflect several episodes of fluvial and deltaic progradation, marked by thick sandstones of the Queen City, Sparta, and Yegua Formations. The formations dominated by progradational sandstones are interlayered with relative marine advances marked by marine shales of the Reklaw, Weches, and Cook Mountain Formations. Low-permeability marine shale of the Reklaw Formation, for example, restricts groundwater movement between aquifers in the Carrizo Formation and overlying Queen City Formation in the Claiborne Group (fig. 10).

There is appreciable use of groundwater in the Brazos River alluvium for irrigation, and this deposit has been named a minor aquifer by the Texas Water Development Board (Ashworth and Hopkins, 1995; Hovorka and Dutton, 2001). Pleistocene and Holocene (Quaternary) alluvium also underlies the valleys of the Colorado and Trinity Rivers. Alluvium exchanges water between the Carrizo–Wilcox aquifer and the rivers. Groundwater in the bedrock formations can discharge into the alluvium, and water moves between the alluvial deposits and the surface-water channels. Alluvium can also store water that is recharged to the banks of rivers during flood flow; bank storage is released back to the rivers during low flow. Because of such interaction, alluvium in those three river valleys was included as a layer in the model. Because river alluvium was not the focus of this study, this model should not be used to assess water resources of the alluvium without additional calibration of the modeled hydrologic properties of the alluvium.

4.2 Structure

Depositional patterns of Carrizo–Wilcox sediments have been influenced by the tectonic evolution of the Gulf of Mexico basin since its opening more than 180 million years ago. Early history of the basin included rifting and creation of numerous subbasins. During the Jurassic, marine flooding and restricted circulation resulted in accumulation of halite beds in these subbasins (Jackson, 1982). Subsidence continued as the rifted continental crust cooled. The sediment column records the effects of changes in relative rates of sediment progradation, basin subsidence, and sea-level change. More than 50,000 ft of sediment has accumulated in the Gulf of Mexico basin (Salvador, 1991).

The San Marcos Arch (fig. 14) is a structurally high basement feature beneath the central part of the Texas Coastal Plain separating the East Texas and South Texas basins, areas that had greater rates of subsidence. The Carrizo Formation and Wilcox Group drape over the San Marcos Arch. The structural effect on the Carrizo–Wilcox aquifer is obscured in figure 15, however, because the line of section turns from southwest to south and the San Marcos Arch plunges (increases in depth) toward the coast. The Sabine Uplift, which lies at the northern edge of the study area and extends into Louisiana, is another broad structural dome. Its topographic expression influenced sediment deposition in the East Texas Basin during the Tertiary (Fogg and others, 1991). The East Texas Basin is one of the major subbasins formed early in the Mesozoic, and it had significant thicknesses of halite deposition. Subsidence, tilting, and differential loading by Cenozoic sediments caused the

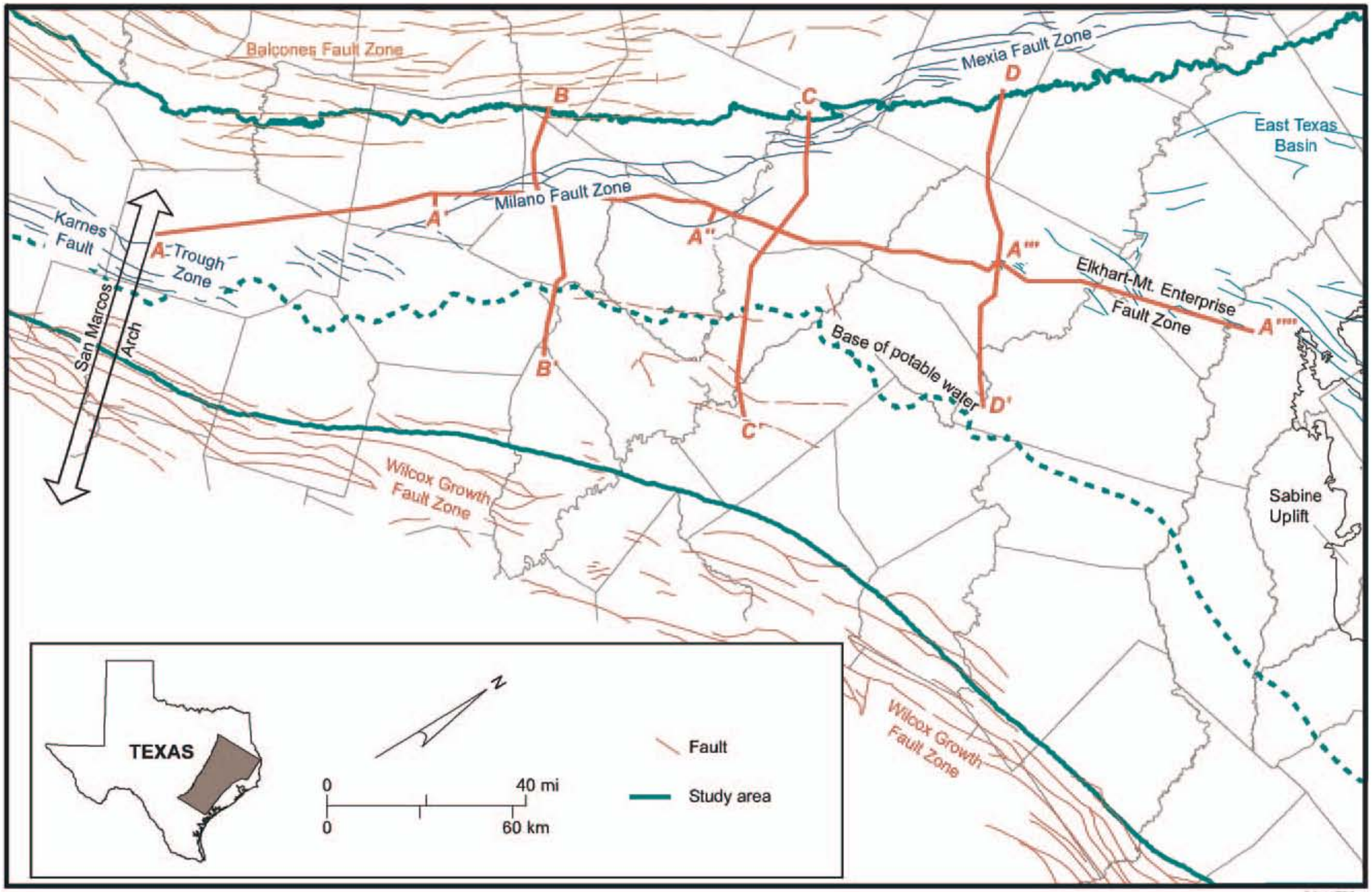

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Figure 14. Geologic structure in the study area. Modified from Ewing (1990). Lines of sections shown in figures 15 and 16.

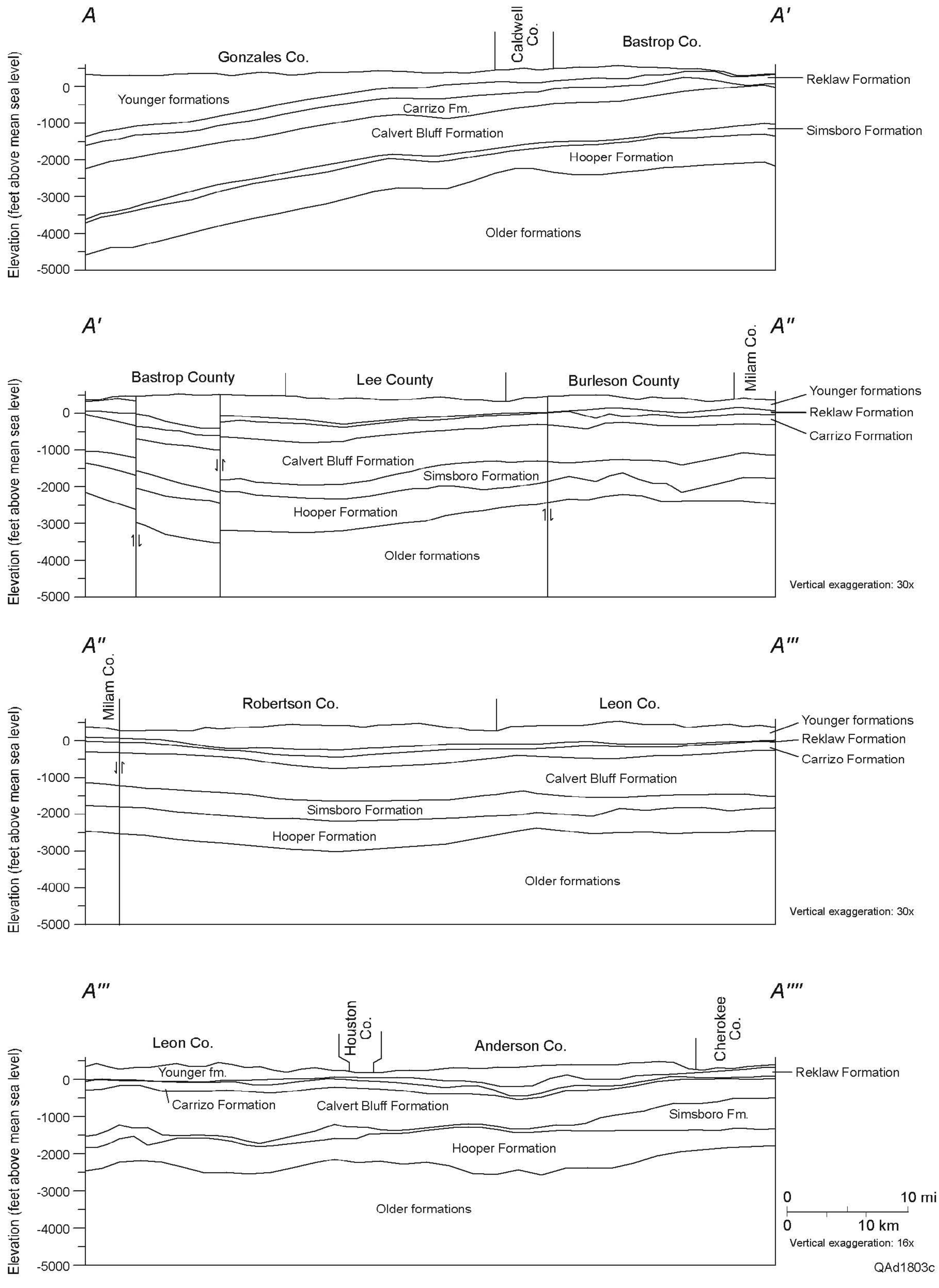

Figure 15. Vertical strike-oriented profile of the formations making up the Carrizo–Wilcox aquifer and adjacent formations. Strike section A–A⁗ shown in figure 14.

displacement of halite beds and the formation of various salt-tectonic features such as salt ridges and salt diapirs or domes (Jackson, 1982).

The Wilcox Group was the first major progradation during the Cenozoic. The Carrizo–Wilcox aquifer, therefore, occurs in a regional setting in which formation dip and thickness increase toward the Gulf of Mexico basin (fig. 16). Dip of the older formations increased as they were buried by younger sediments and as the basin subsided. As subsidence continued during progradation and deposition, formation thickness increased toward the Gulf.

Various fault zones are associated with the basin history of crustal warping, subsidence, and sediment loading. From coastward to inland, these include (1) the Wilcox Growth Fault Zone, (2) the Karnes-Milano-Mexia Fault Zone, and (3) the Balcones Fault Zone (fig. 14).

The Wilcox Growth Fault zone lies at the eastern limit of the study area (fig. 14). The growth or listric faults formed as thick packages of Wilcox sediment prograded onto the uncompacted marine clay and mud deposited in the subsiding basin beyond the Cretaceous shelf edge. Continued downward slippage on the gulfward side of the faults and sustained sediment deposition resulted in the Wilcox Group thickening across the growth fault zone (Hatcher, 1995). Petroleum exploration drilling and geophysical studies within the study area have indicated that many of these large, listric growth faults can offset sediments by 3,000 ft or more. The listric fault planes are curved, the dip of the faults decreases with depth, and the faults die out in the deeply buried shale beds. Complex fault patterns evolved, with antithetic faults forming various closed structures. The growth fault zone forms structural traps that hold major oil and gas reservoirs in the Wilcox Group (Fisher and McGowen, 1967; Galloway and others, 1983; Kosters and others, 1989). A few Wilcox Group oil fields

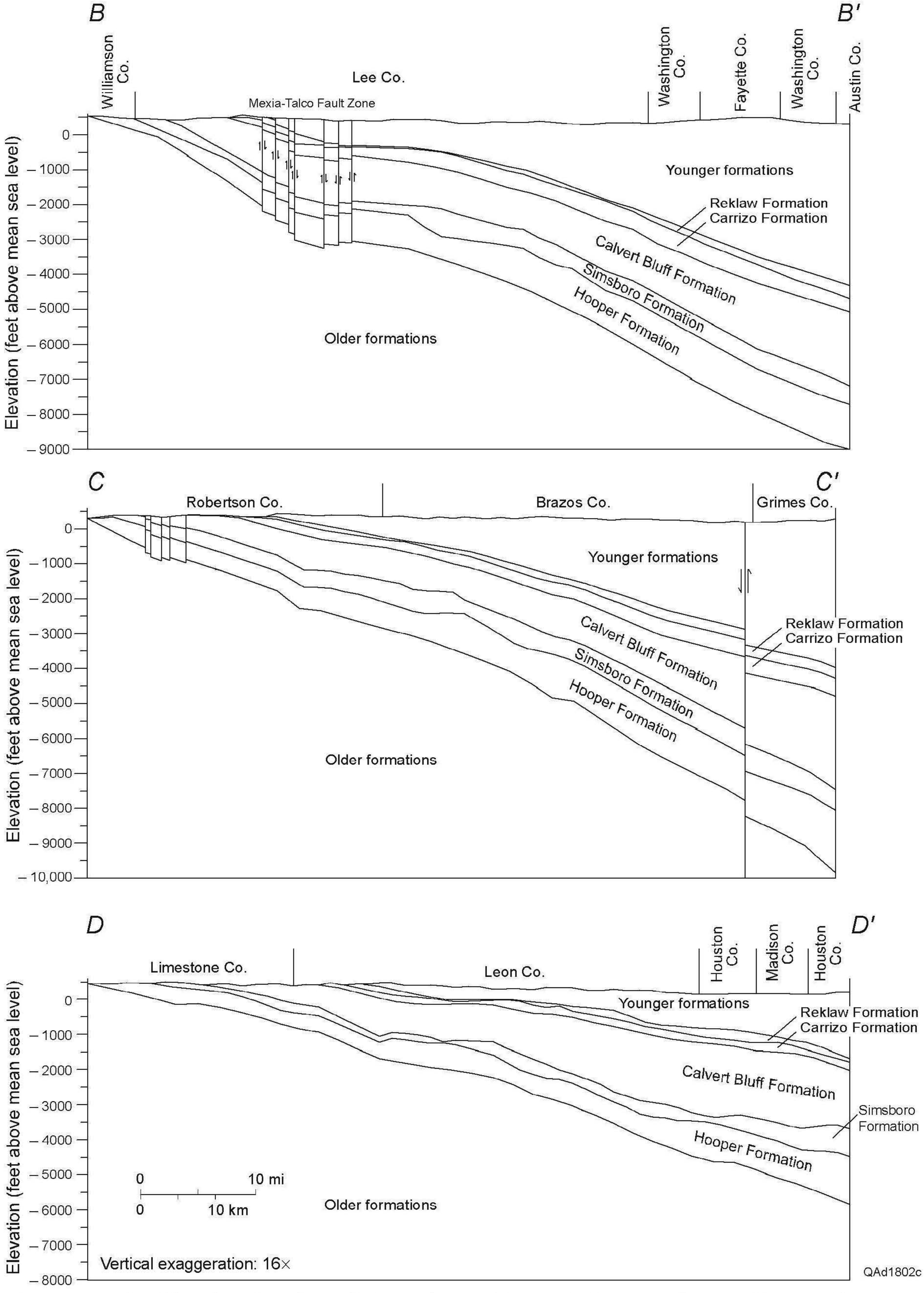

Figure 16. Vertical dip-oriented profile of the formations making up the Carrizo–Wilcox aquifer and adjacent formations. Dip sections B–B′, C–C′, and D–D′ shown in figure 14.

associated with other faults lie updip of the growth fault zone (Fisher and McGowen, 1967; Galloway and others, 1983).

Displacement of halite beds resulting from subsidence, tilting, and sediment loading is the likely mechanism resulting in a zone of normal faults that offset Carrizo–Wilcox strata in the study area, including the Karnes Trough Fault Zone, Milano Fault Zone, and Mexia Fault Zone (fig. 14) (Jackson, 1982; Ewing, 1990). These fault zones in this report are collectively referred to as the Karnes-Milano-Mexia Fault Zone. The fault zone marks the updip limit of the Jurassic Louann Salt (Jackson, 1982). Displacement along the Karnes-Milano-Mexia Fault Zone occurred throughout Mesozoic deposition along the Gulf Coast and continued at least through the Eocene, resulting in noticeable syndepositional features. Numerous faults with as much as 800 ft of displacement that exhibit no syndepositional features are also present throughout the Karnes-Milano-Mexia Fault Zone (Jackson, 1982). In the central and southwest portions of the model, the Karnes-Milano-Mexia Fault Zone displaces sediments by more than 1,000 ft in some areas, restricting the hydraulic communication between outcrop and downdip sections of the aquifer (fig. 16a, b). The Karnes-Milano-Mexia Fault Zone goes updip of the Carrizo–Wilcox aquifer near the northwestern corner of the study area (fig. 14).

Flexure across the structural high between the East Texas Basin and the Gulf of Mexico basin formed extensional faults and associated graben structures of the Elkhart-Mt. Enterprise Fault Zone (fig. 14). This fault zone offsets Carrizo–Wilcox sediments by several hundred feet (Jackson, 1982).

The Balcones Fault Zone consists of numerous fault strands that swing from northwesterly in the southern part of the model area to north-northwesterly in the central and northern part of the area (fig. 14). Faults in this trend are of normal displacement, dominantly dipping to the southeast (basinward), although some northwest-dipping synthetic faults occur (Collins and Laubach, 1990). Fault strands are spaced roughly 1 to 3 mi apart and have throws of 15 to 300 ft (Nance and others, 1994; Collins, 1995). Although the Balcones trend follows the thrust-fault trends of the late Paleozoic Ouachita orogen (Ewing, 1990), activity is limited to the Late Cretaceous and Tertiary (Collins and Laubach, 1990). The zone results from tilting along the perimeter of the Gulf Coast basin, flexure, and gulfward extension (Murray, 1961; Collins and others, 1992). Some evidence points toward movement of this system as recently as Plio-Pleistocene times (Collins and Laubach, 1990).

Structure of the aquifer system also consists of the physical dimensions of the aquifer and its confining layers: the six surfaces describing the elevations of the tops and bottoms and the position of the sides of the model layers. Of all the input data, aquifer-system geometry is probably the best characterized. Structure of the top and bottom of the aquifer is defined by numerous wells, topography of the land surface is mapped, water levels are repeatedly measured to define the top of the aquifer in the outcrop zone, and geologic maps show the lateral extent of formation outcrops. Although formation thickness was not defined exactly at every point in the aquifer, the uncertainty is acceptable and generally does not greatly impact results of a model.

Construction of structural surfaces of layer elevations for input to the computer model required compilation and digitizing of structure information from a number of sources. Sources on subsurface structure included Bebout and others (1982), Ayers and Lewis (1985), Thorkildsen (unpublished data on Carrizo–Wilcox aquifer groundwater modeling and water-quality analysis, East Texas), Kaiser (1990), and Hosman and Weiss (1991). In addition, we used tabulated geologic determinations from geophysical logs contained in the Bureau of Economic Geology Geophysical Log Library. A three-arc second digital elevation model (DEM) of the study area was downloaded from a U.S. Geological Survey (USGS) Website. DEM data were used to define the top elevations of aquifers in their outcrop. Several hundred new stratigraphic picks were made from geophysical logs of oil and gas wells in Anderson, Caldwell, Gonzales, Guadalupe, and Houston Counties. Locations of logs were digitized from Ayers and Lewis (1985) and estimated from county highway maps.

These several data sets are spatially dissimilar, so merging them required both GIS and geostatistical software packages. Construction of layer structure surfaces made use of data as follows:

- Base of Hooper Formation included information from Ayers and Lewis (1985), Thorkildsen (unpublished data), Hosman and Weiss (1991), and outcrop DEM data.
- Base of Simsboro Formation included information from Ayers and Lewis (1985), Kaiser (1990), and outcrop DEM data. The Thorkildsen (unpublished) data were used in areas not otherwise covered.
- Base of Calvert Bluff Formation included information from Ayers and Lewis (1985) and outcrop DEM data. The Thorkildsen (unpublished) data were inserted in areas not otherwise covered.
- Base of Carrizo Formation included information from Ayers and Lewis (1985), Thorkildsen (unpublished data), Hosman and Weiss (1991), and outcrop DEM data.
- Base of Reklaw Formation included information from Ayers and Lewis (1985), Thorkildsen (unpublished data), and outcrop DEM data. The surface formed by these data was extrapolated to areas in the eastern corner of the model.
- Top of Reklaw Formation included information from Ayers and Lewis (1985), Thorkildsen (unpublished data), and outcrop DEM data.

Layer elevations were checked for vertical consistency by mapping layer thickness calculated using a triangulated irregular network method. False points inserted at appropriate locations corrected areas having a vertical discrepancy. Layer elevations were extended to areas lacking geophysical control data by kriging layer thickness, recalculating layer elevations from the kriged surface, and merging the recalculated elevation surface into data-poor areas.

Alluvial deposits associated with the Colorado, Brazos, and Trinity Rivers most likely have a significant impact on the interaction of surface water and groundwater in the outcrop of the Carrizo–Wilcox aquifer. Areal limits of the alluvium associated with the Colorado, Brazos, and Trinity Rivers were digitized from McGowen and others (1987), Proctor and others (1988), Proctor and others (1993a, b), and Shelby and others (1993). The upper surface of the alluvium was taken as ground surface and assigned by draping USGS DEM data onto model cell centroids in the areas underlain by alluvium. Thickness of alluvium was estimated from data on well depth and well-screen position (Wilson, 1967; http://www.twdb.state.tx.us/data/waterwell/well_info.html). The lower surface of alluvium was mapped by subtracting alluvium thickness from DEM for each model cell.

Elevation of the base of the Wilcox Group (base of Hooper Formation) ranges from ground surface at the updip limit of the formation to as much as 12,000 ft below sea level at the downdip limit of the study area (fig. 17). Maps of layer elevation shown in figures 17 through 21 indicate a fixed position of the base of freshwater. The base of freshwater shown on these illustrations is taken from the TWDB map of the freshwater extent of the Carrizo–Wilcox aquifer and is included in the structure maps for reference. The base of freshwater in the Hooper Formation lies some distance farther updip than that shown on the map, which is defined mainly by the downdip limit of freshwater in the Carrizo Formation.

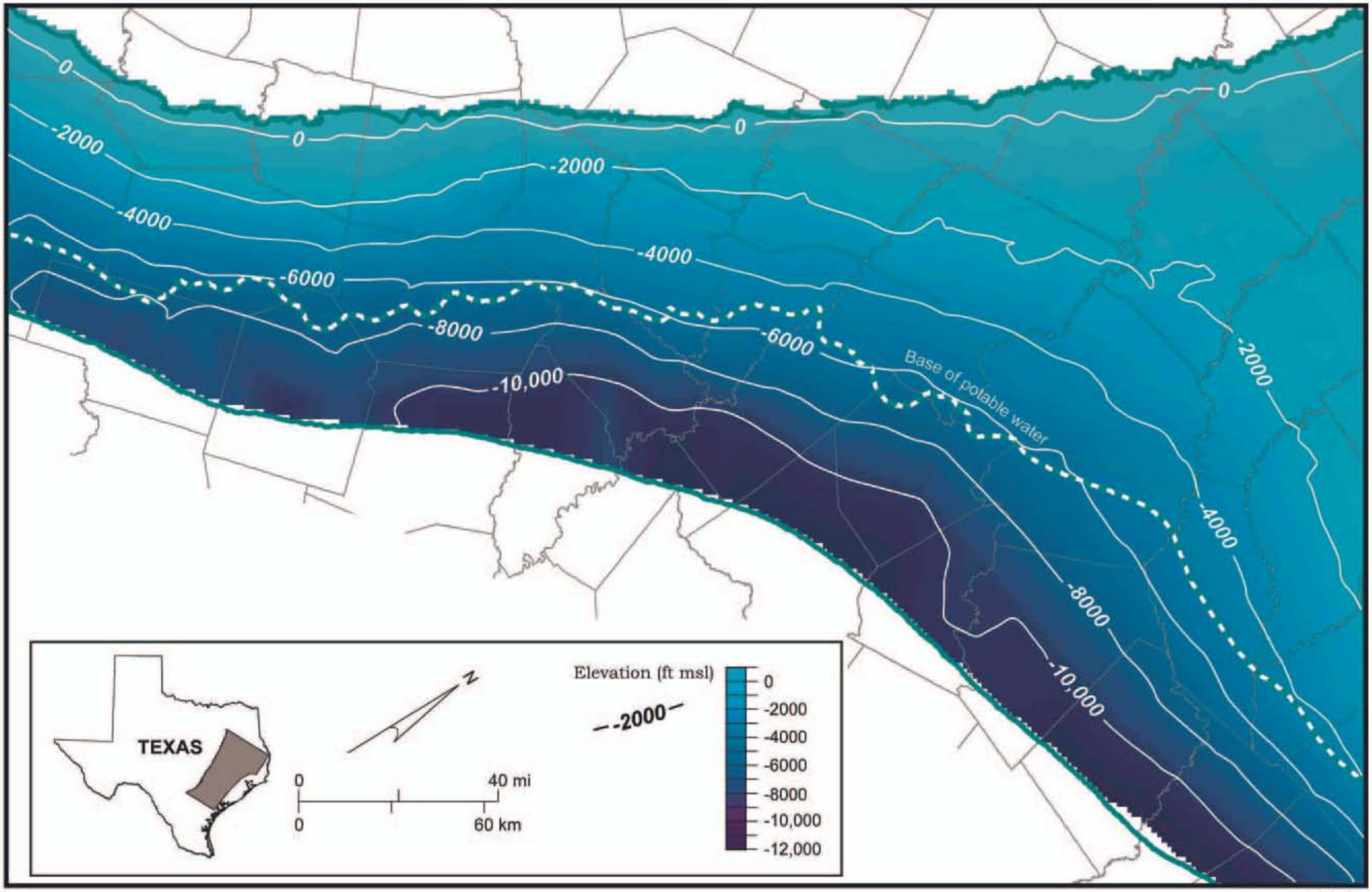

Figure 17. Elevation of the base of the Hooper Formation (base of Wilcox Group).

Structural elevations of the Simsboro and Calvert Bluff Formations (figs. 18, 19) show the same general features of a surface gently dipping to the southeast toward the Gulf of Mexico. The strike of contours on the structural surfaces changes from north-northeast to east and reflects basement structure. The contours strike eastward south of the East Texas Basin and Sabine Uplift. The East Texas Basin lies between the 0-ft elevation contours of the base and top of the Carrizo Formation (figs. 20, 21, respectively) in the northern part of the study area—between the outcrops of the Carrizo Formation to the northwest and northeast. The top of the Reklaw Formation (fig. 22) shows the same major structural features as do the underlying formational contacts. The saddle in the structure of the Reklaw Formation top in Anderson County, lying between the 0-ft elevation contours, marks the southern end of the East Texas Basin.

Thicknesses of each formation were tallied from the geophysical log sources, compiled in a database, and contoured in figures 23 through 26. Each formation thickens southeastward toward the Gulf of Mexico. The freshwater section of the Hooper Formation is mainly less than 1,200 ft thick (fig. 23). Thickness of the Simsboro Formation is greatest (up to 500 ft; fig. 24) in the central part of the study area where the center of deposition was in the Rockdale Delta (Fisher and McGowen, 1967). Because the focus of the model was on the freshwater aquifer, not as much data were compiled for the part of the study area downdip (eastward) of the base of freshwater. This fact and interpolation between different data sets make the mapped thickness of the Simsboro Formation in the deepest part of the study area appear irregular. The thickest part of the Simsboro Formation lies in the northeastern corner of the study area. Thickness of the Calvert Bluff likewise increases downdip and toward the Gulf of Mexico (fig. 25). The thickest part of the Calvert Bluff is in the central part of the study area.

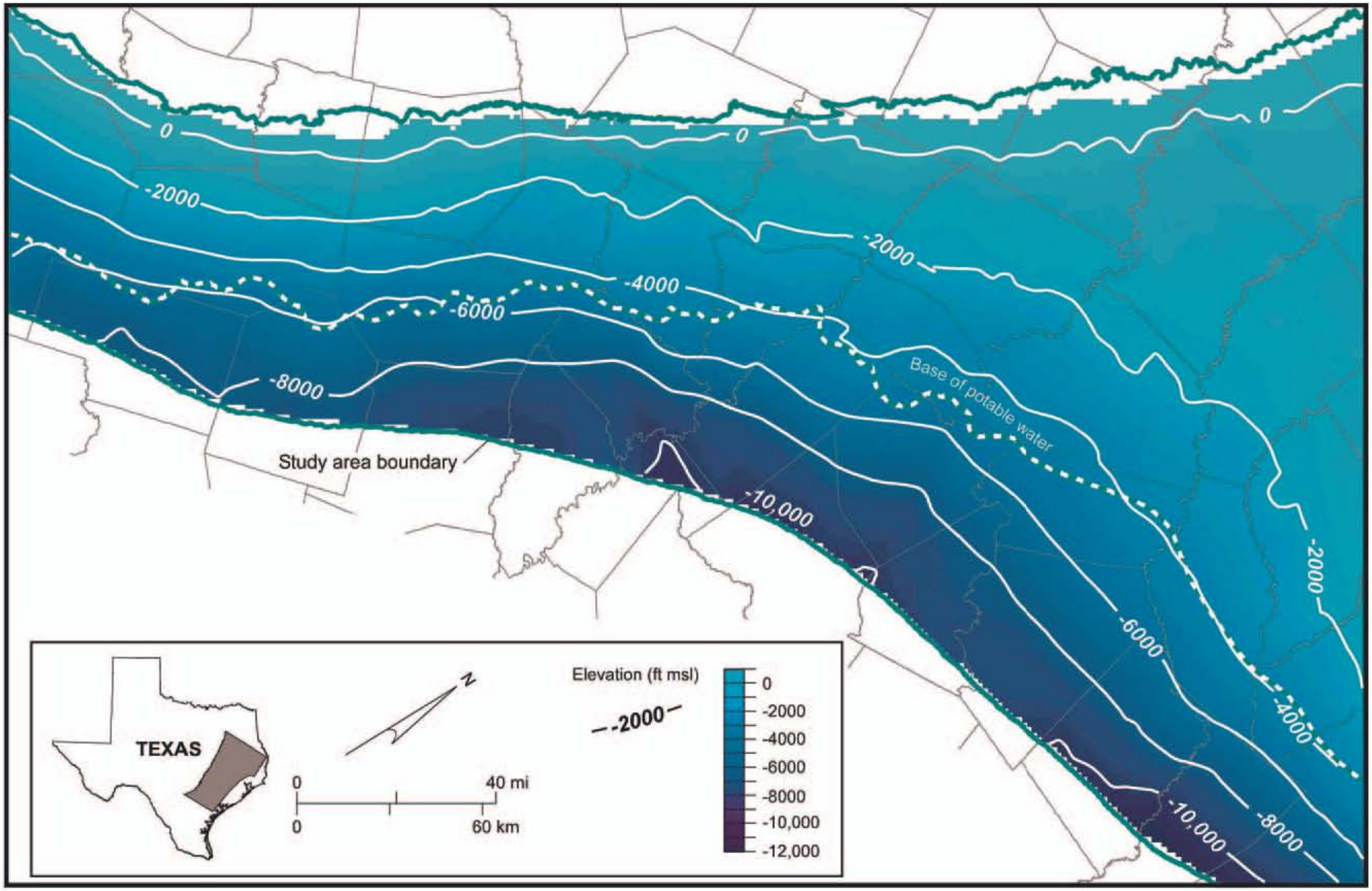

Figure 18. Elevation of the base of the Simsboro Formation (top of Hooper Formation).

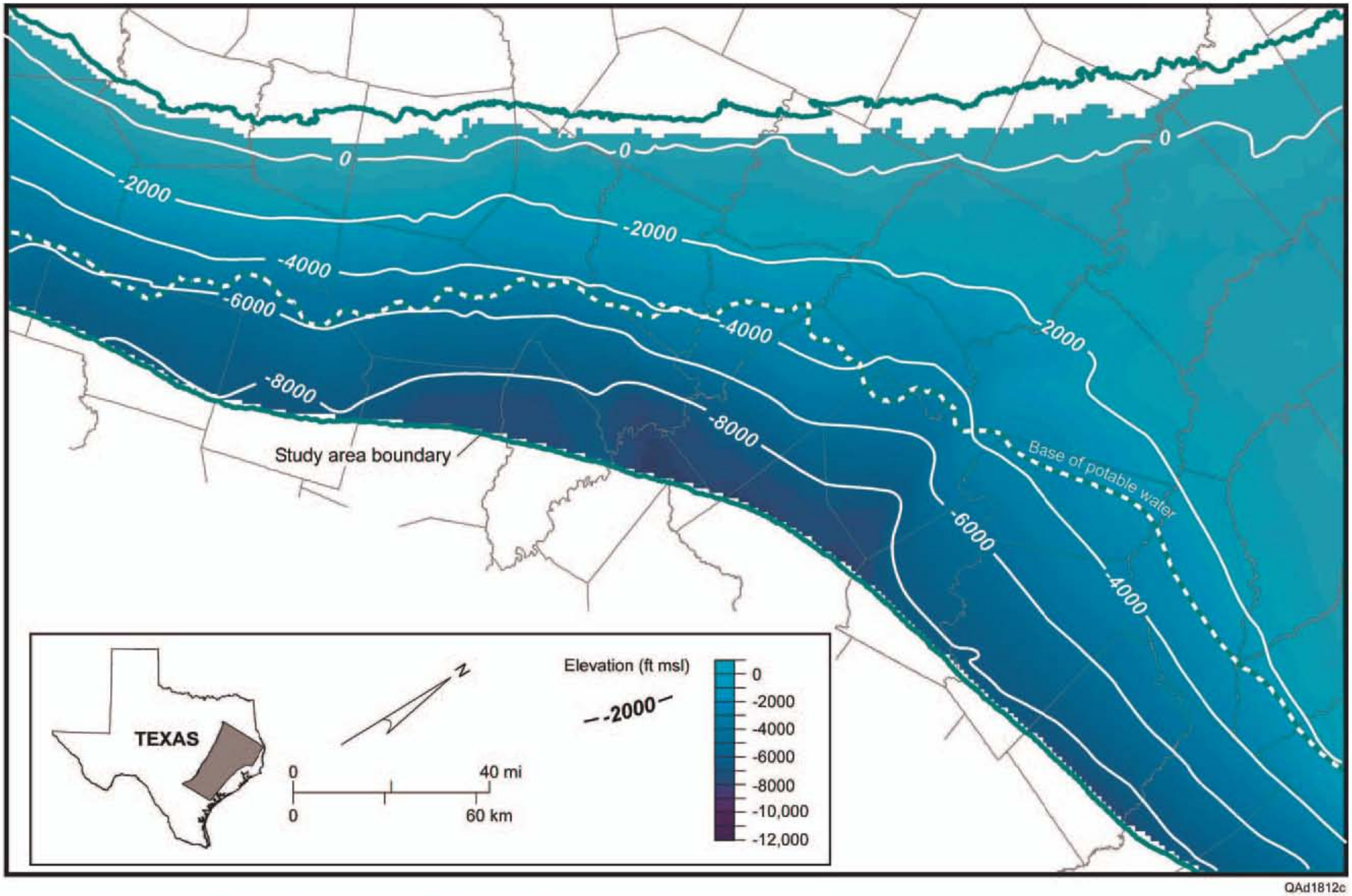

Figure 19. Elevation of the base of the Calvert Bluff Formation (top of Simsboro Formation).

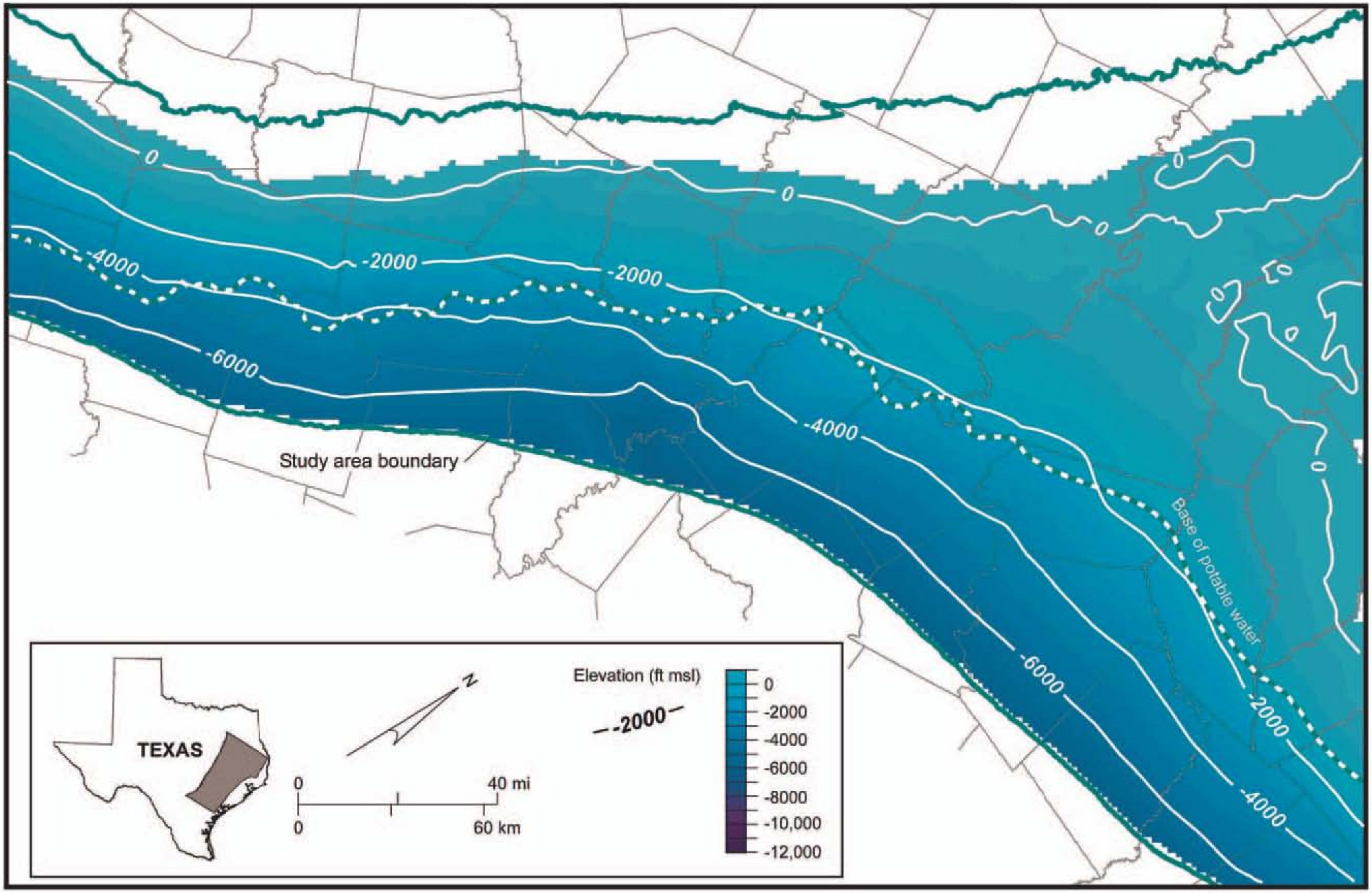

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Figure 20. Elevation of the base of the Carrizo Formation (top of Calvert Bluff Formation).

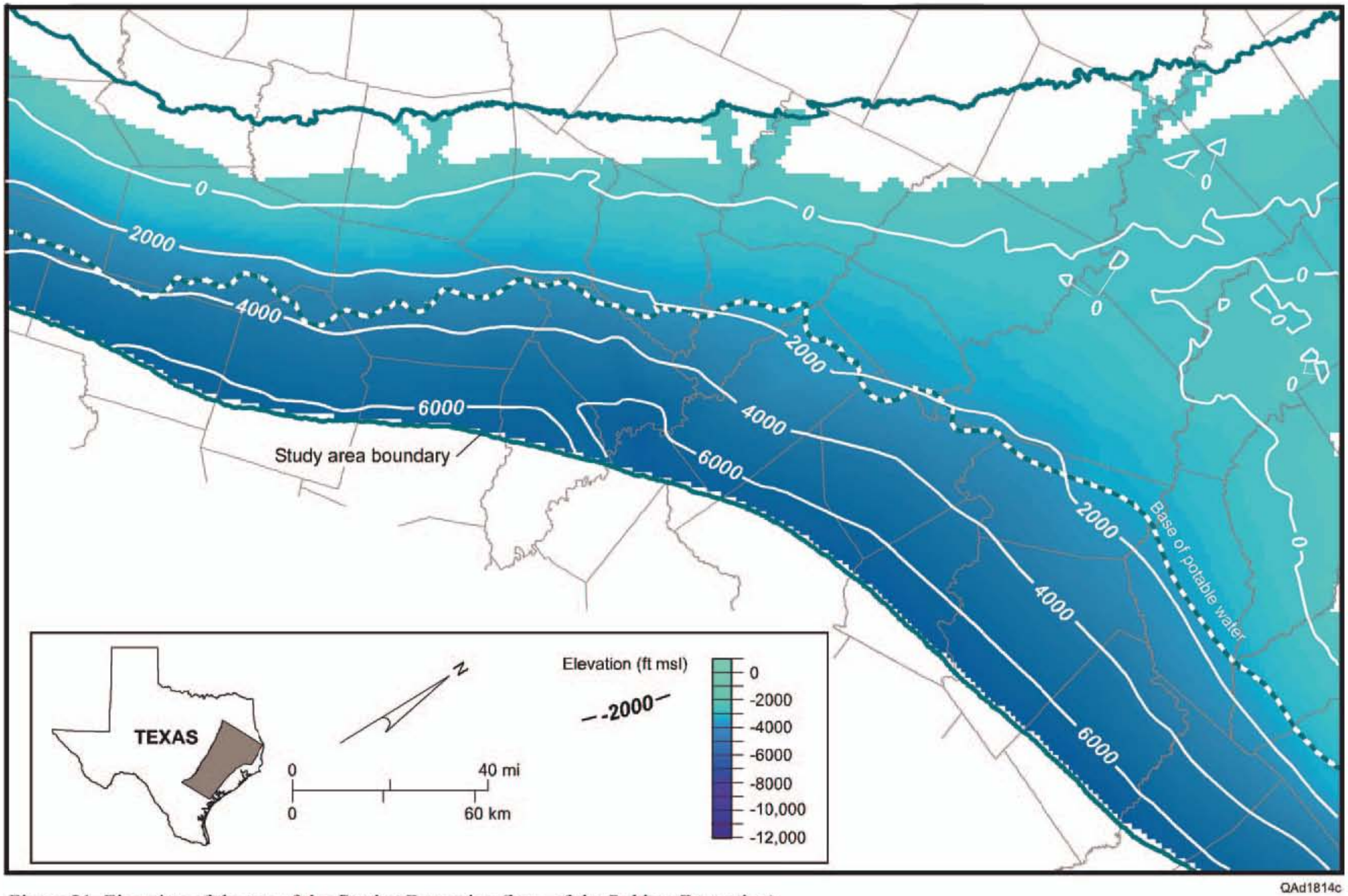

Figure 21. Elevation of the top of the Carrizo Formation (base of the Reklaw Formation).

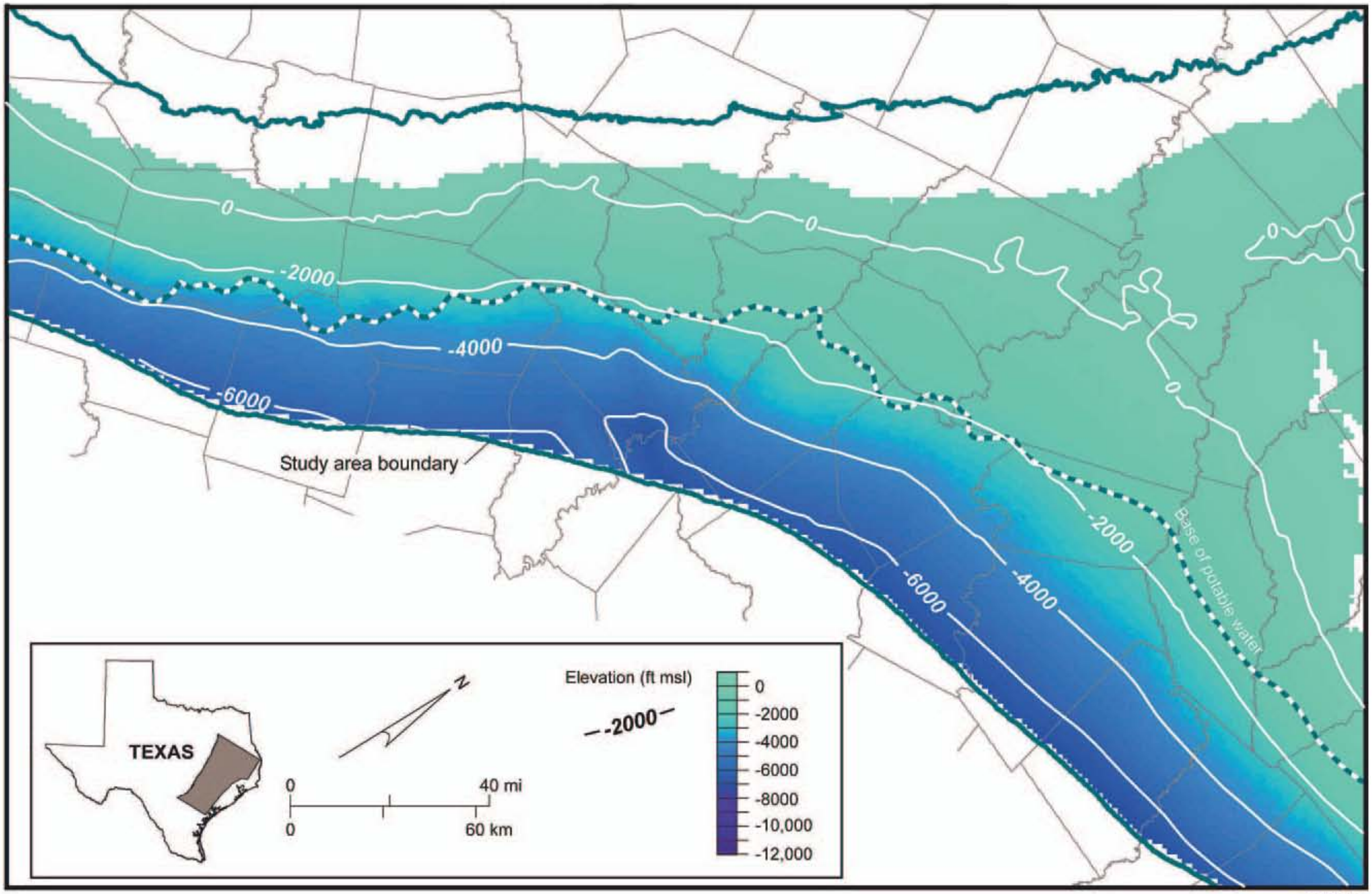

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Figure 22. Elevation of the top of the Reklaw Formation.

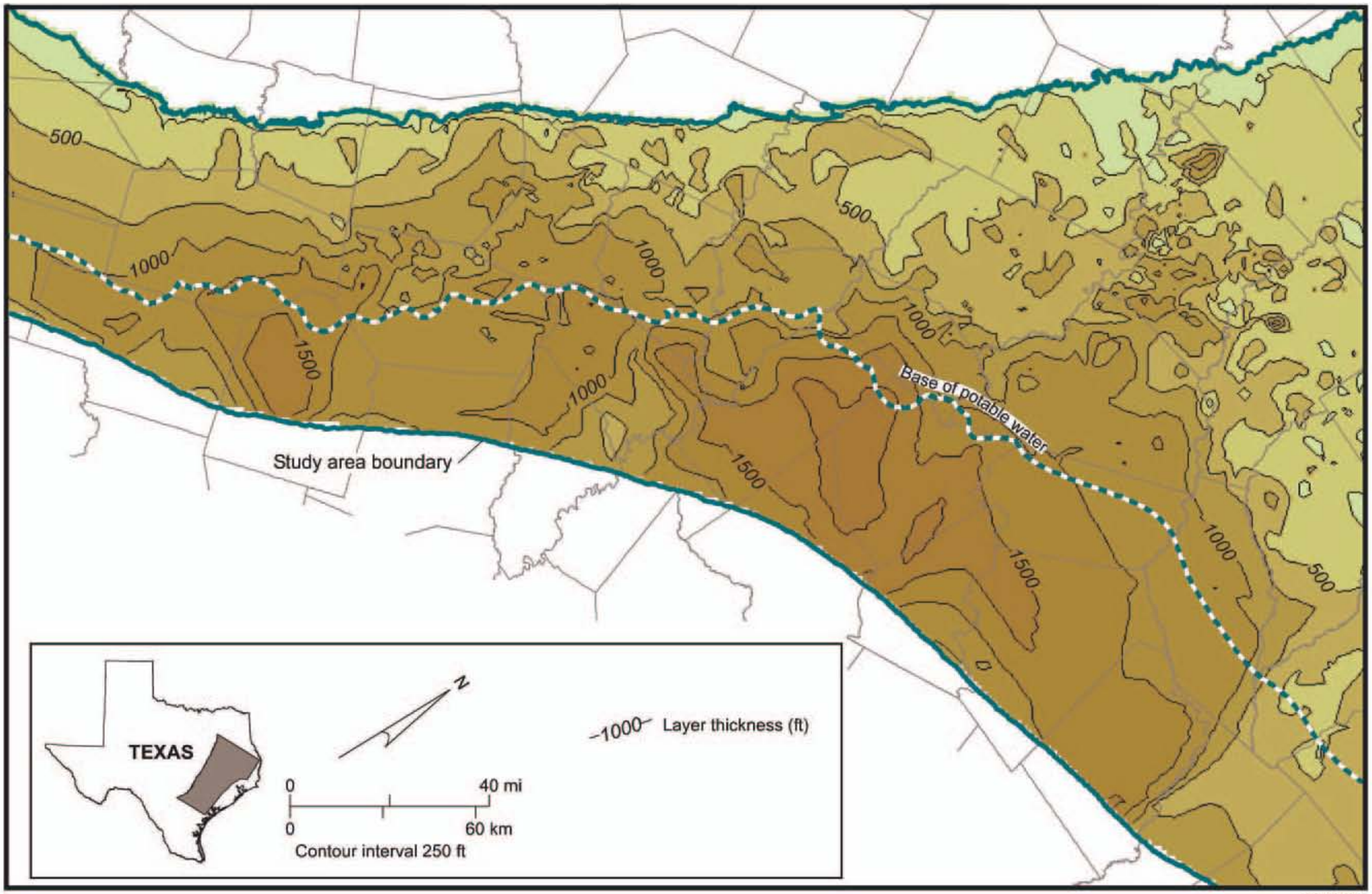

Figure 23. Total thickness of the Hooper Formation.

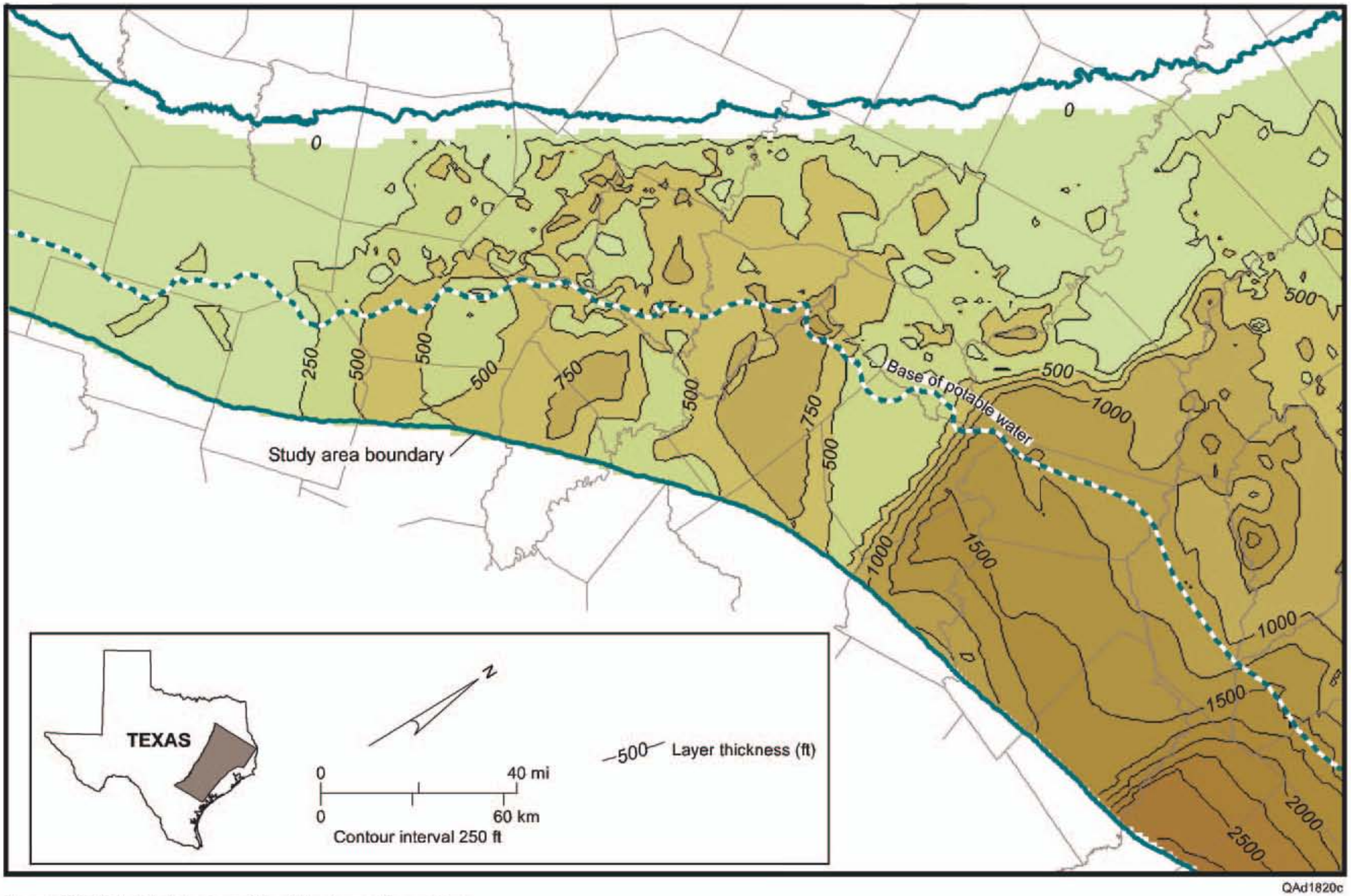

Figure 24. Total thickness of the Simsboro Formation.

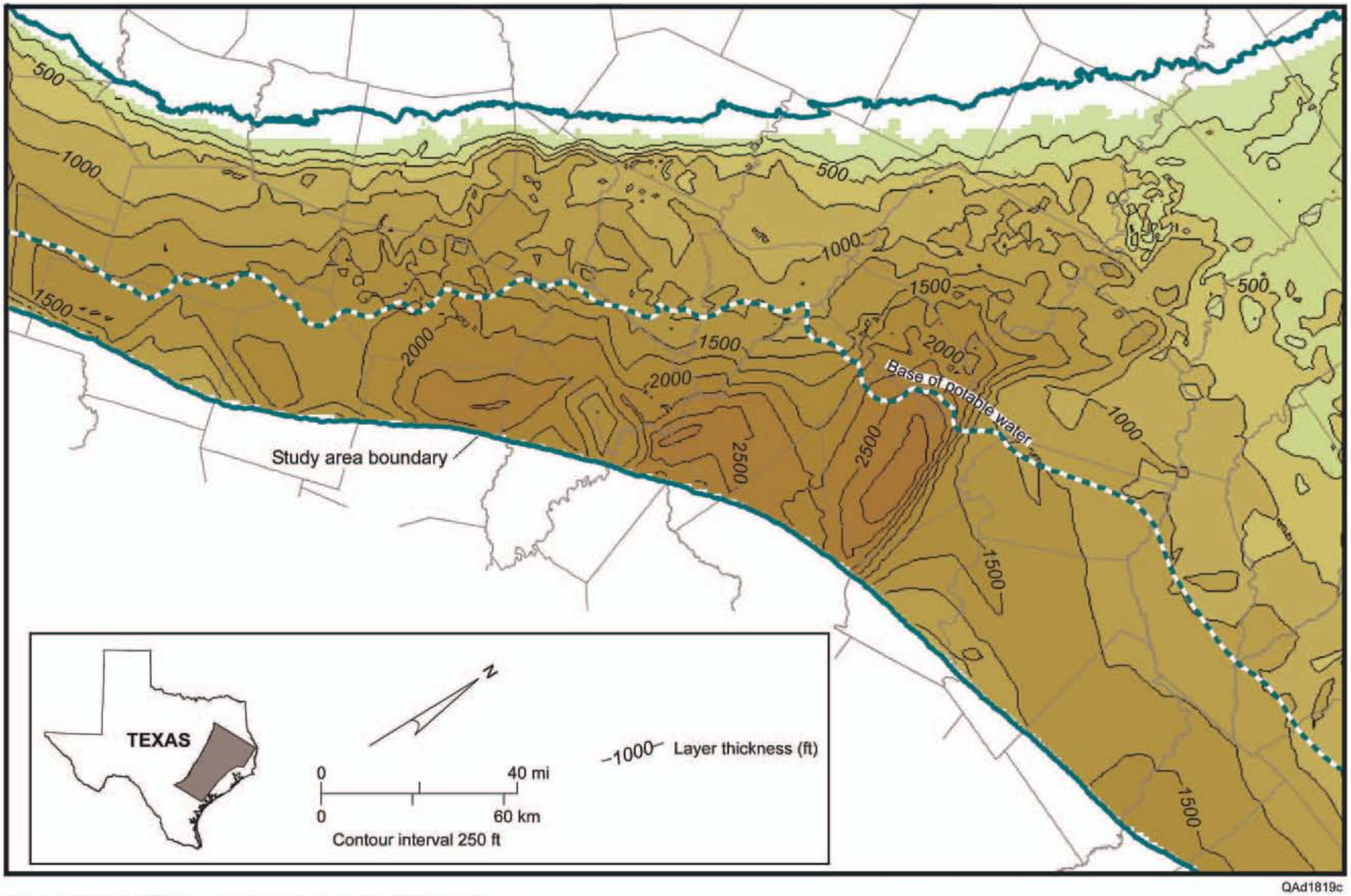

Figure 25. Total thickness of the Calvert Bluff Formation.

Thickness of the Carrizo Formation does not vary downdip as much as in the other formations (fig. 26). Its thickness increases, however, toward the south across the study area. The center of deposition of Carrizo sediments had shifted southward, unlike the earlier Wilcox sediments (Hamlin, 1988). Thickness of the Reklaw Formation in the study area ranges from less than 100 ft to locally more than 300 ft. In the East Texas Basin the formation is from 100 ft to more than 300 ft thick. Thickness of Colorado River alluvium ranges from about 30 to 70 ft in Bastrop County. Alluvium thickness beneath the floodplains of the Brazos and Trinity Rivers in the study area averages about 30 to 50 ft in Milam, Robertson, Henderson, Freestone, and Anderson Counties.

4.3 Water Quality

Water-quality data were compiled from both hydrologic and petroleum-industry sources. Data on total dissolved solids for fresh groundwater in the aquifer were compiled from the TWDB online groundwater database; reports on public water-supply wells compiled by the Texas Commission on Environmental Quality (TCEQ), formerly the Texas Natural Resources Conservation Commission (TNRCC); permit files at the Railroad Commission of Texas (RRC); and individual water-supply companies and well owners. Data on formation waters in Wilcox reservoirs were purchased from IHS Energy Group, Houston. Charge balance for 89 percent of freshwater chemical analyses and 92 percent of formation waters is within ±5 percent.

Data on total dissolved solids (TDS) were posted using ArcView® and manually contoured. Data are insufficient to allow regional mapping of water quality by layer;

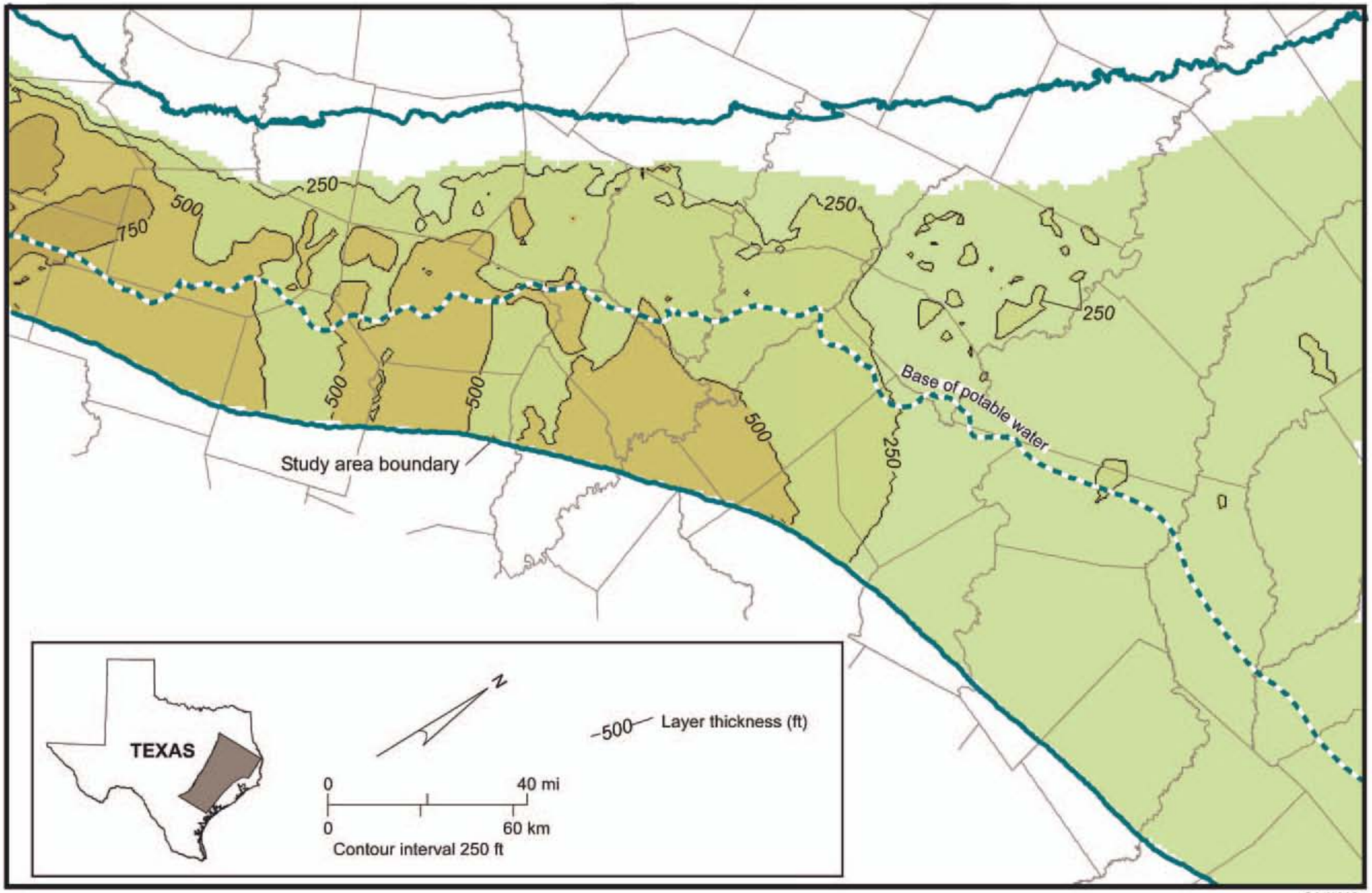

Figure 26. Total thickness of the Carrizo Formation.

figure 27 is a composite map of TDS in the Carrizo–Wilcox aquifer. The downdip limit of the base of potentially potable water in the aquifer as defined by the TWDB was represented by the contour of 3,000 mg/L TDS.

TDS in the outcrop of sand-rich parts of the Carrizo–Wilcox aquifer of Central Texas varies generally from 100 mg/L near the water table to 300 mg/L (fig. 27). Locally TDS can exceed 1,000 mg/L. Most of the confined part of the aquifer has TDS of <500 mg/L, especially in well-interconnected sand-rich zones. Hydrochemical types (Piper, 1944), highly variable in the shallow subsurface, tend to change toward the sodium-bicarbonate ($NaHCO_3$) type as groundwater moves farther downdip in the aquifer. This trend follows a typical pattern of Gulf Coast groundwaters, with ion exchange and incongruent solution of minerals prevalent reactions (Foster, 1950). Salinity variation might also result from leakage of poor-quality water from low-permeability, sand-poor deposits (Henry and others, 1979; Dutton, 1985).

Downdip of the 500 mg/L TDS contour, salinity increases rapidly at 250 to 450 mg/L/mi to the limit of potable water at 3,000 mg/L. Salinity continues to increase at a rate of as much as 1,000 mg/L/mi across the brackish-water zone between 3,000 and 10,000 mg/L and as much as 12,000 mg/L/mi across the saline zone between 10,000 and 100,000 mg/L (fig. 27). In the central and north part of the study area, TDS varies between 10,000 and 50,000 mg/L updip of the growth fault zone. In the south, groundwater with TDS of less than 5,000 mg/L extends into the growth fault zone (Dutton and others, 2002).

The chemical composition of the formation waters associated with oil fields matches that of three water types (sodium-acetate, sodium-chloride, and calcium-chloride waters) identified by Morton and Land (1987) and Land and Macpherson (1992) as typical of

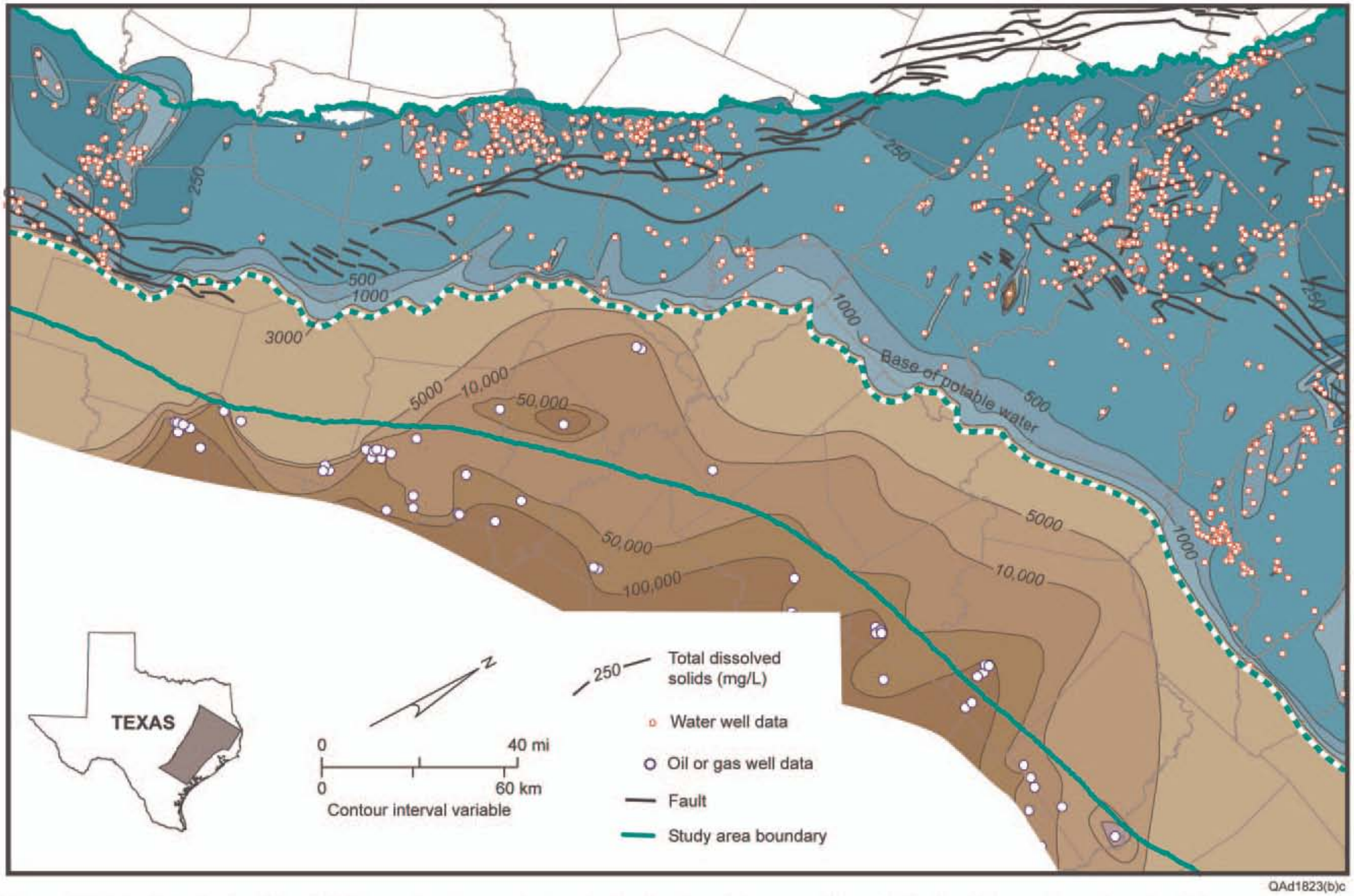

Figure 27. Total dissolved solids (TDS) content of groundwater in the Carrizo–Wilcox aquifer and in the saline section downdip of the aquifer.

the Cenozoic saline section beneath the Texas Coastal Plain. Land and Macpherson (1992) suggested that sodium-chloride water originated from dissolution of halite by groundwater and that sodium-acetate water derived from seawater by sulfate reduction and other mineralogic reactions, including dilution by water released from the smectite-to-illite change. The calcium-chloride water was derived from water moving up faults from the underlying Mesozoic section (Land and Macpherson, 1992).

The downdip extent of freshwater in the Carrizo–Wilcox aquifer may be affected partly by the Karnes-Milano-Mexia Fault Zone, which breaks up the continuity of transmissive sandstones between the outcrop and the deeper, subsurface part of the aquifer (Dutton and others, 2002). Through the middle of the study area, displacement of faults is as much as 1,000 ft (Ayers and Lewis, 1985). The continuity of major sandstones in the Simsboro and Carrizo Formations is disrupted, and locally the Carrizo Formation does not crop out. The width of the freshwater zone in the Carrizo–Wilcox aquifer, as seen in plan view and measured from the outcrop to the downdip limit of freshwater, is only 20 to 30 mi in Central Texas (fig. 27). The major faults die out southwest, where the aquifer is as much as 80 mi wide. To the northeast, the fault zone passes updip of the outcrop and does not affect fluid flow in the Carrizo–Wilcox aquifer. In East Texas the freshwater zone is recharged on both the western and eastern sides of the East Texas Basin and is more than 60 mi wide (fig. 27).

4.4 Water Levels and Regional Groundwater Flow

Subsurface fluid-pressure regimes in the Gulf of Mexico basin include hydropressured, transitional, and geopressured zones (Parker, 1974; Jones, 1975; Bethke, 1986). Hydropressured conditions are typical of near-surface aquifers; their pressure-depth gradient plots along a trend of approximately 0.43 psi/ft. The geopressured zone has pressure-depth gradients of more than 0.7 psi/ft (Loucks and others, 1986).

4.4.1 Data and Methods

To construct maps of the potentiometric surface of the Carrizo–Wilcox aquifer, we pooled data from the freshwater part of the aquifer and from the adjacent, more saline part of the Wilcox Group. Data for the freshwater part of the Carrizo–Wilcox aquifer and the Queen City aquifer were obtained from records of water levels measured in water wells listed in the Texas Water Development Board (TWDB) online groundwater database (http:\\www.twdb.state.tx.us). We selected the earliest measurements in each part of the study area to best represent predevelopment or pseudo-steady-state water levels. Most of the water levels used in the maps were measured in the 1950s, but some were measured as early as the 1930s. Contouring of the water-level measurements took into account topographic elevation of the ground surface.

The process of selecting water levels for calibration and verification of the model involved several steps.

(1) A Microsoft Access database containing TWDB water-level records was compiled for the counties in the study area.

(2) Data quality was reviewed. Wells with three or more historical water-level measurements were candidates for use. For the steady-state calibration, water-level measurements of various dates were selected on a county-by-county basis to include the earliest available measurements. This was necessary because pumping that may have affected water levels started at various times in the study area.

(3) Hydrographs were constructed and inspected for candidate wells. Well hydrographs were discarded if they showed erratic trends near the calibration or verification dates (1990 and 2000, respectively).

(4) Calibration data were assigned to model layers mainly on the basis of the TWDB aquifer code. Where the aquifer code was insufficient (e.g., designated as Wilcox Group), we also compared the calculated elevation of the base of the well against layer elevation; elevation of screened intervals where reported was also checked.

(5) During calibration and verification, we continued to check assignment of well hydrographs by layers. Most changes were for wells assigned to a layer on the basis of total well depth. Some cases were found where the well was drilled only a short distance into a layer; if screen information was reported it might show that the well had been completed in the overlying aquifer unit. It is possible that some wells assigned to one model layer may be screened in an overlying layer.

Water-level measurements from the Bryan-College Station well field were included in the calibration data set. Static water-level measurements from the Simsboro Formation prior to well-field development form an important water-level calibration point in the deep artesian portion of the aquifer. Water-level measurements taken when a well is not pumping are considered static water-level measurements. Simulated water levels reflect drawdown caused by groundwater withdrawal assigned to model cells. Adjusting static water levels for the Bryan-College Station well field is appropriate for comparison with simulated results for model cells. The adjustment followed the method of Anderson and Woessner (1992 , p. 147 –149). An initial water-level recovery was estimated using known transmissivity, average pumping rate, and assumed elapsed recovery time. Initial recovery was projected to an equivalent for a 1-mi grid cell. The correction factor is small relative to measured and simulated changes in water level.

To extend the maps of water-level elevation farther downdip across the saline part of the study area, data on fluid pressure from Wilcox gas wells were compiled from Lasser, Inc. (2000). We extracted data on bottom-hole pressure, cumulative gas production, and measurement depth for 583 Wilcox gas wells in the study area. We checked pressure decline against production and found that the earliest pressure readings sufficed to help us estimate original pressure for each well. Some pressure readings are obviously affected by production in nearby wells. To cull much of the reduced-pressure data we took the highest pressure readings in a 400-mi^2 area (20- × 20-mi area), leaving 31 data points. We then calculated the equivalent water pressure (P_w) by subtracting capillary pressure (P_c) from recorded bottom-hole gas pressure (P_g) using equation 1 (modified from Amyx and others, 1960, p. 138, equations 3 through 6):

$$Pw = Pg - Pc = Pg - H\,(\rho w - \rho g) \qquad (1)$$

where ρ_w and ρ_g are water and gas densities, respectively, and H is the height of the gas column between the measurement point and the reservoir's gas-water contact. Gas density was calculated by applying a gas compressibility (z) factor (Brill and Beggs, 1974).

Capillary pressure increases with height above the gas-water contact. We found few data on elevation of the gas-water contact for the gas fields included in the culled list. We assumed that the typical measuring point for pressure data in Wilcox gas fields in the study area was 100 ft above the gas-water contact (Kosters and others, 1989). In one field the measuring point was 30 ft above the gas-water contact. If our 100-ft value overestimates height of the measuring point above the gas-water contact, the map of potentiometric surface in the downdip gas fields underestimates actual hydraulic head. Finally, we estimated hydraulic head by (1) dividing water pressure by the specific weight of saline water, assumed to be 0.465 psi/ft, and (2) adding pressure head to the elevation head at the measurement point. We merged the same mapped potentiometric surface of the Wilcox geopressured zone with those of the updip aquifers in the Simsboro and the Carrizo Formations (figs. 28, 29).

4.4.2 Predevelopment or Steady-State Distribution of Hydraulic Head

Before aquifer development, water levels in and near the outcrop generally follow topography (figs. 28, 29). Hydraulic head in the freshwater-bearing aquifer is higher beneath upland areas and drainage divides than beneath river valleys and the area downdip of the outcrop (figs. 28, 29; Fogg and Kreitler, 1982; Fogg and others, 1991; Thorkildsen and Price, 1991; Dutton, 1999). Hydraulic head is also higher (>300 ft; figs. 28, 29), where the Carrizo–Wilcox aquifer is recharged at its outcrop across the Sabine Uplift area (Fogg and others, 1991). The Carrizo–Wilcox aquifer in the East Texas Basin area is recharged from both the Sabine Uplift and the aquifer outcrop on the northwestern side of the basin. Between the Sabine Uplift and the aquifer outcrop on the west side of the basin, water-level elevations in both the Simsboro and Carrizo Formations are less than 300 ft (figs. 28, 29). Hydraulic head decreases toward the northeast corner of the study area, reflecting the topographic elevation of less than 100 ft msl in the Angelina River valley.

These patterns of water-level elevation suggest that groundwater moves from the upland areas toward river bottomlands in the outcrop and also downdip to deeper parts of the aquifer. Groundwater in the Simsboro and Carrizo Formations generally is unconfined where the formations crop out and confined where the formations are overlain by the Calvert Bluff and Reklaw Formations (fig. 11). The fact that water levels are highest in the outcrop

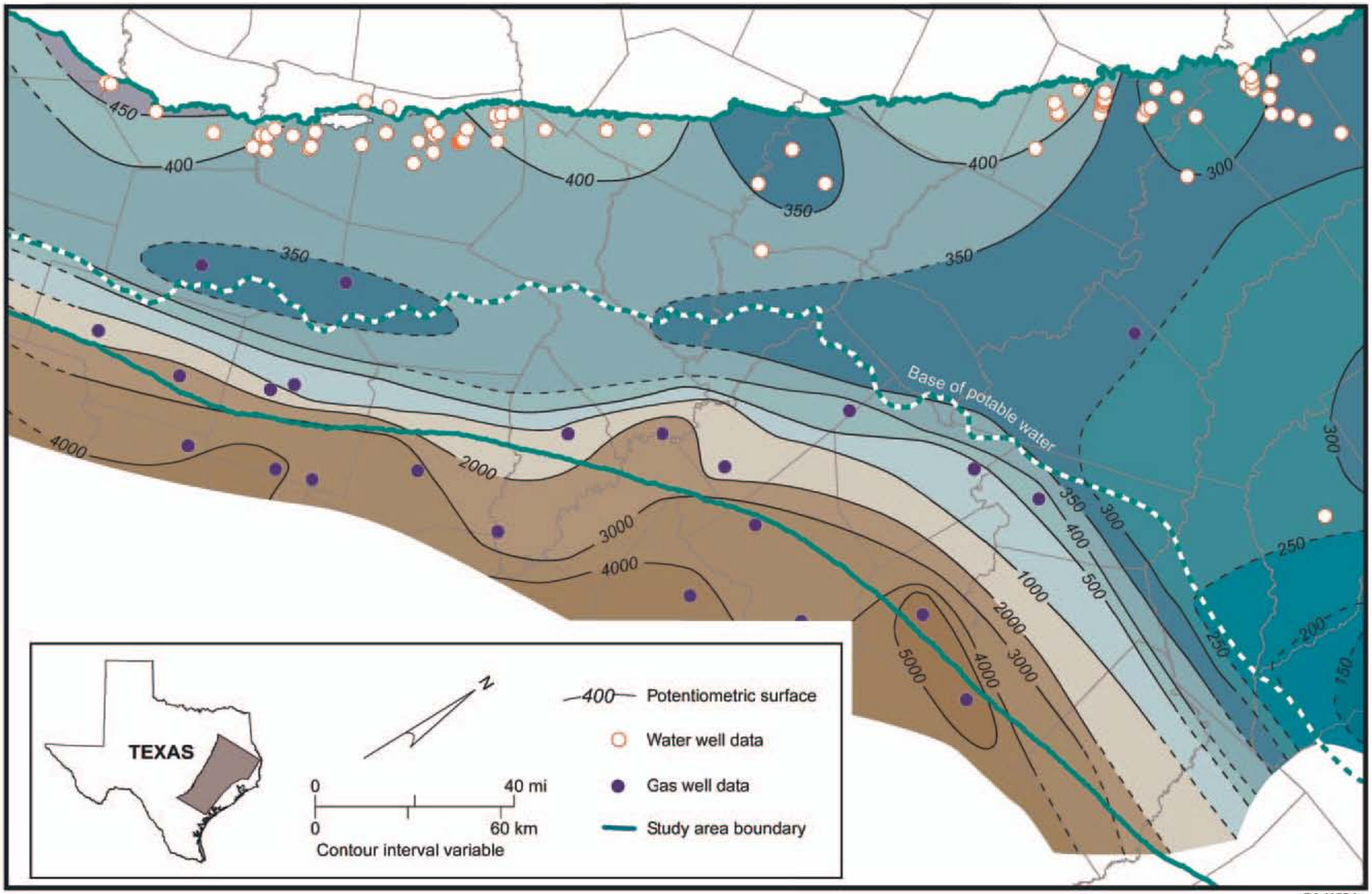

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Figure 28. Water-level elevation under "predevelopment" conditions in the Simsboro aquifer based on measurements made between 1936 and 1953.

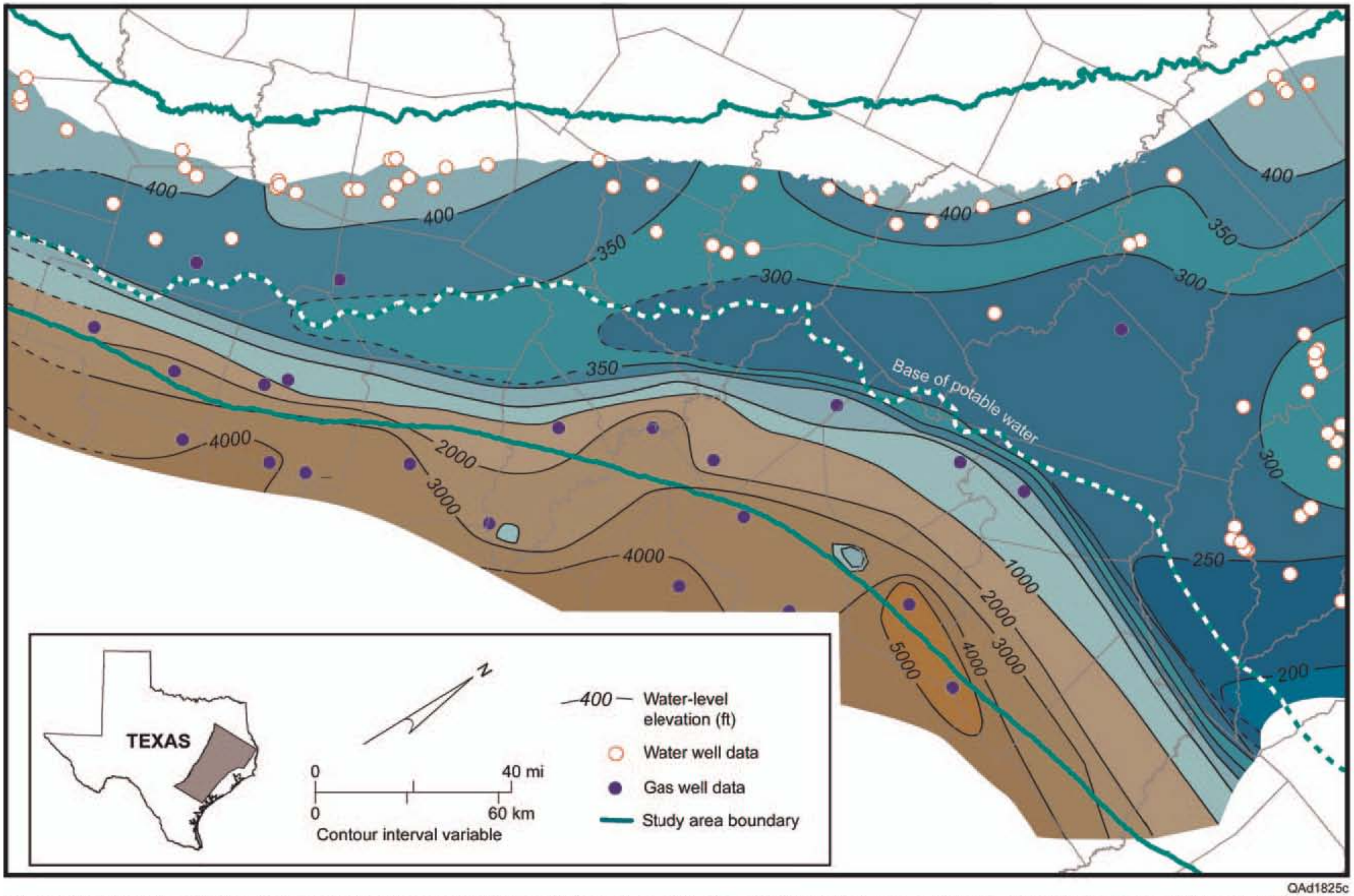

Figure 29. Water-level elevation under "predevelopment" conditions in the Carrizo aquifer based on measurements made between 1901 and 1955.

beneath the upland areas indicates that most recharge naturally occurs there under historical and present conditions.

Hydraulic head in the aquifer system is continuously distributed in three spatial dimensions. Figures 28 and 29 show the horizontal component of the hydraulic-head distribution and indicate the potential for lateral flow of groundwater in the Simsboro and Carrizo aquifers. The potential for vertical movement of groundwater between the units of the Carrizo–Wilcox aquifer is proportional to the vertical gradient in hydraulic head. Vertical gradients in hydraulic head between the Queen City and Carrizo–Wilcox aquifers in the East Texas Basin, including parts of Anderson, Cherokee, Freestone, Henderson, and Leon Counties in the model area, show the potential for downward leakage from the Queen City aquifer to the Carrizo–Wilcox aquifer everywhere except beneath major stream valleys (Fogg and Kreitler, 1982). The groundwater model by Dutton (1999) found that under steady-state conditions, cross-formational movement of groundwater was downward beneath upland areas and upward beneath the major stream valleys. Groundwater withdrawal from the aquifers can locally change the vertical gradient.

Fluid pressure in the deepest part of the modeled area is transitional between hydropressured and geopressured conditions. A transition interval between hydropressured and truly geopressured conditions is typical of Gulf of Mexico deposits. Geopressure is thought to result from a combination of (1) rapid burial of uncompacted sediments, (2) presence of low-permeability sediments and fault zones that restrict movement or release of deeply buried fluid, and (3) conversion of bound water to pore water from the temperature-controlled mineralogic phase change of smectite to illite (Bethke, 1986; Harrison and Summa, 1991). Bethke (1986) concluded that a low-permeability seal is critical for development and preservation of geopressured conditions in the Gulf of Mexico Basin;

geopressure would have bled off without bounding seals. The updip limit of the geopressured zone occurs in the thick shale section and shale-bounded growth fault zone that lies downdip of the Cretaceous shelf margin around the Gulf of Mexico Basin.

Hydraulic head calculated for formation water in equilibrium with gas pressures in Wilcox reservoirs varies from less than 400 ft to more than 5,000 ft across the study area (figs. 28, 29). A hydraulic-head minimum appears to lie near or within a zone about 10 to 12 mi downdip of the base of freshwater. The gradient in hydraulic head in the confined part of the Carrizo–Wilcox aquifer is approximately 0.001 to 0.002, directed toward the Gulf of Mexico. The gradient reverses direction and is steeper, approximately 0.02 to approximately 0.04, directed inland from the geopressured zone.

Given the decrease in hydraulic head with groundwater flow downdip from the aquifer outcrop (downdip-directed gradient) and the presence of geopressured conditions in the deep Wilcox Group, hydraulic head must reach a minimum in the Carrizo–Wilcox aquifer at some point downdip of the outcrop, beyond which the hydraulic-head gradient reverses and head increases across the geopressured zone toward the Gulf of Mexico. We show the "valley" of minimum hydraulic head, located between the aquifer and the geopressured zone, sloping or dipping to the northeast, toward the area of the Sabine River valley with the lowest topographic elevation in the study area. The presence of a hydraulic-head minimum indicates that there is appreciable vertical flow between formations. It is possible that the vertical component may be greater than the lateral component of groundwater flow in that zone.

The updip-directed gradient in hydraulic head and salinity implies some fluid movement out of the geopressured zone under initial reservoir conditions. As pointed out by Bethke (1986) if there had been much fluid movement, geopressure would have bled off through geologic time, and saline formation waters would extend much closer to the outcrop. The amount of updip and vertical movement of fluid from the geopressured zone may be limited by fluid density, formation dip, and hydraulic conductivity. Additional work needs to be done on a local scale to quantify the mass flux of water and solutes out of the geopressured zone (Harrison and Summa, 1991).

One implication of the reversal in gradient in hydraulic head is that there may have been a stagnation zone (Tóth, 1978) in the area downdip of the base of freshwater. Rate of lateral movement of groundwater within this stagnation zone may have been close to zero. Very slow rate of flow is also a consequence of the density of fluid and the dip of the formation structure.

As previously noted, significant reductions in reservoir pressure have occurred with production of gas from the Wilcox gas fields in the growth fault zone. The regional gradient in hydraulic head between the geopressured zone and the freshwater part of the Carrizo–Wilcox aquifer has undoubtedly changed. It was beyond the scope of this study to map the historic or transient change in fluid pressures in the Wilcox gas fields.

Water-level elevations in the Queen City aquifer generally lie between 200 and 400 ft in the area south of the Trinity River, lower in valleys and higher in upland areas (fig. 30). The Queen City aquifer is the first major aquifer overlying the Carrizo–Wilcox aquifer. Water levels in the Queen City aquifer in the study area are highest beneath areas of higher topography between the Trinity and Neches Rivers and between the Neches and Angelina Rivers (fig. 6).

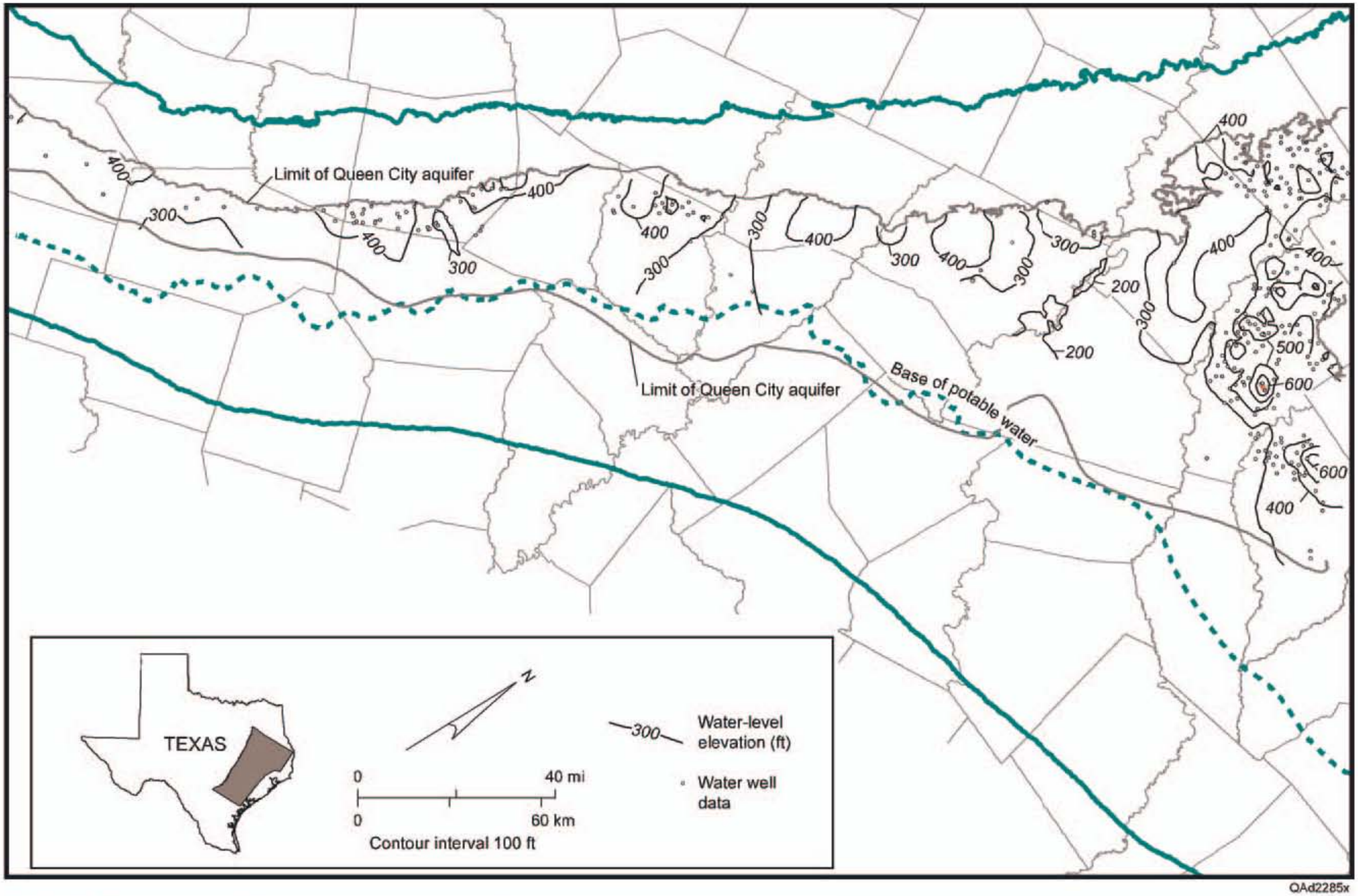

Figure 30. Water-level elevation under "predevelopment" conditions in the Queen City aquifer.

4.4.3 Postdevelopment Changes in Hydraulic Head

Groundwater has been produced from the Carrizo–Wilcox aquifer for more than 50 yr. The Bryan-College Station well field, for example, was developed in the 1950s. At the center of the Bryan-College Station well fields water-level elevations in the Simsboro aquifer that were initially about 350 to 355 ft above mean sea level (msl) had decreased to about 160 to 165 ft msl by 1990 (fig. 31) and to about 10 to 20 ft msl by 2000 (fig. 32). At the center of the Lufkin-Angelina County well field in the Carrizo aquifer, hydraulic head had decreased from a predevelopment level of about 270 ft msl to more than 260 ft below sea level by 1990 (fig. 33) and to more than 300 ft below sea level by 2000 (fig. 34). The maps of hydraulic head in 1990 and 2000 (figs. 31 through 34) show the continued effect of recharge from the Sabine Uplift area, with water-level measurements of more than 300 ft msl. The maps also show a drop in water level in northern Cherokee and southern Smith Counties and parts of adjacent counties that are a result of pumping beyond the northern boundary of the study area.

Decline in water level in the confined part of the aquifer downdip of the outcrop results from a decrease in artesian pressure in the aquifer. The top of the aquifers (figs. 18 through 21) lies far beneath the levels to which water rises in the artesian wells of the Carrizo–Wilcox aquifer. When groundwater is pumped from the aquifer, much if not most of the loss of hydraulic head comes from small changes in pressure applied to grains of sand and clay and other sediment, as well as the binding cement that make up the matrix of the aquifer.

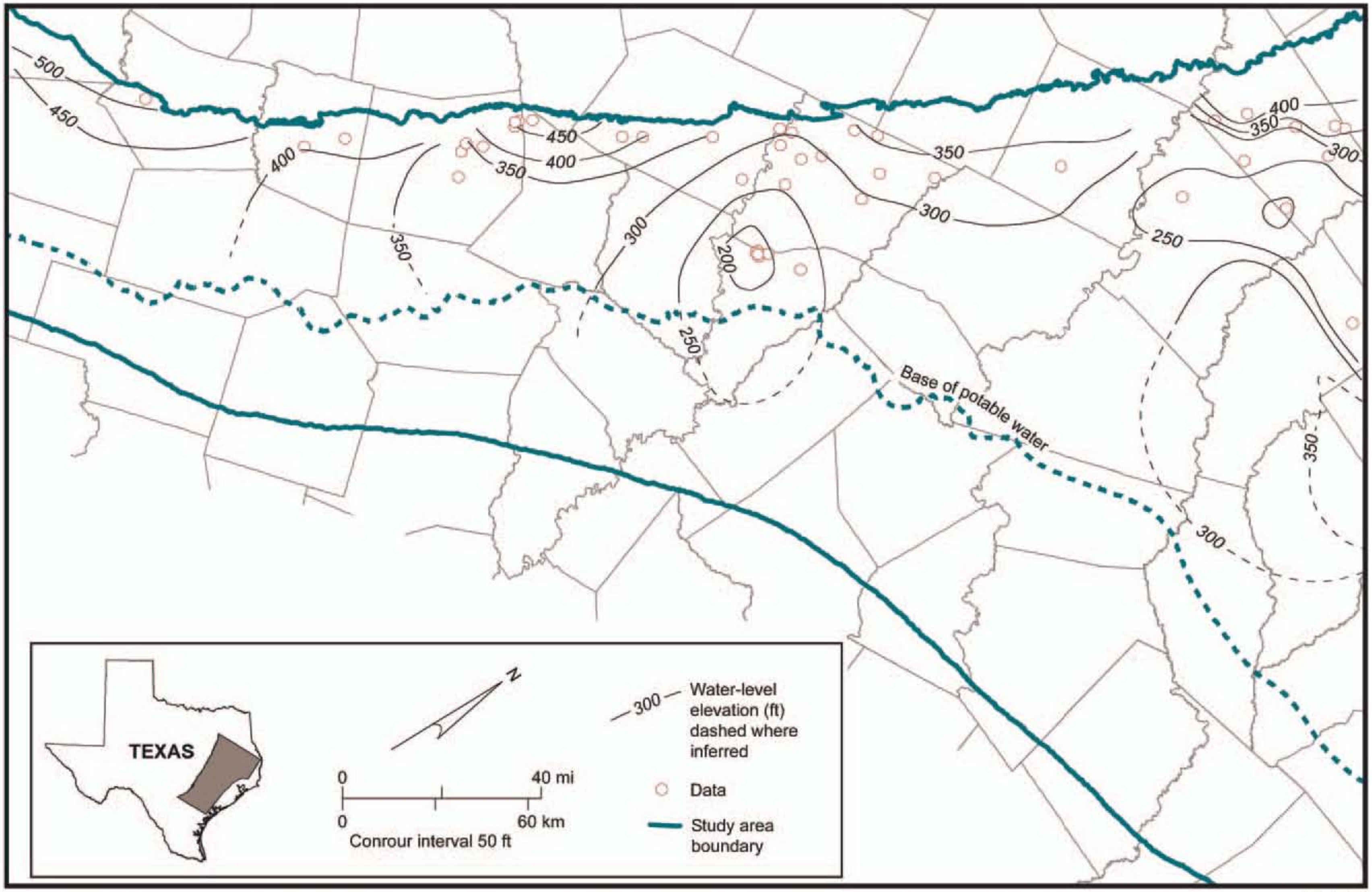

Figure 31. Water-level elevation in the Simsboro aquifer measured during 1987 through 1990 and used for the 1990 model-year calibration.

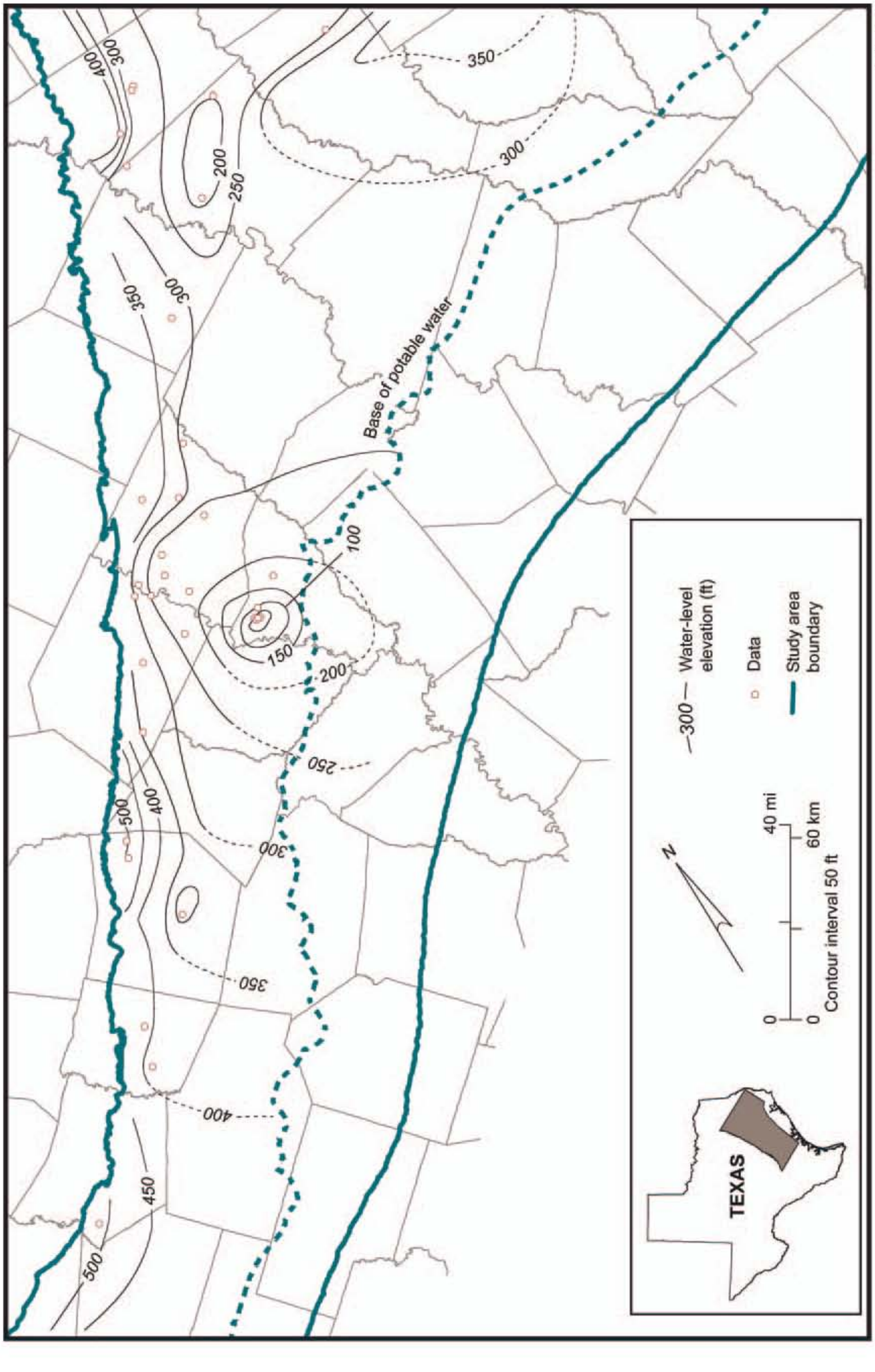

Figure 32. Water-level elevation in the Simsboro aquifer measured during 1995 through 2000 and used for the 2000 model-year calibration.

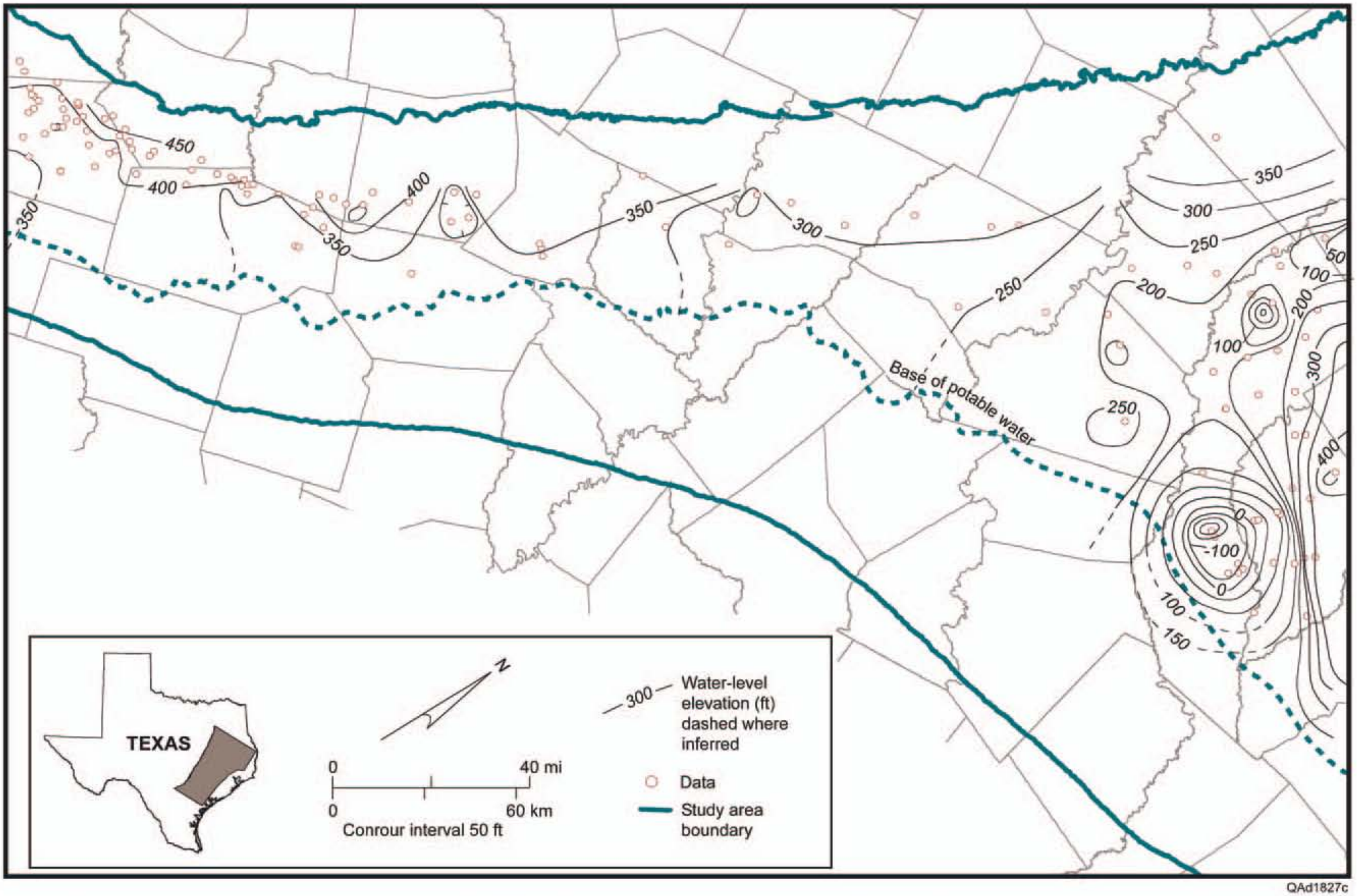

Figure 33. Water-level elevation in the Carrizo aquifer measured during 1987 through 1990 and used for the 1990 model-year calibration.

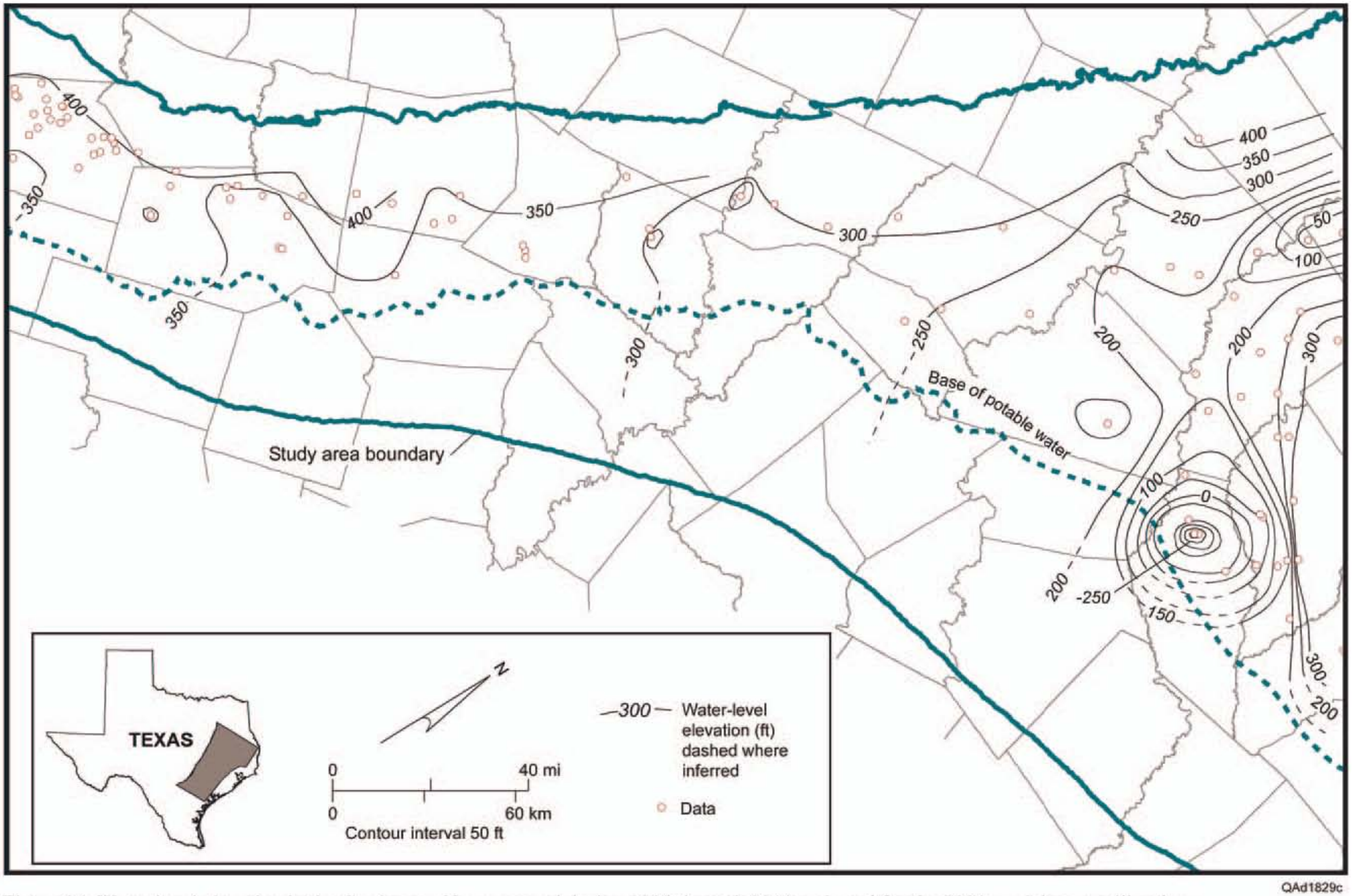

Figure 34. Water-level elevation in the Carrizo aquifer measured during 1995 through 2000 and used for the 2000 model-year calibration.

Most hydrographs of water level in the Hooper Formation show only slight variations over the past 20 to 30 yr (fig. 35) because there has not been much pumping from that part of the Carrizo–Wilcox aquifer. A well in Bastrop County shows a slight water-level rise and a well in Freestone County shows a slight water-level fall. Most of the wells in which water-level measurements in the Hooper Formation are available are close to its outcrop (fig. 36). Hydrographs for the Simsboro aquifer show more fluctuation and generally a decline in water levels (fig. 37). These patterns reflect greater rates of pumping from the Simsboro Formation than from the Hooper Formation. Hydrographs of Calvert Bluff water levels show a range of characteristics: steady levels, gentle declines, and fluctuations (fig. 38). Water levels in Angelina County, at the northern edge of the study area, have shown some of the greatest changes (fig. 39). In general, however, outside of the areas of large withdrawals of groundwater, water-level change in most of the Carrizo–Wilcox aquifer has been slight and gradual.

We also looked at hydrographs of water levels in the Queen City aquifer to evaluate whether water-level fluctuations needed to be taken into account in setting the model's upper boundary. In general, water levels in the Queen City aquifer have remained steady throughout the past several decades. Of 126 well records examined, only 6 cases were seen in which water-level decline was significant, as much as 105 ft. Wells showing appreciable decline include 3469901 (Smith County), 3727103 (Nacogdoches County), 3841701 (Leon County), 3956301 (Leon County), 3955302 (Leon County), and 6708604 (Fayette County). Water-level records from other nearby wells do not show much decline, indicating that these reported changes are local and not regional.

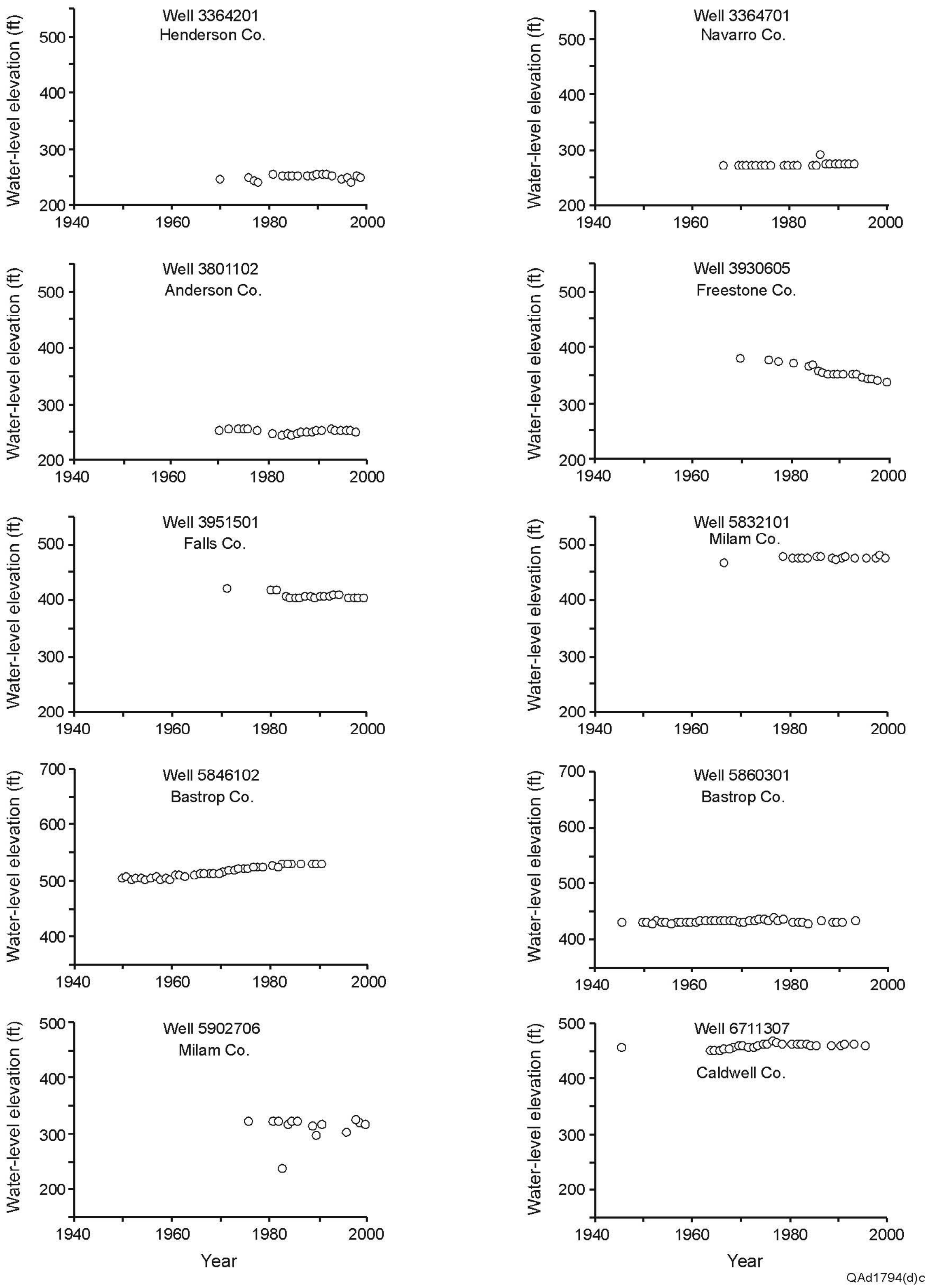

Figure 35. Hydrographs for 10 representative wells in the Hooper Formation (layer 6). Locations of wells shown in figure 36.

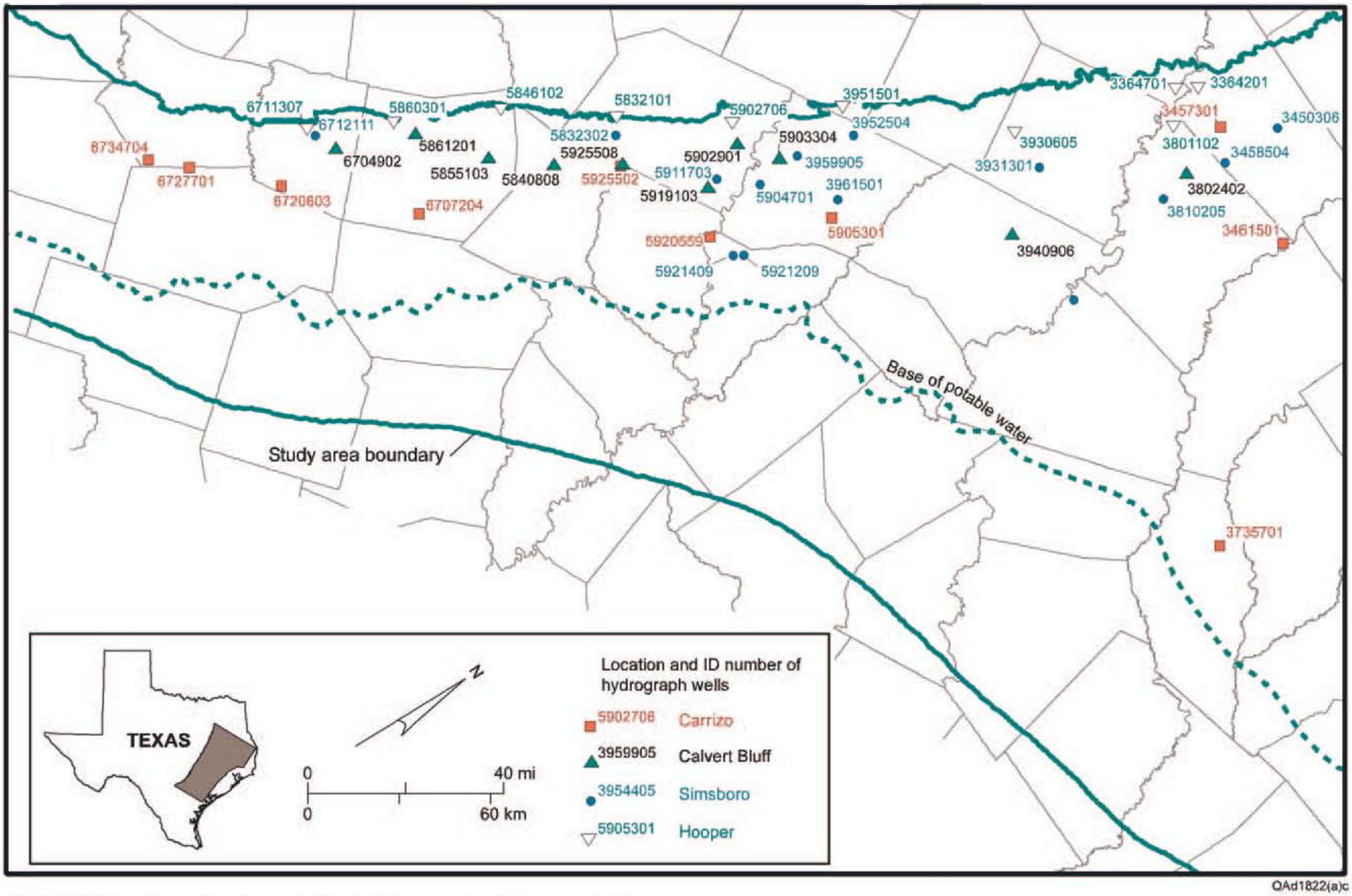

Figure 36. Locations of water wells for which hydrographs are presented.

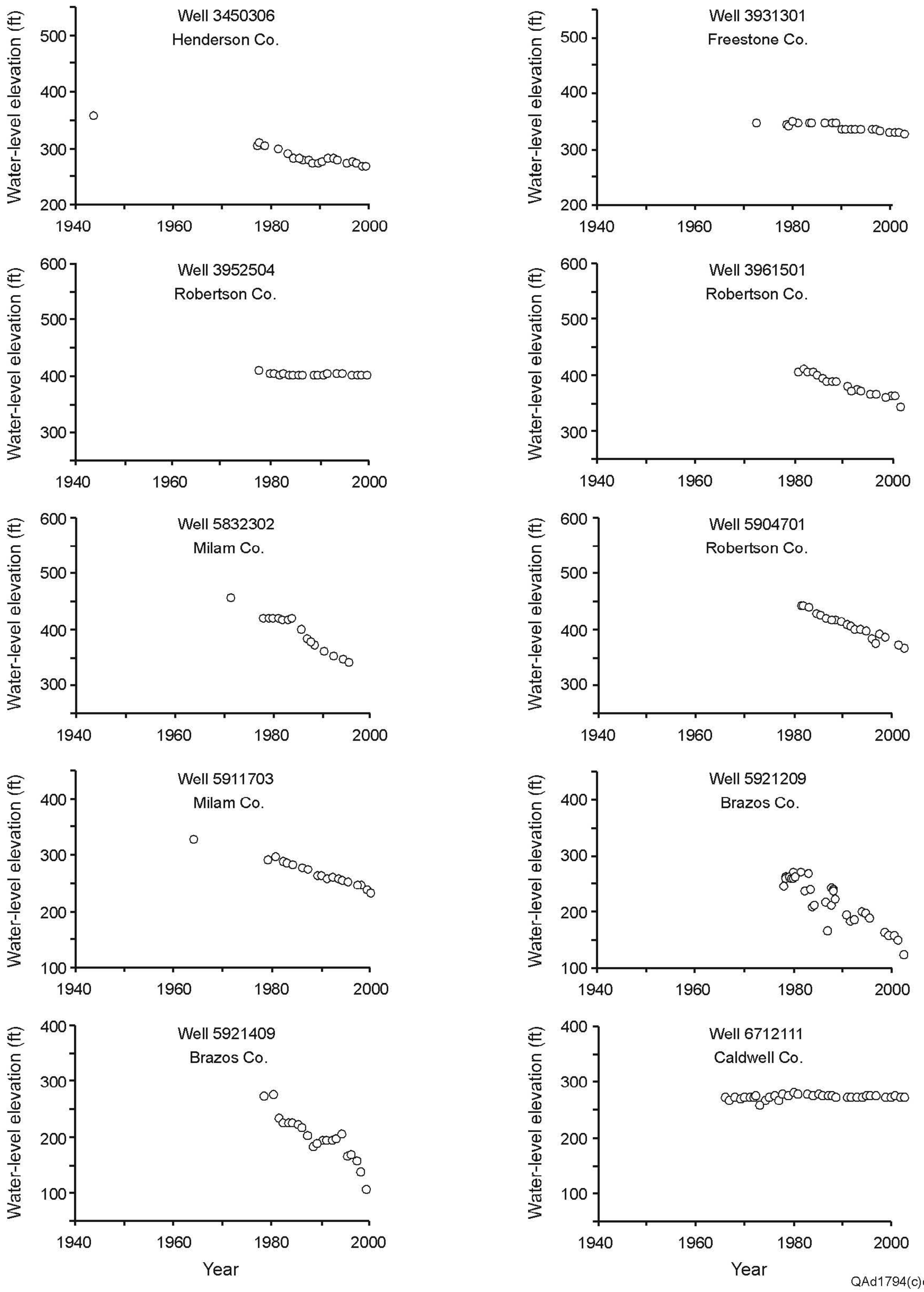

Figure 37. Hydrographs for 10 representative wells in the Simsboro Formation. Locations of wells shown in figure 36.

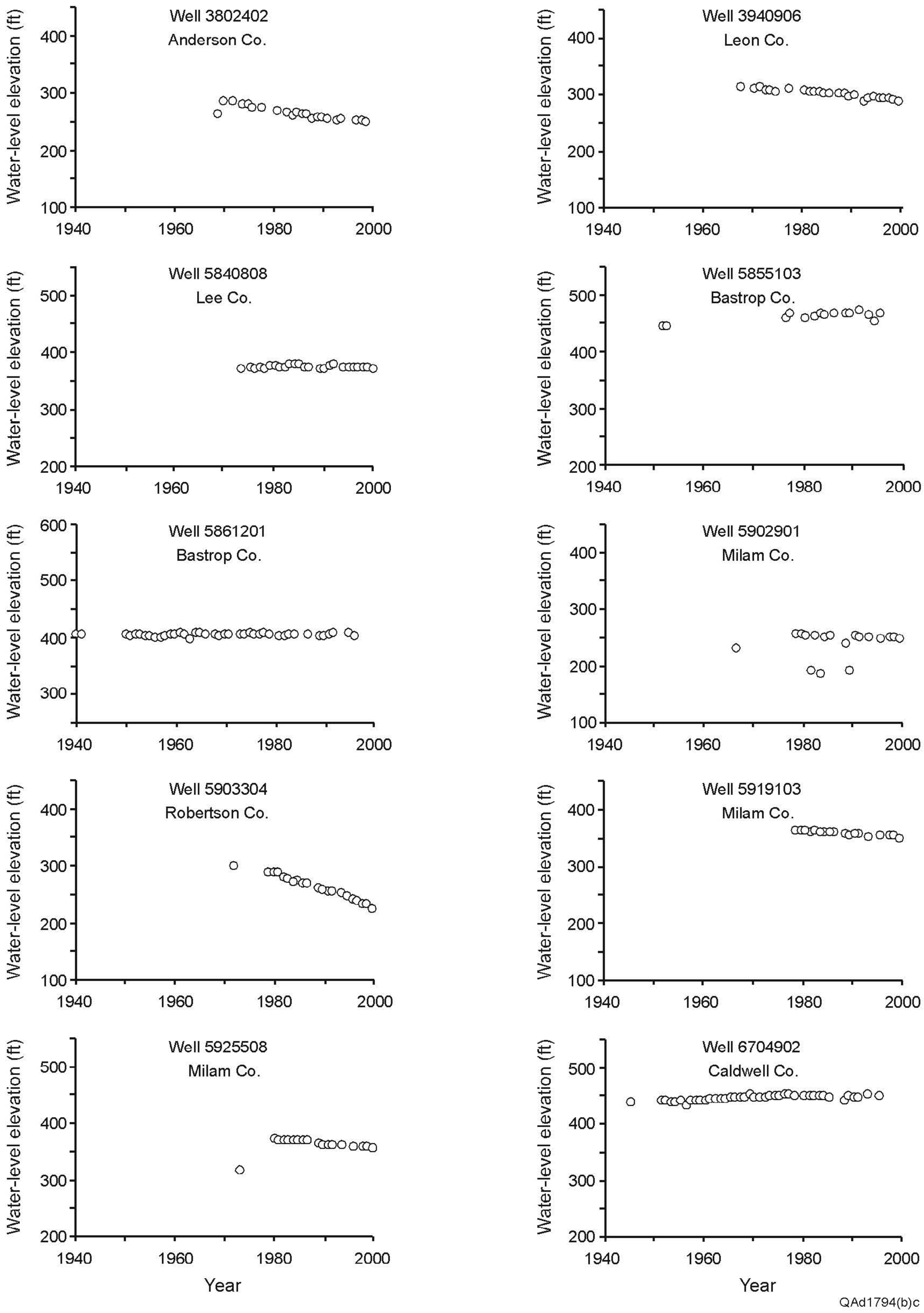

Figure 38. Hydrographs for 10 representative wells in the Calvert Bluff Formation. Locations of wells shown in figure 36.

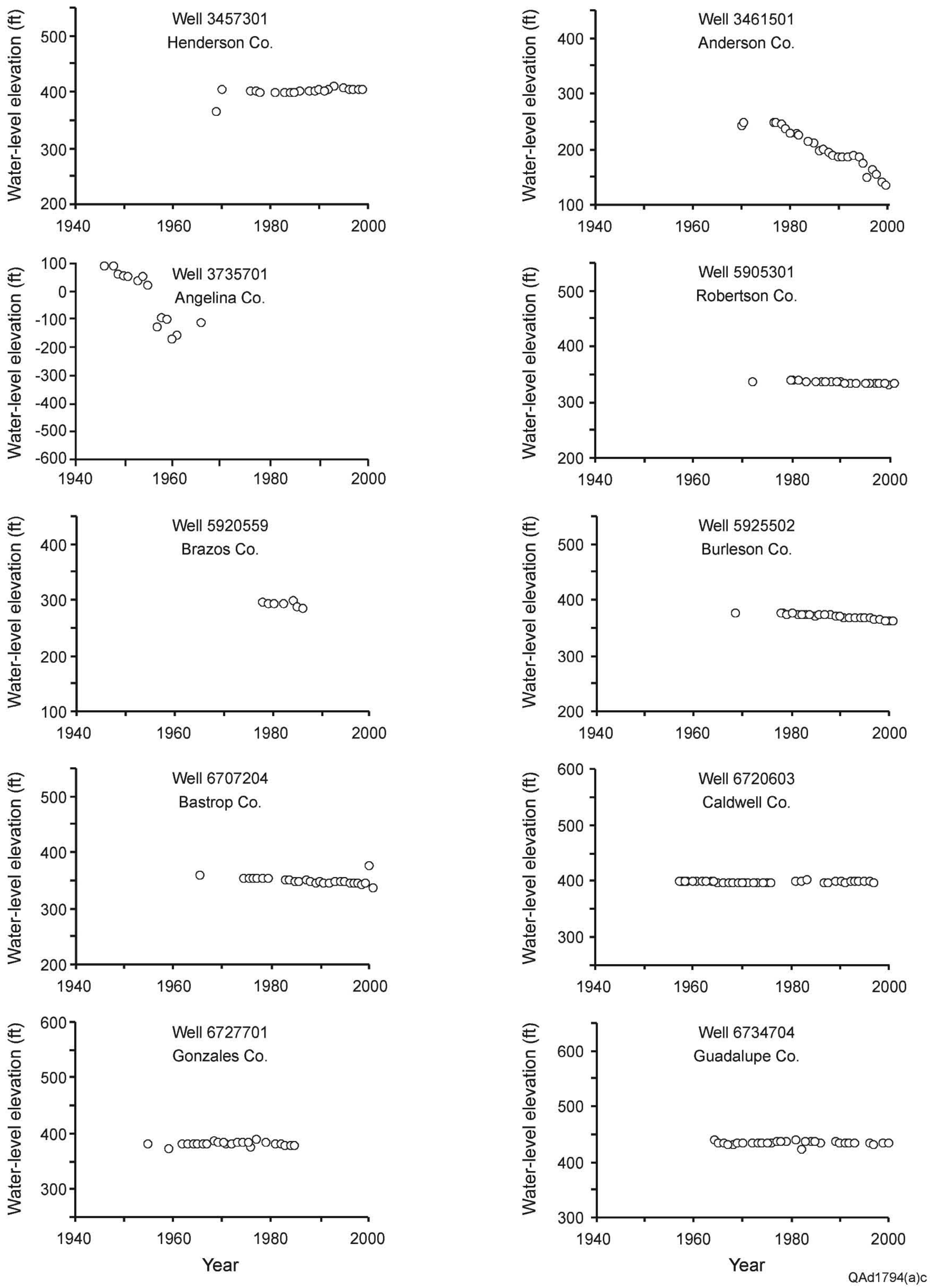

Figure 39. Hydrographs for 10 representative wells in the Carrizo Formation. Locations of wells shown in figure 36.

4.5 Recharge

Recharge occurs when water moving downward from the ground surface reaches the water table of the aquifer. Recharge to the Carrizo–Wilcox aquifer in this study area occurs mostly from deep drainage of water through the soil and unsaturated zone. To the southwest in the Carrizo aquifer, significant recharge occurs as loss of surface water flow from streams crossing the aquifer outcrop (Intera and Parsons Engineering Science, 2002b). In this report, we do not include cross-formational movement of groundwater as recharge.

Recharge rates have been estimated in several previous studies of the Carrizo–Wilcox aquifer, most of which were modeling studies (Scanlon and others, 2002). Few direct or field measurements have been made previously. Estimates of recharge rate range from 0.1 to more than 5 inches/yr (fig. 40). Thorkildsen and Price (1991) estimated an average rate of 1 inch/yr for the Carrizo–Wilcox outcrop on the basis of model calibration. Dutton (1999) calculated an area-weighted recharge rate close to 1 inch/yr, with higher rates in the Simsboro and Carrizo aquifers and much lower rates in the Hooper and Calvert Bluff aquitards. Dutton (1999) followed Ryder (1988) and Ryder and Ardis (1991) in assuming that recharge in upland areas of the Simsboro and Carrizo aquifers is 2 to 4 inches/yr.

In general, only a small amount of annual rainfall reaches the water table because most rainfall runs off, is evaporated from soils or surface-water bodies, or is transpired by plants. Plant transpiration and soil-water evaporation are collectively referred to as evapotranspiration (ET). Dutton (1990) estimated that about 10 percent of precipitation may end up as recharge. With smaller recharge rates, the percent of precipitation that is recharged to groundwater in the Hooper or Calvert Bluff aquitard is smaller.

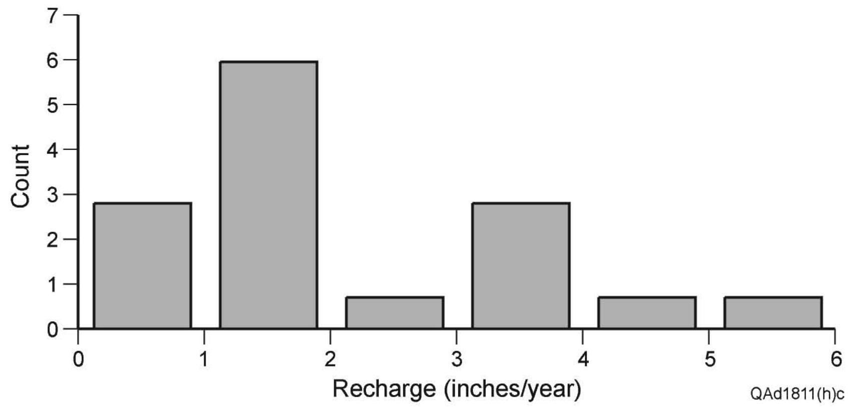

Figure 40. Recharge rates estimated in previous hydrologic studies of the Carrizo–Wilcox aquifer. Data from Scanlon and others (2002).

Rejected recharge is the concept that much of the water that reaches the water table as recharge in the unconfined part of the aquifer does not travel downdip into the confined part of the aquifer. Rejected recharge leaves the unconfined part of the aquifer by discharge to seeps and springs in valleys, discharge to rivers and streams, and evapotranspiration in river bottomland areas. Rejected recharge generally does not include withdrawal of groundwater by wells in the unconfined aquifer. The water that cycles through the unconfined aquifer, therefore, is not available for withdrawal by wells in the confined part of the aquifer. Captured recharge is the concept that drawdown of water levels in the confined part of the aquifer increases the gradient in hydraulic head and draws more groundwater from the unconfined to confined parts of the aquifer. In addition, drawdown of water levels in the unconfined aquifer, owing to pumping of wells in either the unconfined or confined parts of the aquifer, results in a decrease in the discharge of groundwater to rivers and streams and may reduce actual evapotranspiration. Groundwater that is "captured" by the confined aquifer reflects a change in the water budget of the aquifer.

As mentioned previously, seasonal trends in precipitation and evapotranspiration vary across the study area (figs. 7, 9). Precipitation during October through May is less subject to ET and can move deeper into the soil profile (Dutton, 1982; Dutton, 1990). Recharge, therefore, might be greater during the period between October and May than at other times of the year.

Previous studies indicate that there is more recharge through the predominantly sandy Simsboro and Carrizo Formations than through the clay-rich Hooper, Calvert Bluff, and Reklaw Formations. Hydrologic properties of the soils developed on these formations reflect the predominant grain texture of the underlying formations. Figure 41 shows the spatial variation in vertical permeability of soil as mapped from the TNRIS State Soil Geographic

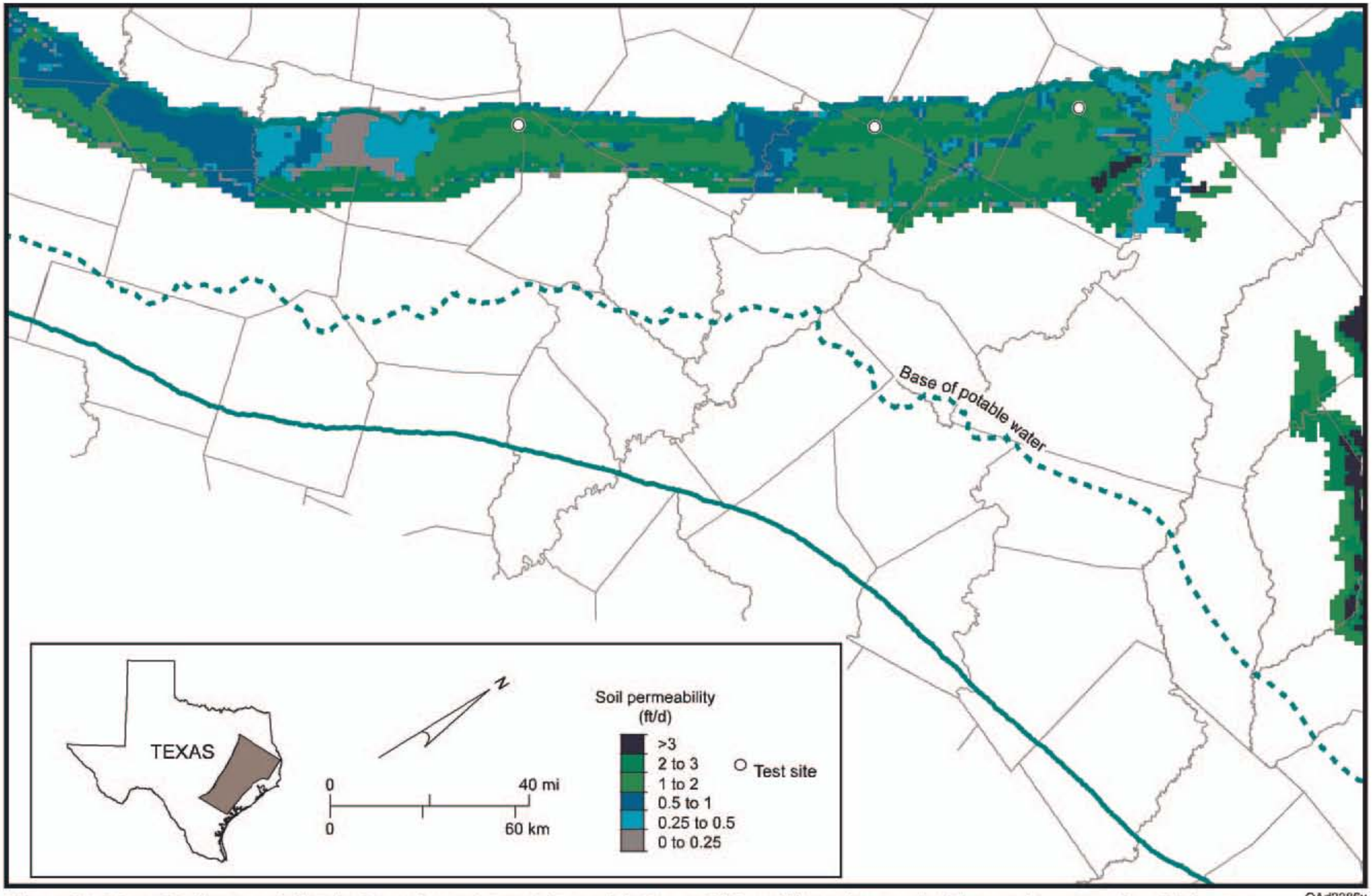

Figure 41. Map of soil permeability in the recharge area of the model. Permeability calibrated as vertical harmonic mean using thickness and permeabilities of soil layers. Test sites for using environmental tracers for estimating recharge rate were located in the outcrop of the Simsboro aquifer in Bastrop, Lee, Robertson, and Freestone Counties.

Database (STATSGO) data. Most soils are described with A, B, and C soil horizons. The STATSGO data include information on thickness and permeability of the three horizons. We calculated the harmonic mean of permeability, in which permeability is limited by thick horizons of low permeability. This approach takes into account the presence of clay-rich B horizons that commonly form so-called "hardpans" in the soils of the Wilcox Group and Carrizo Formation (Dutton, 1990). Figure 41 shows that soil permeability is typically more than 2 ft/d in the outcrop of the Simsboro and Carrizo Formations and about 1 ft/d in the outcrop of the Hooper and Calvert Bluff Formations. Soil permeability is also more than 2 ft/d in the outcrop of much of the Reklaw Formation. South of the Colorado River and north of the Trinity River, soil permeability is fairly uniform throughout the Wilcox Group. As previously mentioned, the major sands that define the Simsboro Formation are mainly between the Colorado and Trinity Rivers.

Recharge rates vary during seasonal, annual, and longer time periods and differ across the outcrop according to vegetation, slope, soils, and other factors. However, the movement of water downward from soil through the thick (>30-ft) unsaturated zone above the Simsboro and Carrizo aquifers is controlled more by the hydrological properties of the unsaturated zone than the annual precipitation rate. Fluctuation in recharge rate at the water table is much less than fluctuation in annual precipitation. In addition, fluctuation in recharge rate lags fluctuation in precipitation rate owing to time of travel through the unsaturated zone. Fluctuation in annual rate of precipitation results mainly in changes in amount of water stored in the unsaturated zone. In this report we refer to typical or representative rates of recharge. As the preceding discussion shows, however, a single number does not adequately describe differences in recharge rates across the study area. Additional work is needed to document the average and variability of recharge rates.

4.5.1 Field Methods

Field measurements were made to (1) assess results of previous model-based estimates of recharge rate for use in this model; (2) evaluate whether recharge rates assigned in the model should be less than 1 inch/yr, 1 to 4 inches/yr, or more than 4 inches/yr; and (3) begin developing improved techniques for quantifying recharge rate using field data. Details of the field tests and results are given in appendix A. Data were collected at seven locations across three test areas: Bastrop and Lee Counties, Robertson County, and Freestone County (fig. 41). The approach was to analyze "environmental tracers" extracted from soil core. The environmental tracers included chloride in soil water and tritium (^{3}H) and tritium/helium in groundwater. Cores were collected using a hollow-stem auger on a CME Mobile 75 drilling rig. Cores were taken continuously with depth until auger refusal or until the water table was encountered. No drilling fluid was used to avoid contamination of samples.

Sediment samples were collected for laboratory measurement of water content and chloride concentrations. Chloride extracted from soil cores was analyzed by ion chromatography (detection limit 0.1 mg/L) at the New Mexico Bureau of Mines. Gravimetric water content was measured in the laboratory at the Bureau of Economic Geology by oven drying samples at 105^{o}C for 24 to 72 hr. Groundwater samples were collected from all seven test holes for tritium analysis and from three wells for tritium/helium analysis. Tritium samples were analyzed at the University of Miami Tritium Laboratory. Helium concentrations and helium isotope ratios (^{3}He/^{4}He) in the samples were measured at the University of Utah.

4.5.2 Field Results

Average water content in each soil profile was not highly variable and ranged from 0.13 to 0.18 g/g (fig. 42, table 1). Minimum water content ranged from 4 to 8 percent by weight. Maximum water content ranged from 22 to 40 percent by weight, indicating that some soil samples were close to water saturation. Spatial variability in water content could be qualitatively related to soil texture. Water content was highest near the water table in most profiles. Average chloride concentration in the unsaturated zone ranged from 23 to 519 mg/L (fig. 43, table 1). Chloride concentration was highly variable at each location; there was no systematic variation in chloride concentration with depth.

Recharge rates (R) were calculated from the ratio between chloride concentration in rainfall and in the soil samples using equation 2:

$$R = Cl_P/Cl_s \times P \qquad (2)$$

where Cl_P and Cl_s are concentrations of chloride in precipitation and soil water, respectively, and P is precipitation rate. Recharge rates were calculated for that part of soil profiles that generally represents the last 50 yr. In some cases recharge rates appear to show that a 50-yr transit time corresponds to a very narrow depth interval. Recharge rates estimated from the soil-chloride data ranged from 0.2 to 1.4 inches/yr. The time required for chloride to accumulate in the various soil profiles ranged from approximately 100 to 2,800 yr. Primary assumptions of the chloride mass balance approach are that water movement is downward and that there are no subsurface sources or sinks of chloride. The first assumption is valid because in broad areas between surface-water bodies, the main direction of water movement

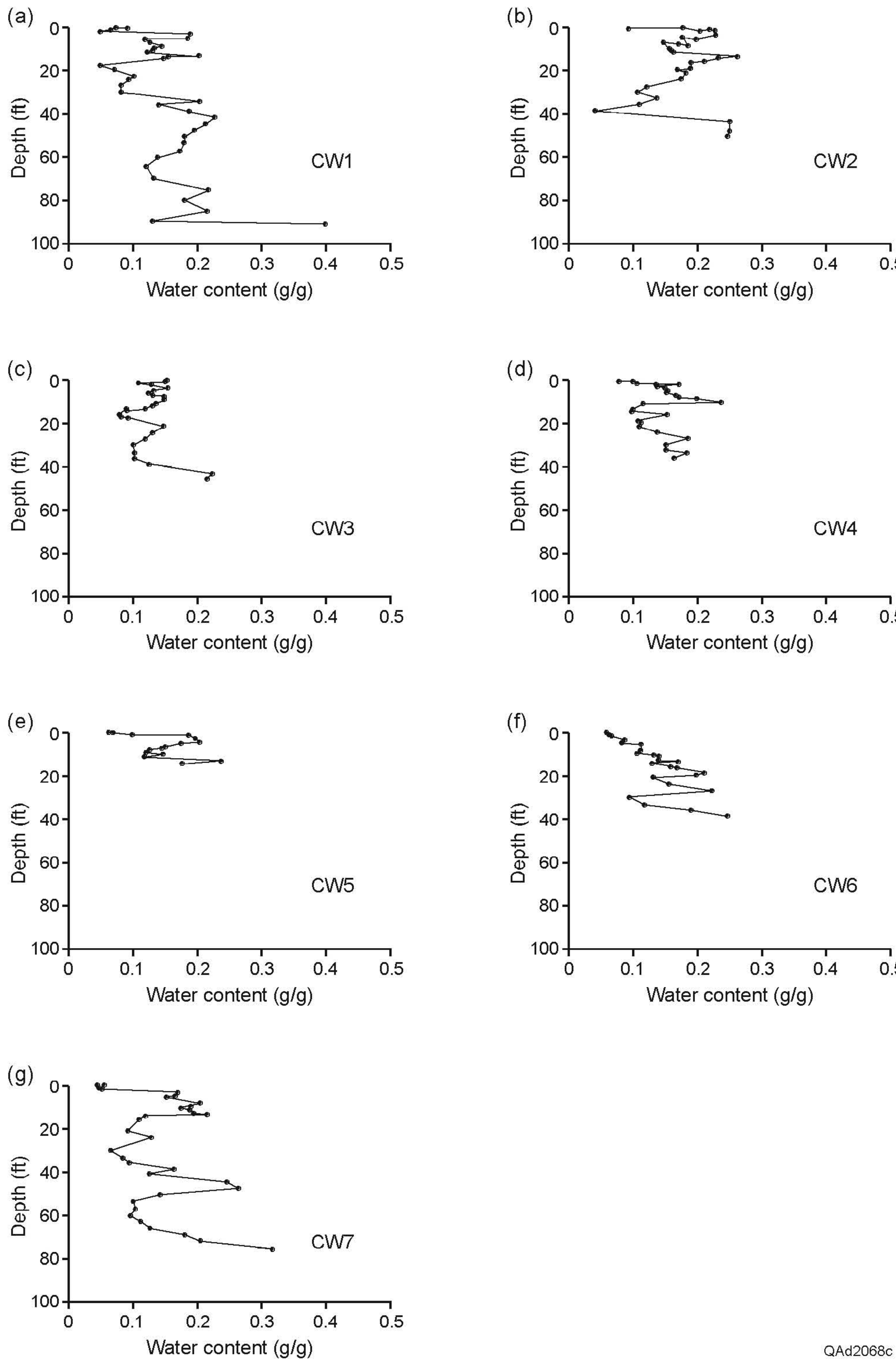

Figure 42. Variation with depth in water content in soil cores. CW1 and CW2 from Bastrop and Lee Counties, respectively, CW6 and CW7 from Robertson County, and CW3 to CW5 from Freestone County (figure 41).

Table 1.Water content, chloride concentration, and estimated recharge based on unsaturated zone (uz) chloride concentrations, chloride concentrations in groundwater (gw) and associated recharge rates, and age of the chloride profile.

Borehole no.	Water content uz (g/g)			Chloride uz (mg/L)			Recharge rate (uz) (in/yr)	Cl (gw) (mg/L)	Recharge rate (gw) (inches/yr)	Age (yr)
	Mean	Min.	Max.	Mean	Min.	Max.				
CW-1	0.21	0.08	0.34	245	10	1907	0.79	180	0.20	2815
CW-2	0.18	0.04	0.26	23	11	37	1.42	25	1.34	110
CW-3	0.13	0.08	0.22	35	12	125	1.02	5	6.22	112
CW-4	0.14	0.08	0.24	259	51	1131	0.24	32	1.06	846
CW-5	0.15	0.06	0.24	325	145	684	0.20	22	1.54	360
CW-6	0.13	0.06	0.25	239	72	560	0.20	33	1.02	700
CW-7	0.14	0.05	0.32	518	52	2206	0.20	107	0.31	2480

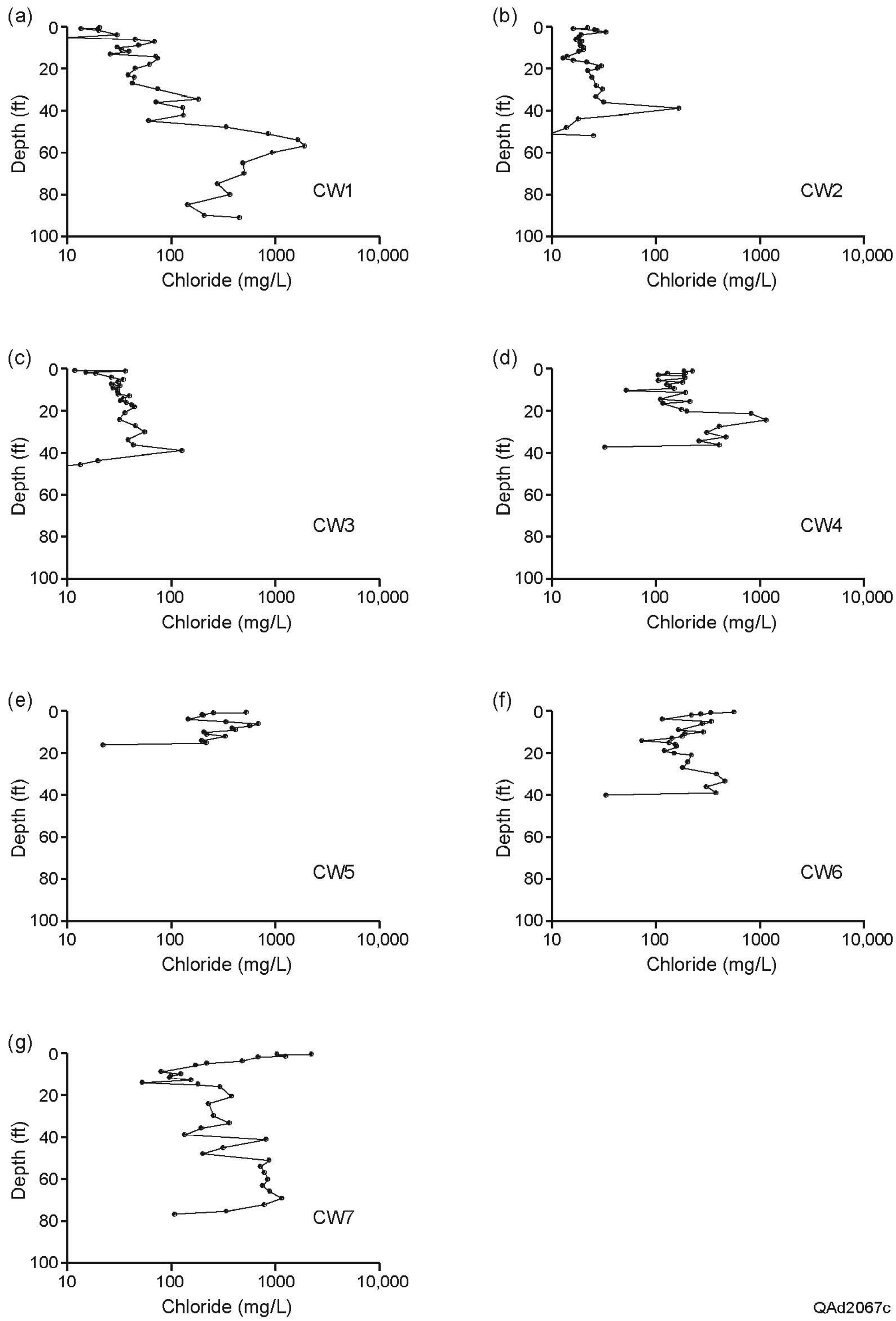

Figure 43. Variation with depth in soil-water chloride in soil cores. CW1 and CW2 from Bastrop and Lee Counties, respectively, CW6 and CW7 from Robertson County, and CW3 to CW5 from Freestone County (figure 41).

is vertical and the direction in the hydrogeologic setting of the study area, the direction of net flow of water in the unsaturated zone, is downward. The second assumption is also reasonable for these tests in the Simsboro Formation outcrop (Dutton, 1985, 1990).

Chloride concentration was generally lower (5 to 180 mg/L) in groundwater than in the unsaturated zone (table 1, appendix A). Recharge rates calculated using equation 2 for groundwater chloride ranged from 0.2 to 6.2 inches/yr, generally higher than those based on unsaturated-zone chloride (CW3-CW6). Recharge rates from the two data sets were similar for samples from CW2 and CW7. Low recharge rates calculated for CW1 may be unrepresentative of recharge in this area because groundwater was confined (under slight artesian pressure) in this borehole. The low recharge rate for CW7 may reflect additional chloride from old pore fluids (Dutton, 1985) because clay content was high in this borehole. The higher recharge rate at CW3 may represent focused recharge because surface water was ponded nearby. Preferential flow may result in low chloride concentrations in the groundwater, reflecting higher rates of recharge. Representative recharge rates based on groundwater chloride concentrations range from 1 to 1.5 inches/yr.

Groundwater tritium concentrations ranged from 0.76 to 3.57 TU (table 2) Tritium levels were greater than the detection limit (~ 0.2 TU) and indicate that a component of water was recharged during the last 50 yr. The age of groundwater was calculated using analyses of tritium/helium from boreholes CW3 and CW4; analytical results for the CW6 sample were invalid. Residence time of the water was calculated to be 2.2 for the CW3 samples and 34.5 yr for the CW4 sample. The ages represent the time of ^{3}He accumulation since it was isolated from the unsaturated zone. Water velocities were calculated by dividing the depth of the sample beneath the water table by the estimated groundwater age, yielding velocities of 0.4 (CW4) to 4 ft/yr (CW3). Recharge rates were calculated by multiplying velocities by

Table 2. Results of ^{3}He, ^{4}He, ^{20}Ne, ^{40}Ar, and N_2 measurements, and calculated tritiogenic helium-3 ($^{3}He^{*}$) and $^{3}H/^{3}He$ ages.

BH no.	^{3}H (TU)	^{3}H error (2σ TU)	R/Ra†	^{4}He cc STP/g‡	^{20}Ne cc STP/g	^{40}Ar cc STP/g	N_2 cc STP/g	$^{3}He^{*}$ TU	Age (yr)
CW-1	0.76	0.18							
CW-2	3.25	0.22							
CW-3	3.3	0.22	1.072	4.41E-08	1.99E-07	4.72E-04	0.0150	0.4	2.2
CW-4	3.57	0.24	1.072	9.35E-08	2.97E-07	7.04E-04	0.0251	21.4	34.5
CW-5	2.43	0.2							
CW-6	3.05	0.2	0.986	5.80E-08	2.59E-07	5.66E-04	0.0184	-7.1	
CW-7	1.1	0.18							

† R is the $^{3}H/^{4}He$ ratio of the sample; Ra is the $^{3}He/^{4}He$ ratio of the air standard
‡ STP Standard temperature and pressure
^{3}H error reported as two standard deviations (2σ)

average porosity (assumed to be 35 percent). A recharge rate of 1.6 inches/yr estimated for CW4 is similar to that from the groundwater chloride concentration (32 mg/L). A recharge rate of 16.7 inches/yr was estimated for CW3 samples, and was much higher than the rate estimated from groundwater chloride concentration. Rates in excess of 4 inches/yr probably reflect a component of recharge that is locally focused from surface ponds.

Preliminary field results indicate that the sampled parts of the Simsboro Formation have similar recharge rates in that there was more variability within sample areas than between areas. Judging by these results, average recharge rate in this part of the Simsboro appears to range from about 1 to 4 inches/yr. These data are consistent with previous model estimates (fig. 40). Groundwater chloride concentration seems to provide a reliable basis for recharge estimation in this study area. Unsaturated-zone chloride concentration generally gave lower estimates of recharge rate than did groundwater chloride. Further study is needed to evaluate the application of these environmental-tracer techniques for the estimation of recharge rate in the study area.

4.6 Interaction of Surface Water and Groundwater

A large amount of the recharge that occurs in the upland outcrop of the Carrizo–Wilcox aquifer moves along short flow paths within the outcrop toward discharge areas beneath the topographically low lying areas in river bottomlands. Some flow paths are very short and issue in springs that form the headwaters of local streams. Most natural groundwater discharge may be to springs and seeps and to evapotranspiration in river bottomlands. Groundwater in the bedrock Carrizo–Wilcox aquifer also moves into the Quaternary alluvial deposits that floor the valleys of the Colorado, Brazos, and Trinity

Rivers. Groundwater discharge to the streams and rivers that cross the outcrop of the Carrizo–Wilcox aquifer makes up the base flow of these surface waters. Most of the discharge is probably from the Simsboro and Carrizo aquifers, and less is from the Hooper and Calvert Bluff aquitards. Estimates of natural groundwater discharge, therefore, require analysis of the flow of these surface waters.

The following streams and rivers occur in the study area and were included in the model: San Antonio River, Cibolo Creek, Guadalupe River, San Marcos River, Plum Creek, Cedar Creek, Colorado River, Big Sandy Creek, Middle Yegua Creek, East Yegua Creek, Little River, Brazos River, Little Brazos River, Walnut Creek, Duck Creek, Steele Creek, Navasota River, Big Creek, Upper Keechi Creek, Tehuacana Creek, and Trinity River (fig. 2). Cronin and Wilson (1967) summarized hydrogeologic information about alluvium beneath the Brazos River valley. Much more hydrogeologic information is available about the Brazos River alluvium, designated a minor aquifer, than for alluvium in the Colorado or Trinity River valleys.

Where the water table is above the streambed and slopes toward the stream, the stream receives groundwater from the aquifer; that is called a gaining reach (i.e., it gains flow as it moves through the reach). Where the water table is beneath the streambed and slopes away from the stream, the stream loses water to the aquifer; that is called a losing reach. Where impounded surface-water rises above the base-level elevation of groundwater in the river valleys, water can leak out of the reservoir and be a source of recharge.

Base flow is the contribution of groundwater to gaining reaches of a stream or river. After runoff from storm events has drained away, the natural surface-water flow that continues is base flow from groundwater. Streams can have an intermittent base flow, which is usually associated with wet winters and dry, hot summers. Larger streams and rivers might have a perennial base flow. Direct exchange between surface and groundwater is limited to the outcrop.

Slade and others (2002) compiled the results of 366 gain-loss studies since 1918 that included 249 individual stream reaches throughout Texas. A total of five gain-loss studies were conducted on two streams in the study area: the Colorado River and Cibolo Creek. Results presented here are for stream reaches that cross the outcrop area. Table 3 reports the average annual flow at gages nearest the upstream extent of the Wilcox Group outcrop. Streams having headwaters within the outcrop of the Carrizo–Wilcox aquifer by definition have zero inflow from upstream.

Two methods were used to characterize interaction of surface and ground waters: low-flow studies and base-flow separation. First, details of historical low-flow studies conducted on any streams across the Carrizo–Wilcox aquifer within the model domain were reviewed. Second, data from stream gages located on the outcrop were analyzed using techniques of base-flow separation to obtain quantitative estimates of groundwater discharge to the streams.

4.6.1 Low-Flow Studies

Low-flow studies involve flow measurements at many locations on a stream within a short period of time, ideally when flow is low and no significant surface runoff occurs. Low-flow studies were conducted on the Colorado River in 1918 and on Cibolo Creek in 1949, 1963, and 1968. To use these results we estimated where gage sites were located relative to the outcrop of the aquifer. In all four studies, surface-water flow increased downstream as the stream crossed the aquifer outcrop, indicating gaining conditions at the time the studies were performed.

Table 3. Average flow of streams in study area.

Modeled stream name	Initial flow (acre-feet/yr)	Referenced gage
San Antonio River	40,861	USGS 08178565 San Antonio River at Loop 410 at San Antonio, TX
Cibolo Creek	16,606	USGS 08185000 Cibolo Creek at Selma, TX
Guadalupe River	330,192	USGS 08168500 Guadalupe River above Comal River at New Braunfels, TX
San Marcos River	283,749	USGS 08172000 San Marcos River at Luling, TX
Plum Creek	35,777	USGS 08172400 Plum Creek at Lockhart, TX
Cedar Creek	0	NA
Colorado River	1,622,898	USGS 08158000 Colorado River at Austin, TX
Big Sandy Creek	0	NA
Middle Yegua Creek	0	NA
East Yegua Creek	0	NA
Little River	1,264,803	USGS 08106500 Little River at Cameron, TX
Brazos River	2,052,843	USGS 08098290 Brazos River near Highbank, TX
Little Brazos River	0	NA
Walnut Creek	0	NA
Duck Creek	0	NA
Steele Creek	0	NA
Navasota River	79,970	USGS 08110325 Navasota River above Groesbeck, TX
Big Creek	0	NA
Upper Keechi Creek	0	NA
Tehuacana Creek	63,217	USGS 08064700 Tehuacana Creek near Streetman, TX
Trinity River	3,765,815	USGS 08065000 Trinity River near Oakwood, TX

In the 1918 Colorado River study, flow across the aquifer outcrop increased from about 61 to 97 cubic feet per second (cfs), an increase of 36 cfs. Flow at the Smithville gage during this low-flow study was 101 cfs. A flow of 101 cfs is exceeded 99.9 percent of the time at the Smithville gage. This indicates that even during conditions of extremely low flow, the Colorado River has been a gaining reach across the outcrop of the Carrizo–Wilcox aquifer. A flow study in August 1985 included only the downstream half of the outcrop area and, in contrast to the 1918 study, resulted in an average *loss* of 1,832 acre feet per year per river mile. There were, however, releases of large volumes of water from Highland Lakes reservoirs during the 1985 study, so study results are not representative of low-flow conditions. The 1985 study data, therefore, were not used in this analysis.

Three Cibolo Creek studies spanned a range of flow conditions across the outcrop of the Carrizo–Wilcox aquifer. In each case, flow increased across the outcrop (table 4). Cibolo Creek has been a consistently gaining reach across the outcrop of the Carrizo–Wilcox aquifer over a wide range of flow conditions.

4.6.2 Base-Flow Studies

The part of a stream's flow that is not directly influenced by runoff is considered to be its base flow. Base flow is an accumulation of groundwater discharge across the bed and banks of a stream. Base-flow separation was performed on daily stream-flow data using the Base Flow Index (BFI) program, jointly maintained by the USGS and U.S. Bureau of Reclamation (Wahl, 2001). BFI uses the Standard Hydrologic Institute Method for base-flow separation; this method identifies sudden rises in the hydrograph typical of storm-induced runoff and separates the total stream flow into a daily time series of base flow and storm flow for each gage. Base-flow separation is a standard graphical technique that provides an

Table 4. Summary of low-flow studies in Cibolo Creek.

Year of study	Gain (cfs)	Rate of gain (cfs/mi)	Measured low flow (cfs)	Percent of time flow is exceeded
1949	~10	0.4	14	81
1963	~11	0.5	17	73
1968	~25	1	62	18

estimate of groundwater discharge. For a given day, the program may under- or overpredict base flow; however, the long-term accuracy of the method is commonly accepted. Details of the base-flow separation are given in appendix B.

Seven study reaches were identified that have pairs of stream gages located either entirely on or very near the boundary of the Carrizo–Wilcox outcrop (fig. 44). By isolating study reaches located entirely on the outcrop, we minimized the influence of hydrologic factors external to the base flow from the Carrizo aquifer. The difference in base flow between the upstream and downstream gages is an estimate of the amount of groundwater discharge between the two gages. Estimates of base flow for the Colorado and Navasota Rivers were adjusted to take into account water withdrawals and return flows located between the gages, using information from Water Availability Models (WAM) prepared for the TCEQ. Both adjustments were small relative to total base flow.

Base flow can be small compared with total flow. Base flow in Plum Creek, a tributary of the San Marcos River, for example, is typically less than 10 cfs, whereas total flow can exceed 150 cfs (fig. 45).

Base-flow discharge was converted to unit values by dividing the change in base flow between stations by the intervening area of the watershed on the outcrop (fig. 44). Base-flow duration curves were made from unit daily values. These curves show the percentage of time that each base-flow value was exceeded during the period of record (fig. 46). The shape of the curves is similar for most of the various gaged streams and watersheds. The median (50-percent exceedance) increase in base flow for the appropriate study reach, unitized by area of the drainage basin underlain by the Simsboro and Carrizo aquifers, was used to estimate calibration targets for groundwater discharge for like-sized ungaged streams in the steady-state model. For example, data for the Colorado River were used to estimate targets

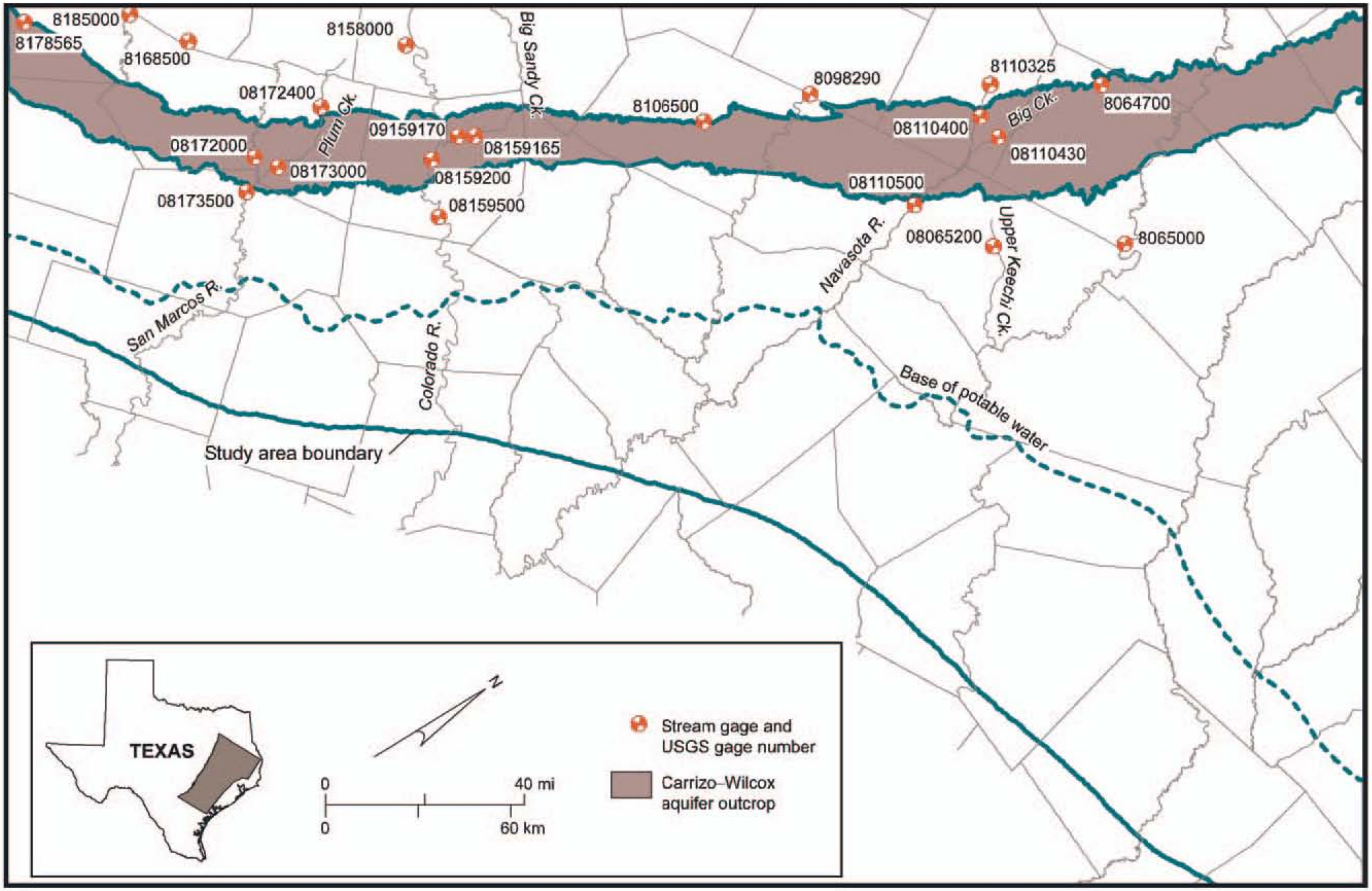

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Figure 44. Location of stream-flow gages used for base-flow separation and stream inflow estimates.

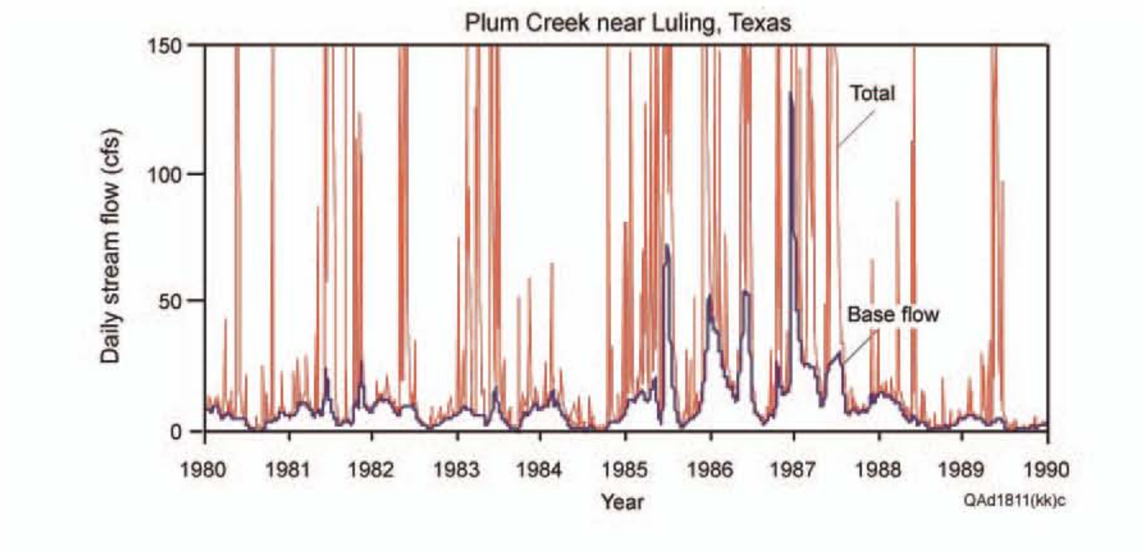

Figure 45. Comparison of total discharge and estimated base flow for Plum Creek near Luling, Texas (gage no. 08173000).

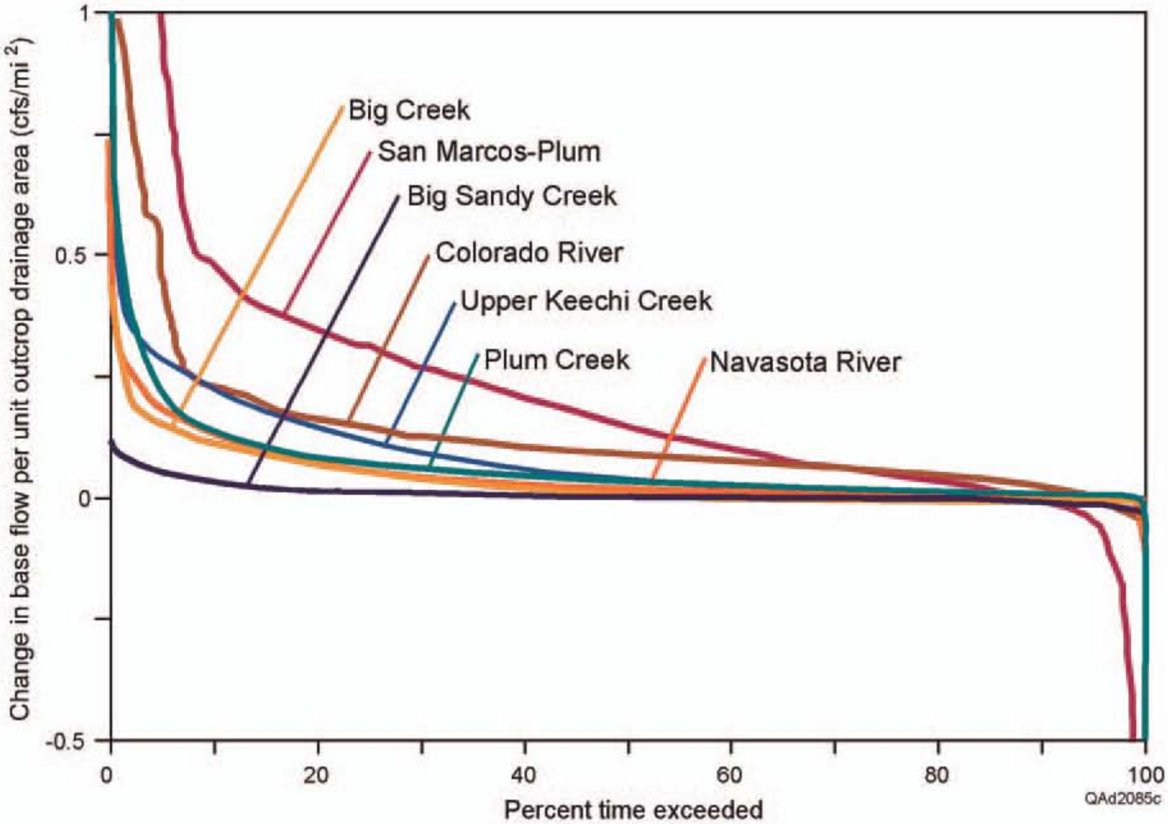

Figure 46. Base-flow increase across the Carrizo–Wilcox outcrop, unitized by area of drainage basin in the outcrop. Base-flow increase assumed to reflect the discharge of groundwater from the Carrizo–Wilcox aquifer. Most of the discharge is from the Simsboro and Carrizo Formations.

for the Brazos and Trinity Rivers, whereas data for Plum Creek were used to estimate targets for Cedar Creek. The median unit base-flow increase (cfs/mi^2) for the appropriate study reach was multiplied by a simple function of the outcrop area of these aquifers in the watershed for the corresponding ungaged stream basins.

4.6.3 Surface-Water Reservoirs

Several lakes and reservoirs are also present: Braunig Lake, Calaveras Lake, Lake Bastrop, Alcoa Lake, Twin Oaks Reservoir, Lake Limestone, Richland-Chambers Reservoir, Fairfield Lake, and Cedar Creek Reservoir (fig. 2). Table 5 lists characteristics of these lakes and reservoirs. Most of these reservoirs overlay the outcrop of the Calvert Bluff Formation (Braunig Lake, Calaveras Lake, Lake Bastrop, Alcoa Lake, Twin Oaks Reservoir, Fairfield Lake) or extend from the Hooper Formation to the Calvert Bluff Formation, overlapping the outcrop of the Simsboro Formation (Lake Limestone, Richland-Chambers Reservoir, Cedar Creek Reservoir). Water-level fluctuations are small, and water levels can be considered constant through time. All the reservoirs lose water to the underlying aquifers or aquitards, but the exact amount is hard to quantify. The relationship between Lake Limestone and the Navasota River provides a way to estimate this reservoir's leakage. Median daily base flow at the first USGS gage station downstream of the reservoir increased by about 7 to 10 cfs after the reservoir was impounded in 1981. Most of the measured increase in base flow may be attributed to reservoir releases (Certificate of Adjudication 12-5165, held by the Brazos River Authority for Lake Limestone, mandates a minimum pass-through release of 6 cfs). The remaining 1 to 4 cfs base-flow increase may be used as an estimate of reservoir seepage at this location.

Table 5. Characteristics of reservoirs in study area.

ID#	Reservoir	Owner	Date impounded	Water-level fluctuations (ft)	Size (acres)
1	Lake Bastrop	Lower Colorado River Authority	1964	1-2	906
2	Alcoa Lake	ALCOA	1952	small	914
3	Twin Oaks Reservoir	Texas Power and Light	1982		1,460
4	Lake Limestone	Brazos River Authority	1978	1-3	13,680
5	Richland-Chambers Reservoir	Tarrant County Water Control	1987	3	44,000
6	Fairfield Lake	Texas Utilities Electric	1969	4	2,353
7	Cedar Creek Reservoir	Tarrant County Water Control	1965	4	34,300
8	Braunig Lake	City of San Antonio	1964	1-2	1,350
9	Calaveras Lake	City of San Antonio	1969	1-2	3,450

4.7 Groundwater Evapotranspiration

As previously mentioned, some recharge leaves the unconfined part of the aquifer by evapotranspiration (ET) in river bottomland areas. In this report this process is referred to as *groundwater evapotranspiration* to distinguish it from ET that takes place in soils across the upland areas. The groundwater model simulates the occurrence and movement of water beneath the water table. ET in the soil zone of the upland areas, along with runoff, reduces the amount of precipitation that drains downward from the root zone to eventually reach the water table. Such ET is not included in the model. Discharge of groundwater from shallow water tables in river bottomlands by the process of evapotranspiration is included in the model. Groundwater ET may be a major component of rejected recharge. The maximum rate of groundwater ET most likely parallels average net lake evaporation rate (fig. 9).

4.8 Hydraulic Properties

Typical of sediments deposited in fluvial and deltaic environments, hydrogeologic properties of the Carrizo–Wilcox aquifer are heterogeneous on local and regional scales (for example, figs. 12, 13). Sand, silt, clay, and lignite are the most common materials found in the Carrizo–Wilcox aquifer. Hydrogeologic properties vary with sediment texture. On a regional scale, hydraulic conductivity of aquifers and confining layers (aquitards) differ vertically and laterally. There is appreciable lateral heterogeneity in hydrogeologic properties related to original depositional systems and subsequent burial diagenesis of the sediments that make up the Carrizo–Wilcox aquifer. Much of the heterogeneity reflects the variations in thickness of sandstones (figs. 12, 13). The thick major sands may have greater hydraulic conductivity than thinner sands, as well as greater lateral continuity (Fogg and others, 1983).

We assume that the aquifer and aquitard materials are isotropic in the horizontal direction. This means that horizontal hydraulic conductivity is the same regardless of direction. Vertical anisotropy (K_v/K_h), the ratio of vertical (K_v) to horizontal (K_h) hydraulic conductivity, expresses the degree to which vertical movement of groundwater may be restricted. Vertical anisotropy is related to the presence of sedimentary structures, bedding, and interbedded low-permeability layers. Mace and others (2000) compiled data on the hydraulic properties of the Carrizo–Wilcox aquifer. Vertical anisotropy is poorly quantified and is generally estimated during model calibration (Fogg and others, 1983; Anderson and Woessner, 1992). Thickness of Carrizo–Wilcox sediments is also variable. Variations in aquifer thickness and hydraulic conductivity produce a range in transmissivity.

Average (geometric mean) hydraulic conductivities of Simsboro and Carrizo sandstones, as calculated from the Mace and others (2000c) data, are similar and higher than those of Hooper and Calvert Bluff sandstones (fig. 47). Average hydraulic conductivity from field tests is about 25 ft/d in the Simsboro Formation and about 20 ft/d in the Carrizo Formation, four to five times greater than average test results in the Hooper and Calvert Bluff Formations (table 6). Average transmissivity of screened parts of the Simsboro and Carrizo Formations are about 1,150 and 500 ft^2/d, respectively, about five to ten times greater than in the Hooper and Calvert Bluff Formations (table 6). The range of hydraulic conductivity data is generally about three orders of magnitude (fig. 47).

Previous studies have shown that simulation of groundwater flow in a heterogeneous aquifer can be sensitive to the spatial distribution of hydraulic conductivity. Our approach to mapping hydraulic conductivity followed these four steps (appendix C):

(1) We posted the hydraulic-conductivity values compiled by Mace and others (2000c). Additional work was needed to assign Mace and others (2000c) data to specific

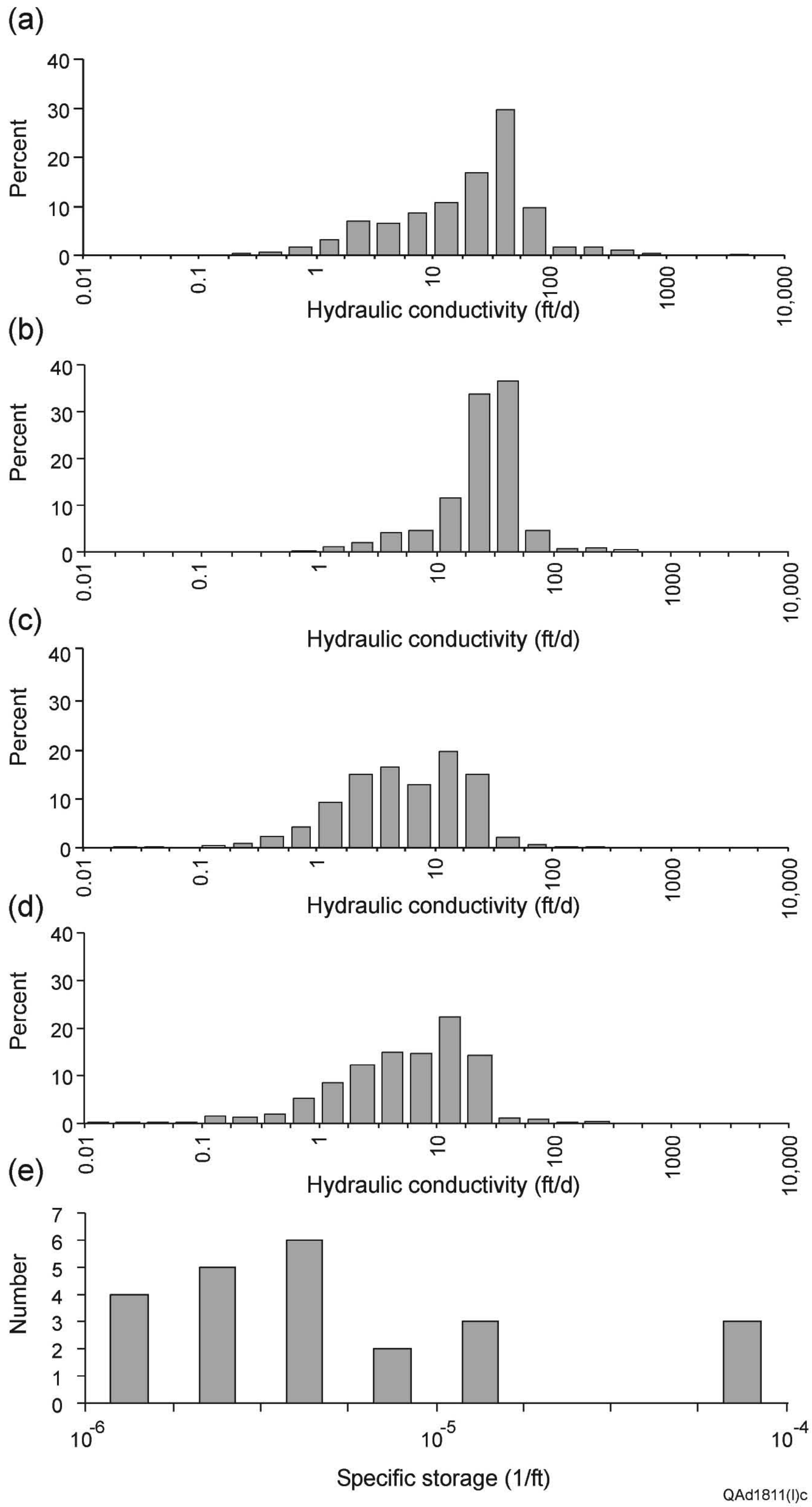

Figure 47. Histograms of hydraulic conductivity in the (a) Carrizo, (b) Simsboro, (c) Calvert Bluff, and (d) Hooper, and (e) specific storage in the Carrizo–Wilcox aquifer. Data from Mace and others (2000).

Table 6. Summary of hydraulic conductivity of the central Carrizo-Wilcox aquifer in the study area.

	Carrizo	Calvert Bluff	Simsboro	Hooper
Model cells				
Horizontal hydraulic conductivity geometric mean (K_h) (ft/d)	6.2	0.9	2.6	0.9
Vertical hydraulic conductivity geometric mean (K_v) (ft/d)	1.3×10^{-3}	9.7×10^{-5}	9.5×10^{-4}	3.5×10^{-5}
Vertical anisotropy geometric mean (K_v/K_h) within layer	2.1×10^{-4}	1.1×10^{-4}	3.7×10^{-4}	7.1×10^{-5}
Vertical anisotropy arithmetic mean (K_v/K_h) within layer	1.2×10^{-3}	2.2×10^{-4}	8.6×10^{-4}	3.4×10^{-3}
Min K_v/K_h	$3. \times 10^{-5}$	$1. \times 10^{-5}$	$4. \times 10^{-5}$	$1. \times 10^{-5}$
Max K_v/K_h	0.85	3.3×10^{-3}	0.03	0.1
Field data (Mace and others, 2000; see fig. 47)				
Horizontal hydraulic conductivity geometric mean (K_h) (ft/d)	19.3	5.6	24.8	5.4

model layers on the basis of well depth, screened interval, and designated aquifer code. Data were posted on maps as the logarithm (base 10) of the reported hydraulic conductivity.

(2) We overlaid the posted values on maps of the net thickness of sandstone in the aquifer layers. To account for the entire study area we used appropriate sandstone-thickness maps from Bebout and others (1982), Ayers and Lewis (1985), and Xue (1994). To supplement these maps, we posted and contoured values of sandstone thickness for a part of Gonzales County.

(3) We contoured hydraulic conductivity using the thickness of sandstones as an interpretive guide. Our conceptual model is that hydraulic conductivity is greatest in the thickest part of the fluvial channel axes because (a) that is where the coarse-grained sands are concentrated and low-permeability silts and clays tend to be absent and (b) thick sandstones tend to be better interconnected and have a higher effective hydraulic conductivity (Fogg and others, 1983). We found qualitative but mappable local correlation between sandstone thickness and hydraulic conductivity.

(4) The contoured maps of hydraulic conductivity were digitized, along with the maps of sandstone thickness, and values of hydraulic conductivity and sandstone thickness were interpolated for each cell of the model.

Because the entire thickness of the aquifer at any location is not made up of sandstone, we calculated average values of horizontal (K_h) and vertical (K_v) hydraulic conductivity using equations 3 and 4:

$$K_h = (K_{hs} \times b_s + K_{hc} \times b_c)/B \qquad (3)$$

$$K_v = B/[(b_s/K_{vs}) + (b_c/K_{vc})] \qquad (4)$$

where K_{hs} and b_s are the horizontal hydraulic conductivity and total layer thickness of sand, respectively; K_{hc} and b_c are horizontal hydraulic conductivity and total layer thickness of clay, silt, and lignite, respectively; and B is total layer thickness. We assumed that local vertical anisotropy is 0.1 for sandstone beds and 0.01 for clay, silt, and lignite beds. We used digitized maps of sandstone thickness and of layer thickness; total thickness of clay, silt, and lignite was estimated from layer thickness minus sandstone thickness.

This approach to assigning hydraulic conductivity to model cells results in average values that are less than the average of measured values (table 6). For example, the average horizontal hydraulic conductivity assigned to the Carrizo Formation in the study area is 6.2 ft/d, whereas the measured average is 19.3 ft/d. Initial values calculated for the Bryan-College Station well field slightly overestimated known hydraulic conductivity. Maximum hydraulic conductivity of thick deposits of Simsboro sandstone in the Rockdale Delta was limited to 30 ft/d, giving a maximum transmissivity of 15,200 ft^2/d.

Having an average hydraulic conductivity for a model layer less than the average measured value can be justified to the extent that (1) total layer transmissivity needs to take into account the part of the aquifer not made up of permeable sandstone, (2) wells of low permeability may be underrepresented in the database because they are not tested, and (3) the model layer includes parts of the formation downdip of the base of freshwater not included in the measured sample population.

Most of the Hooper Formation in the study area has assigned values of horizontal hydraulic conductivity of between 0.1 and 10 ft/d (fig. 48). In the same area, hydraulic conductivity of the Simsboro Formation, averaged over the thickness of the aquifer, is 10 to more than 30 ft/d (fig. 49). The geometry or architecture of hydraulic conductivity as mapped

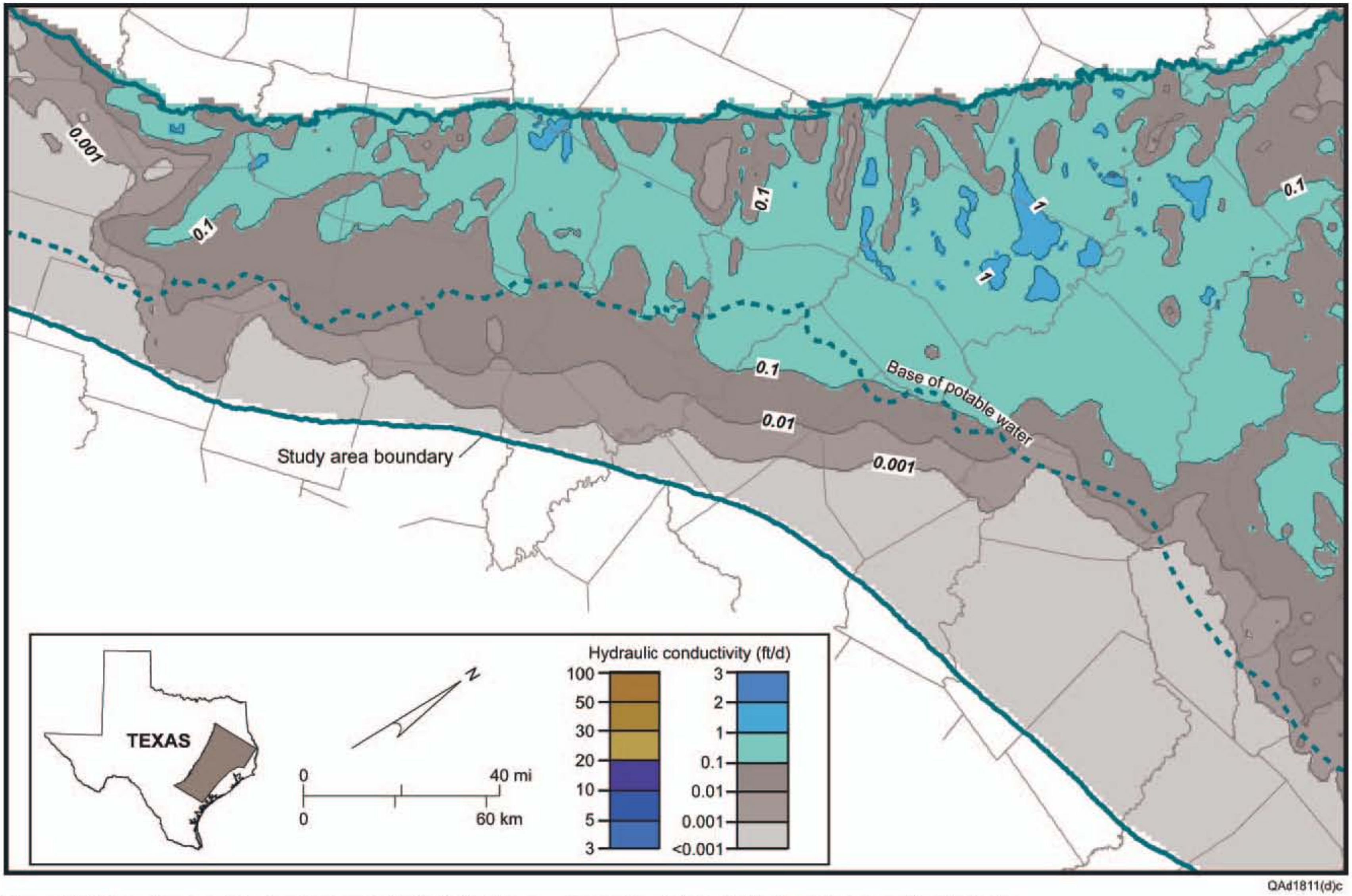

Figure 48. Map of average hydraulic conductivity in the Hooper Formation. Method of calculation described in text.

in the Simsboro Formation and other units reflects the assumption that sandstone thickness is locally correlated with hydraulic conductivity. The areas of high hydraulic conductivity in the Simsboro Formation (fig. 49) correspond to areas of greater sandstone thickness (fig. 12).

Average horizontal hydraulic conductivities of the Hooper and Calvert Bluff Formations are similar (figs. 48, 50; table 6). Hydraulic conductivity of the Carrizo Formation is greatest to the southwest. In the southwest part of the study area, Carrizo sandstones have high hydraulic conductivity in Gonzales and Wilson Counties. In the northern part of the study area, high hydraulic conductivity also corresponds to areas with greater thickness of sandstone in the Carrizo Formation (figs. 13, 51).

The values of vertical hydraulic conductivity calculated using equation 4 were used as initial estimates in the model. Vertical anisotropy of the calibrated model is about 10^{-3} for the Carrizo, Simsboro, and Hooper layers and about 10^{-4} for the Calvert Bluff layer (table 6). Fogg and others (1983) used an anisotropy of 10^{-4} in their model of the Carrizo–Wilcox aquifer in parts of Freestone and Leon Counties, with 10^{-3} as an upper limit. Given other parameter values, 10^{-4} was used to give a good match of the vertical gradient in hydraulic head. They noted that 10^{-4} is much smaller than the commonly assumed ratios for sandstone aquifers.

Specific storage is a proportionality factor between the difference in water inflow and outflow rates and the rate of change of hydraulic head. It measures the volume of water released as a result of expansion of water and compression of the porous media per unit volume and unit decline in hydraulic head. Specific storage × aquifer thickness equals the storativity of the aquifer, which is equal to the volume of water released from a vertical column of the aquifer per unit surface area of the aquifer and unit decline in hydraulic head. Specific storage has units of 1/length and storativity is dimensionless.

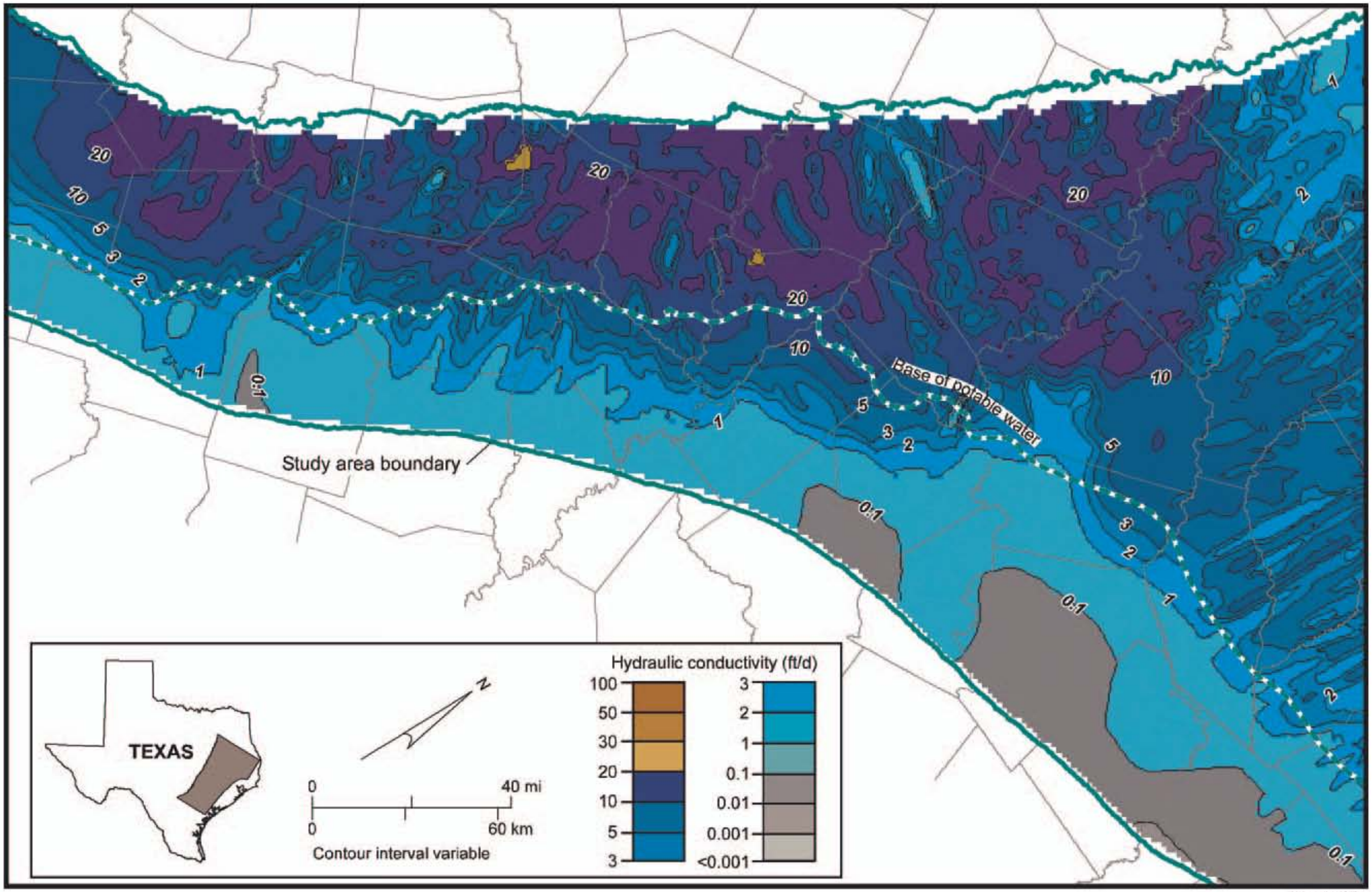

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Figure 49. Map of average hydraulic conductivity in the Simsboro Formation. Method of calculation described in text.

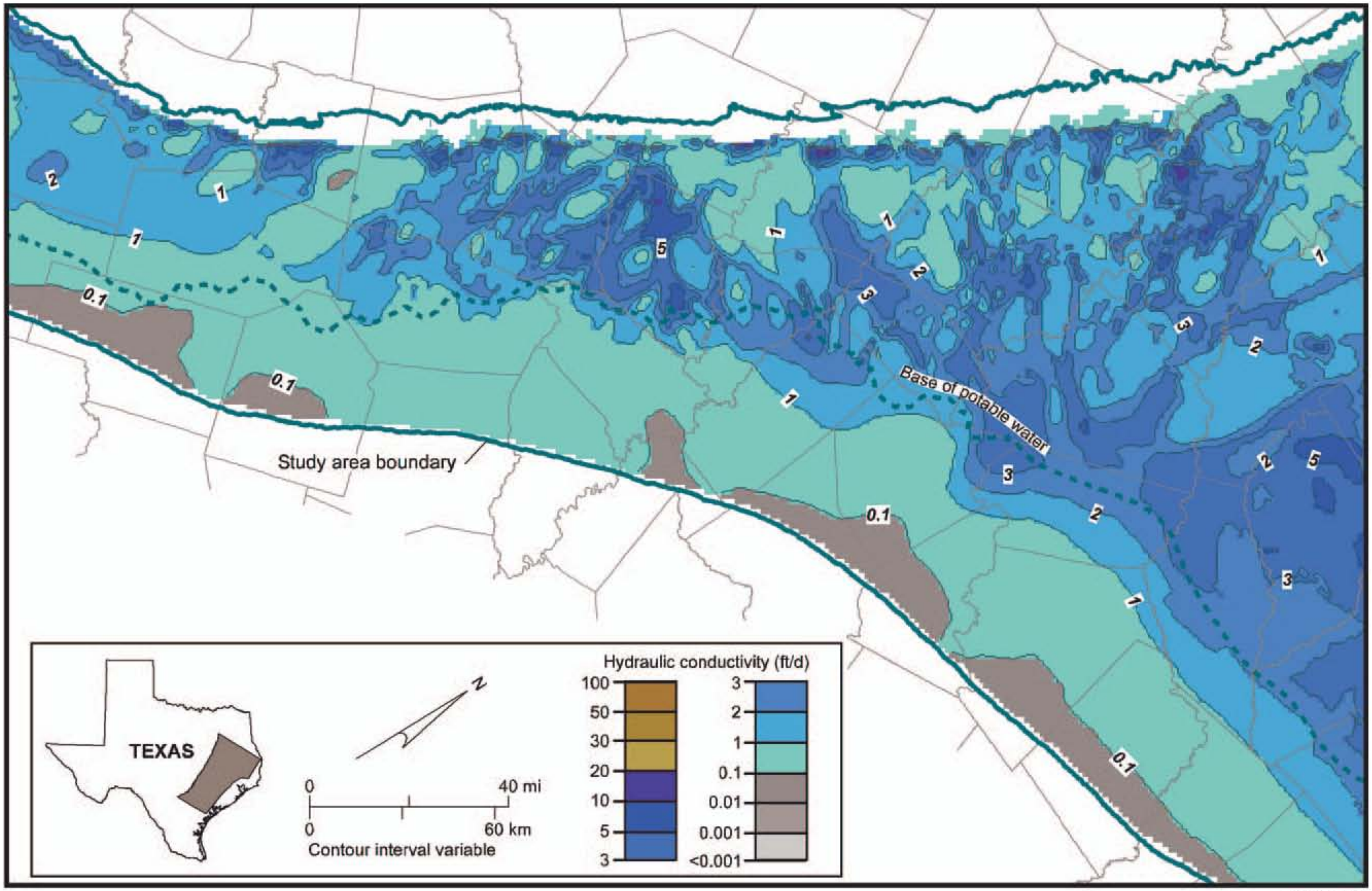
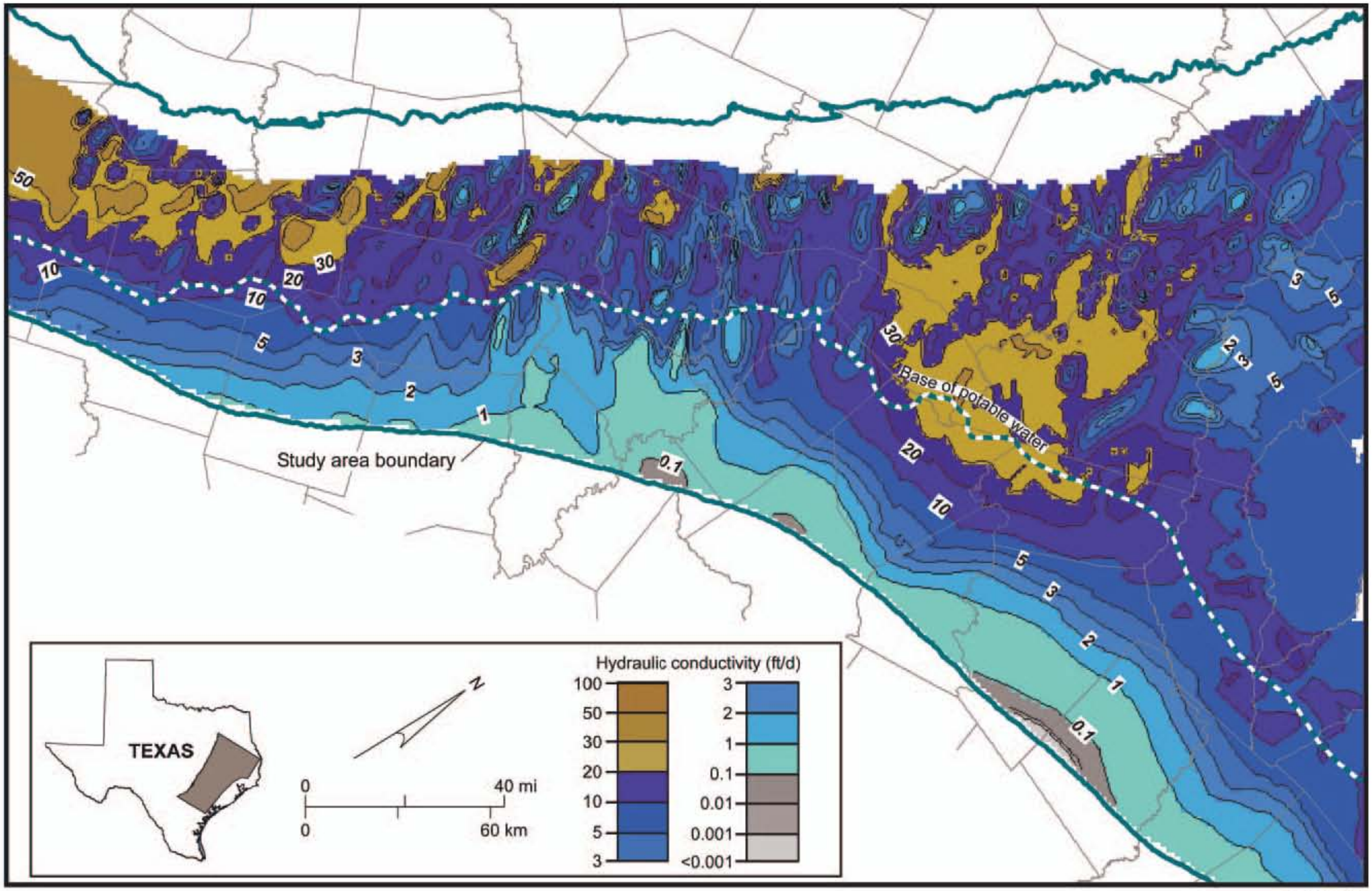


Figure 50. Map of average hydraulic conductivity in the Calvert Bluff Formation. Method of calculation described in text.



QAd1811(b)c

Figure 51. Map of average hydraulic conductivity in the Carrizo Formation. Method of calculation described in text.

Mace and others (2000c) compiled data on specific storage and the coefficient of storage (storativity). All reported results in Mace and others (2000c) are for the confined part of the aquifer. Values of specific storage average $10^{-5.7}$ ft^{-1}, $10^{-4.7}$ ft^{-1}, and $10^{-4.9}$ ft^{-1} in the Carrizo Formation (three data points), Calvert Bluff Formation (four data points), and Simsboro Formation (five data points), respectively. Storativity ranges between 10^{-6} and 10^{-1} in the Carrizo–Wilcox aquifer and averages $10^{-3.5}$ (Mace and others, 2000c).

4.9 Well Discharge

Most pumping from the Carrizo–Wilcox aquifer in the study area has been for municipal public-water supply, manufacturing, and rural domestic water uses. These three uses have made up more than 60 percent of total pumping from the aquifer in the period from 1980 through 2000 (fig. 52; tables 7, 8). In the 1980's, lignite mines began pumping greater amounts of groundwater as part of mining operations. Water withdrawal related to all types of mining activities made up an estimated 25 percent of total production in 2000. Irrigation and stock water uses have made up another 10 to 15 percent of total pumping. This percentage does not include pumping from the Brazos River alluvium. Water use for power, for example, for cooling water for electricity-generating plants, makes up less than 3 percent of total groundwater pumping from the Carrizo–Wilcox aquifer in the study area. The Simsboro and Carrizo layers are the most productive parts of the Carrizo–Wilcox aquifer in the study area, and most pumping has been from these two layers. The Simsboro aquifer is the main development zone for the municipal well field supplying Bryan and College Station in Brazos County. The Carrizo aquifer is the main productive horizon on the

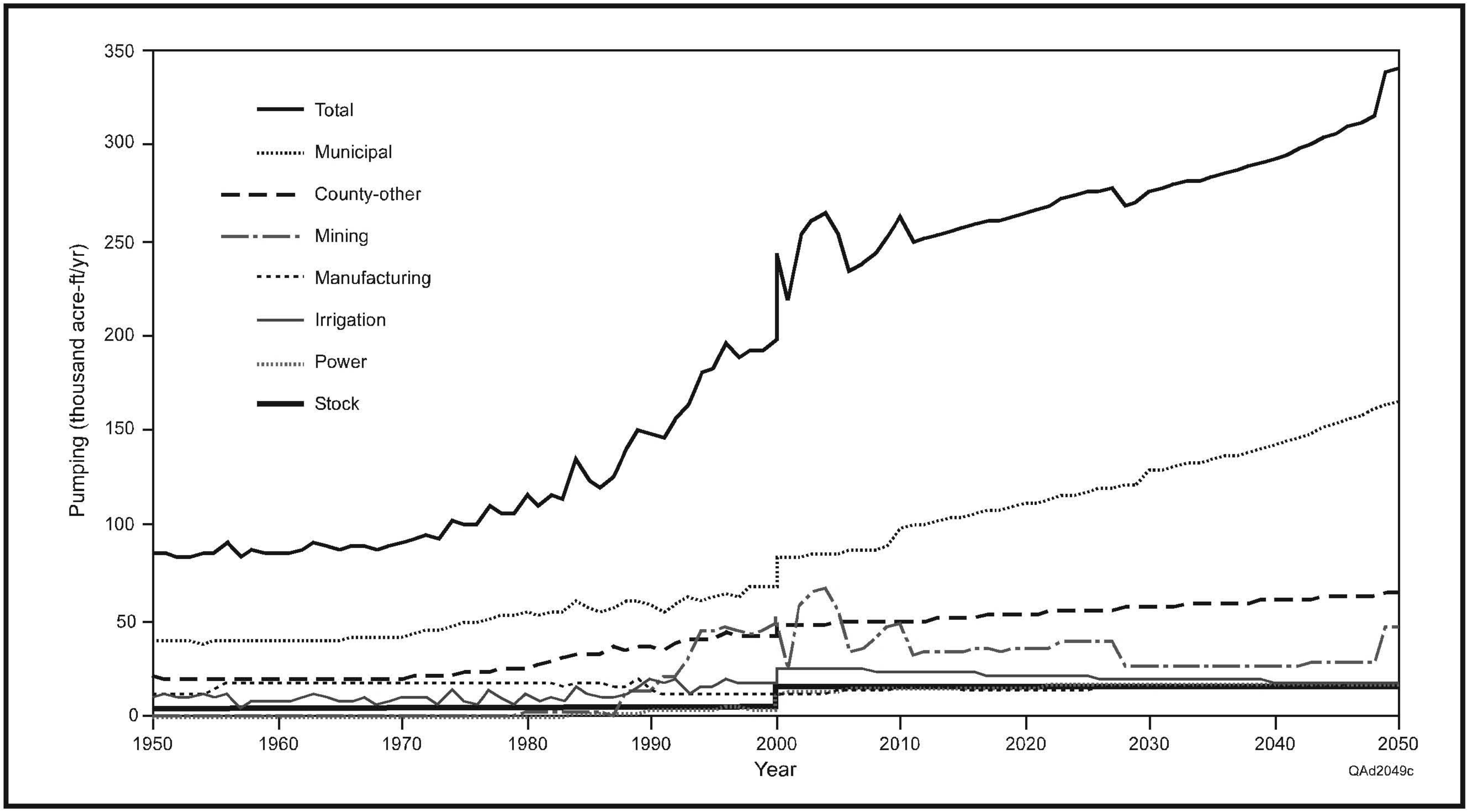


Figure 52. Total groundwater withdrawals from the Carrizo–Wilcox aquifer in the study area. Values for 1980 through 2000 are based on TWDB water-use survey information. Values for 1950 through 1980 are derived from 1980 estimates as described in text. Predictions for 2000 through 2050 are based on predicted dry demands estimated by Regional Water Planning Groups.

Table 7. Rates of groundwater withdrawal (acre-feet per year) from the Carrizo-Wilcox aquifer as assigned within the study area.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	3,552	5,529	8,050	6,789	6,773	6,815	6,783	6,909
Angelina	29,893	24,580	24,405	20,152	19,249	20,450	21,601	23,569
Bastrop	6,002	7,064	9,539	18,049	21,987	20,725	22,083	23,362
Bexar	112	187	64	3,535	3,436	2,456	2,496	2,176
Brazos	20,176	25,303	31,100	39,706	45,110	44,547	48,770	52,421
Burleson	1,157	1,142	1,281	3,338	3,395	3,436	3,495	3,629
Caldwell	2,718	3,896	3,494	7,608	7,972	8,312	8,363	8,390
Cherokee	6,695	7,078	7,664	4,207	4,327	4,530	4,714	5,001
Falls	62	51	40	893	895	904	913	923
Fayette	4	5	5	0	0	0	0	0
Freestone	2,298	2,487	2,889	3,078	3,061	3,084	3,116	3,137
Gonzales	2,639	4,134	2,438	15,693	20,146	29,488	35,093	44,620
Guadalupe	2,308	2,939	1,995	7,623	9,580	11,679	13,193	15,830
Henderson	3,385	4,180	4,517	4,245	4,247	4,252	4,241	4,314
Houston	760	574	866	1,465	1,469	1,475	1,483	1,488
Karnes	1,155	116	95	21	9	4	2	1
Lee	2,007	2,881	3,064	55,737	57,853	58,378	60,173	67,104
Leon	1,838	2,751	2,642	5,570	5,152	5,187	5,291	5,488
Limestone	1,289	2,656	2,246	11,530	11,590	11,725	11,913	12,224
Madison	0	80	48	1,773	1,726	1,684	1,627	1,580
Milam	2,904	15,105	35,448	21,654	21,131	21,127	21,770	23,072
Nacogdoches	6,576	8,007	8,942	7,679	8,150	8,995	9,785	10,532
Navarro	8	7	3	12	12	12	12	12
Robertson	7,070	8,353	22,760	26,695	27,279	30,983	32,125	33,370
Rusk	177	174	167	329	350	374	379	396
San Augustine	154	112	101	341	336	340	338	341
Smith	1,611	2,520	3,050	1,084	1,187	1,302	1,433	1,571
Van Zandt	634	750	829	548	851	767	814	833
Wilson	9,109	15,223	15,976	12,667	11,373	10,183	10,571	11,053
Total	116,293	147,884	193,718	282,021	298,646	313,214	332,577	363,346

Table 8a. Rate of groundwater withdrawal (acre-feet per year) for municipal public water supply from the Carrizo-Wilcox aquifer as assigned in the model.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	672	770	571	534	524	519	512	508
Angelina	17,251	14,555	15,759	12,776	12,547	13,550	14,408	15,812
Bastrop	2,254	1,890	3,242	7,765	8,171	11,356	12,000	13,040
Bexar	77	108	0	985	1,121	1,082	1,113	1,108
Brazos	17,923	22,451	27,878	37,866	42,944	42,277	46,663	50,515
Burleson	776	720	769	791	810	838	853	879
Caldwell	1,492	1,843	1,800	4,187	4,590	5,143	5,452	5,767
Cherokee	4,461	4,134	4,704	2,328	2,273	2,271	2,358	2,469
Falls	0	0	0	0	0	0	0	0
Fayette	0	0	0	0	0	0	0	0
Freestone	964	1,001	1,084	1,178	1,243	1,298	1,320	1,343
Gonzales	996	1,207	1,291	12,230	16,822	26,311	31,969	41,534
Guadalupe	0	0	548	242	232	254	272	277
Henderson	946	1,214	1,141	1,085	1,097	1,117	1,125	1,160
Houston	281	0	273	639	642	647	649	649
Karnes	0	0	0	0	0	0	0	0
Lee	1,093	1,683	1,469	24,367	26,280	27,957	29,673	36,470
Leon	604	720	662	1,227	1,270	1,348	1,422	1,510
Limestone	0	0	0	1,143	1,129	1,131	1,138	1,217
Madison	0	80	48	1,051	1,013	984	930	884
Milam	1,517	1,496	1,119	15,314	14,783	14,781	15,428	16,739
Nacogdoches	4,668	5,066	5,022	1,355	1,565	1,865	2,220	2,680
Navarro	0	0	0	0	0	0	0	0
Robertson	4,423	3,914	4,254	5,626	6,107	9,819	10,640	11,625
Rusk	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	0	0	0
Smith	0	0	0	72	80	81	85	91
Van Zandt	0	0	0	0	0	0	0	0
Wilson	1,451	1,883	2,117	2,369	2,458	2,603	2,754	2,928
Total	61,849	64,735	73,751	135,130	147,701	167,232	182,984	209,205

Table 8b. Rate of groundwater withdrawal (acre-feet per year) for rural domestic water supply from the Carrizo-Wilcox aquifer as assigned in the model.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	2,224	4,413	6,787	5,528	5,590	5,662	5,646	5,774
Angelina	2,310	2,645	3,288	2,057	2,058	2,118	2,123	2,211
Bastrop	1,678	4,101	5,050	7,018	8,120	9,315	10,019	10,247
Bexar	26	68	50	2,550	2,316	1,375	1,383	1,067
Brazos	2,251	2,790	3,106	1,838	2,166	2,275	2,107	1,911
Burleson	366	410	494	1,188	1,213	1,213	1,246	1,342
Caldwell	1,102	1,549	1,530	2,374	2,454	2,343	2,177	1,965
Cherokee	2,109	2,118	2,519	1,296	1,409	1,502	1,587	1,662
Falls	60	49	38	234	236	245	254	264
Fayette	4	5	5	0	0	0	0	0
Freestone	793	960	1,243	1,122	1,050	1,024	1,034	1,031
Gonzales	486	795	914	745	719	698	702	710
Guadalupe	978	1,517	1,374	5,424	7,303	9,298	10,662	13,158
Henderson	1,768	2,344	2,609	2,534	2,536	2,523	2,502	2,534
Houston	459	545	531	709	708	707	709	713
Karnes	54	65	91	0	0	0	0	0
Lee	575	946	1,216	1,691	1,749	1,819	1,906	2,044
Leon	666	1,127	717	1,002	1,078	1,157	1,243	1,343
Limestone	862	965	853	1,199	1,232	1,302	1,379	1,477
Madison	0	0	0	168	162	157	149	141
Milam	1,143	1,016	1,255	1,178	1,188	1,189	1,187	1,179
Nacogdoches	1,644	2,509	2,629	3,943	4,242	4,769	5,219	5,475
Navarro	8	7	3	0	0	0	0	0
Robertson	598	765	846	764	712	692	693	691
Rusk	138	141	143	283	303	328	332	349
San Augustine	136	92	86	274	269	271	269	272
Smith	1,602	2,510	3,042	991	1,086	1,201	1,328	1,460
Van Zandt	467	548	604	499	783	679	697	701
Wilson	850	1,550	1,831	2,654	2,927	3,207	3,897	4,571
Total	25,357	36,550	42,854	49,263	53,609	57,069	60,450	64,292

Table 8c. Rate of groundwater withdrawal (acre-feet per year) for mining water supply from the Carrizo-Wilcox aquifer as assigned in the model.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	0	0	0	168	93	61	40	31
Angelina	0	0	0	0	0	0	0	0
Bastrop	0	1	0	3,228	5,650	0	0	0
Bexar	0	0	0	0	0	0	0	0
Brazos	0	0	0	0	0	0	0	0
Burleson	0	0	0	0	0	0	0	0
Caldwell	0	0	0	16	10	4	0	0
Cherokee	81	125	0	47	23	49	61	76
Falls	0	0	0	0	0	0	0	0
Fayette	0	0	0	0	0	0	0	0
Freestone	18	20	7	32	23	21	21	22
Gonzales	0	0	0	10	9	8	8	9
Guadalupe	0	0	0	198	200	202	207	213
Henderson	265	102	394	164	144	129	115	102
Houston	0	0	0	0	0	0	0	0
Karnes	1,101	52	3	21	9	4	2	1
Lee	0	0	0	26,074	26,224	25,005	25,001	25,000
Leon	0	0	0	1,045	508	384	327	335
Limestone	398	366	447	872	913	976	1,080	1,214
Madison	0	0	0	72	66	56	54	56
Milam	0	12,271	32,537	0	0	0	0	0
Nacogdoches	11	0	0	0	0	0	0	0
Navarro	0	0	0	0	0	0	0	0
Robertson	0	0	11,396	8,572	8,572	8,572	8,572	8,572
Rusk	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	0	0	0
Smith	0	0	0	0	0	0	0	0
Van Zandt	0	0	0	0	0	0	0	0
Wilson	0	0	0	82	48	27	20	14
Total	1,874	12,937	44,784	40,601	42,492	35,498	35,508	35,645

Table 8d. Rate of groundwater withdrawal (acre-feet per year) for manufacturing and industrial water supply from the Carrizo-Wilcox aquifer as assigned in the model.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	346	0	0	139	146	152	165	176
Angelina	10,332	7,380	5,357	5,319	4,643	4,782	5,070	5,546
Bastrop	76	23	30	38	46	54	64	75
Bexar	1	1	1	0	0	0	0	0
Brazos	0	0	14	0	0	0	0	0
Burleson	0	0	0	145	158	171	182	194
Caldwell	1	0	0	65	69	74	79	84
Cherokee	0	0	0	0	0	0	0	0
Falls	0	0	0	0	0	0	0	0
Fayette	0	0	0	0	0	0	0	0
Freestone	0	0	0	0	0	0	0	0
Gonzales	0	0	0	654	687	701	751	797
Guadalupe	19	0	0	1,448	1,548	1,643	1,784	1,926
Henderson	0	0	0	99	106	119	135	154
Houston	0	0	0	12	14	16	19	21
Karnes	0	0	0	0	0	0	0	0
Lee	0	0	0	0	0	0	0	0
Leon	161	308	675	191	192	193	194	195
Limestone	0	0	0	0	0	0	0	0
Madison	0	0	0	82	85	87	94	99
Milam	0	0	0	0	0	0	0	0
Nacogdoches	21	0	0	874	874	874	872	874
Navarro	0	0	0	0	0	0	0	0
Robertson	28	24	0	51	61	72	84	98
Rusk	0	0	0	0	0	0	0	0
San Augustine	0	0	3	0	0	0	0	0
Smith	0	0	0	0	0	0	0	0
Van Zandt	0	0	0	0	0	0	0	0
Wilson	167	47	1	45	53	49	57	66
Total	11,152	7,783	6,081	9,162	8,682	8,987	9,550	10,305

Table 8e. Rate of groundwater withdrawal (acre-feet per year) for irrigation water supply from the Carrizo-Wilcox aquifer as assigned in the model.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	166	30	360	124	124	124	124	124
Angelina	0	0	0	0	0	0	0	0
Bastrop	1,655	734	938	0	0	0	0	0
Bexar	0	0	0	0	0	0	0	0
Brazos	0	0	0	0	0	0	0	0
Burleson	0	0	0	0	0	0	0	0
Caldwell	51	497	156	967	850	746	655	574
Cherokee	44	431	135	50	50	50	50	50
Falls	0	0	0	0	0	0	0	0
Fayette	0	0	0	0	0	0	0	0
Freestone	0	48	32	6	6	6	6	6
Gonzales	531	2,002	104	1,062	916	777	669	577
Guadalupe	1,262	1,390	41	311	296	282	268	255
Henderson	91	19	18	0	0	0	0	0
Houston	0	0	39	37	37	35	38	38
Karnes	0	0	0	0	0	0	0	0
Lee	165	103	211	143	139	136	132	128
Leon	0	0	0	0	0	0	0	0
Limestone	0	0	0	0	0	0	0	0
Madison	0	0	0	0	0	0	0	0
Milam	0	53	301	286	283	281	278	276
Nacogdoches	0	140	1,016	1,035	1,035	1,035	1,035	1,035
Navarro	0	0	0	0	0	0	0	0
Robertson	1,700	1,807	1,847	2,222	2,222	2,222	2,222	2,222
Rusk	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	0	0	0
Smith	0	0	0	0	0	0	0	0
Van Zandt	0	0	0	0	0	0	0	0
Wilson	6,499	11,642	11,919	7,517	5,887	4,297	3,844	3,474
Total	12,164	18,896	17,117	13,760	11,845	9,991	9,321	8,759

Table 8f. Rate of groundwater withdrawal (acre-feet per year) for power water supply from the Carrizo-Wilcox aquifer as assigned in the model.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	0	0	0	0	0	0	0	0
Angelina	0	0	0	0	0	0	0	0
Bastrop	0	0	0	0	0	0	0	0
Bexar	0	0	0	0	0	0	0	0
Brazos	0	58	103	0	0	0	0	0
Burleson	0	0	0	0	0	0	0	0
Caldwell	0	0	0	0	0	0	0	0
Cherokee	0	0	0	86	172	257	257	343
Falls	0	0	0	0	0	0	0	0
Fayette	0	0	0	0	0	0	0	0
Freestone	101	163	110	204	204	199	199	200
Gonzales	0	0	0	993	993	993	993	993
Guadalupe	0	0	0	0	0	0	0	0
Henderson	0	0	0	0	0	0	0	0
Houston	0	0	0	0	0	0	0	0
Karnes	0	0	0	0	0	0	0	0
Lee	0	0	0	1,750	1,750	1,750	1,750	1,750
Leon	0	0	0	0	0	0	0	0
Limestone	0	1,292	916	6,889	6,889	6,889	6,889	6,889
Madison	0	0	0	0	0	0	0	0
Milam	0	0	0	3,250	3,250	3,250	3,250	3,250
Nacogdoches	0	0	0	0	0	0	0	0
Navarro	0	0	0	0	0	0	0	0
Robertson	0	1,527	4,035	7,756	7,902	7,902	8,211	8,459
Rusk	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	0	0	0
Smith	0	0	0	0	0	0	0	0
Van Zandt	0	0	0	0	0	0	0	0
Wilson	0	0	0	0	0	0	0	0
Total	101	3,040	5,164	20,928	21,160	21,240	21,549	21,884

Table 8g. Rate of groundwater withdrawal (acre-feet per year) for stock water supply from the Carrizo-Wilcox aquifer as assigned in the model.

County	1980	1990	2000	2010	2020	2030	2040	2050
Anderson	144	317	332	296	296	296	296	296
Angelina	0	0	0	0	0	0	0	0
Bastrop	340	315	280	0	0	0	0	0
Bexar	8	10	13	0	0	0	0	0
Brazos	0	0	0	0	0	0	0	0
Burleson	15	12	18	1,214	1,214	1,214	1,214	1,214
Caldwell	72	7	9	0	0	0	0	0
Cherokee	0	270	305	401	401	401	401	401
Falls	2	2	2	659	659	659	659	659
Fayette	0	0	0	0	0	0	0	0
Freestone	423	295	412	535	535	535	535	535
Gonzales	626	130	129	0	0	0	0	0
Guadalupe	49	31	32	0	0	0	0	0
Henderson	315	501	354	363	363	363	363	363
Houston	20	29	23	69	68	69	68	67
Karnes	0	0	0	0	0	0	0	0
Lee	173	149	168	1,711	1,711	1,711	1,711	1,711
Leon	407	597	588	2,105	2,105	2,105	2,105	2,105
Limestone	29	33	31	1,427	1,427	1,427	1,427	1,427
Madison	0	0	0	400	400	400	400	400
Milam	243	269	237	1,627	1,627	1,627	1,627	1,627
Nacogdoches	232	293	275	472	434	452	440	468
Navarro	0	0	0	12	12	12	12	12
Robertson	322	316	382	1,704	1,704	1,704	1,704	1,704
Rusk	39	33	24	46	46	46	47	46
San Augustine	18	20	12	67	67	68	69	69
Smith	9	11	8	20	20	20	20	20
Van Zandt	167	202	224	49	68	88	117	132
Wilson	143	101	109	0	0	0	0	0
Total	3,796	3,943	3,967	13,177	13,157	13,197	13,215	13,256

north side of the study area, where the Simsboro sands are thin. Lufkin, Jacksonville, and other cities in East Texas get groundwater from the Carrizo aquifer. Carrizo sandstones also thicken to the south, providing groundwater resources, for example, in Gonzales County.

There are two issues associated with pumping: how much pumping there has been through time and where it has been located. Because most pumping has not been volumetrically metered, it is generally estimated indirectly, making it a possibly large source of calibration error in this and other numerical models. Accurate estimates of water withdrawals by pumping have been found to be key to calibrating predictive groundwater models (Konikow, 1986).

We relied on the results of water-use surveys (WUS) conducted by the TWDB to estimate groundwater use in the study area. TWDB reports WUS survey results by aquifer for river basins within counties and cross-listed by cities and industries responding to the survey. Annual pumping reported by river basin was aggregated by county for each of the main water-use groups: irrigation, manufacturing, mining, municipal, power, rural domestic, and stock. Municipal, manufacturing, and power water use was associated where possible with specific wells identified by user. In some cases we had to assume locations of wells near cities. Total annual pumping by user was prorated equally among all identified wells.

The TWDB developed predictive pumpage data sets for 2000, 2010, 2020, 2030, 2040, and 2050, subdivided into seven water-use categories. The source of the data sets was water-demand projections from the regional water plans as contained in Volume II of the 2002 State Water Plan (SWP) (TWDB, 2002). TWDB compared demand projections, currently available supplies, and associated strategies for water user groups listed in the SWP for the 2000-through-2050 planning cycle. TWDB adjusted predicted pumpage estimates so that the value to be used in the various GAM models did not exceed projected demands. Records associated with groundwater use were assigned to various aquifers.

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW

The conceptual model of flow in the Carrizo–Wilcox aquifer includes the following points (fig. 53):

- Groundwater flows primarily from outcrop recharge areas, especially where sandy soils are present in the Carrizo and Simsboro Formations (Henry and Basciano, 1979), to discharge areas in low-lying areas such as river bottomlands, to wells, and to deeper regional flow paths including cross-formational flow.
- Recharge rates vary with soil properties; there is more recharge to the Simsboro and Carrizo aquifers than to other layers of the aquifer.
- Some flow paths are relatively short and remain in the unconfined part of the aquifer. These short flow paths beneath the outcrop are from upland areas toward discharge zones in low-lying areas.
- Other flow paths pass deeper into the confined part of the aquifer. Much of the recharge to the outcrop is discharged to rivers and streams or evapotranspired.
- Most groundwater contribution to the base flow of rivers and streams crossing the outcrop is from the Simsboro and Carrizo Formations.
- The proportion of recharge that reaches the confined aquifer increases with increased pumping as discharge to rivers and streams and evapotranspiration in the outcrop area decreases.
- Cross-formational flow of groundwater within the Carrizo–Wilcox aquifer is probably directed mostly downward beneath the upland areas that cross surface-water divides and mostly upward beneath low-lying river bottomlands (Fogg and others, 1983; Dutton, 1999), although this pattern may change with groundwater withdrawal from wells.

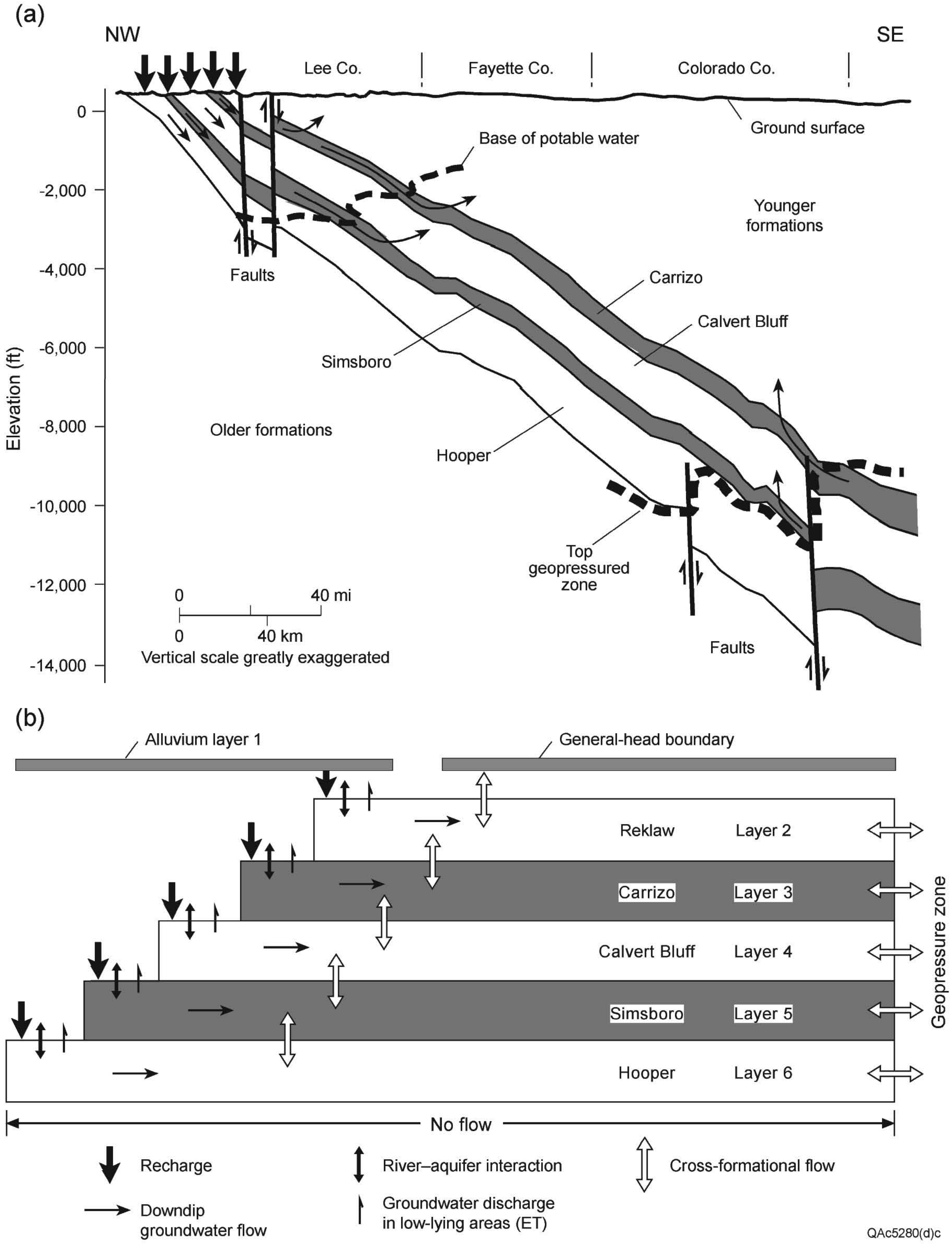


Figure 53. Conceptual model of the aquifer showing (a) hydrostratigraphic cross section with recharge and groundwater movement within and between model layers and (b) how the conceptual model translates into the computer model of the aquifer. Modified from Dutton (1999).

- Groundwater recharged in the upland outcrop areas follows arcuate flow paths moving toward the areas beneath stream valleys, where there is a tendency for upward discharge into the overlying formation.
- Some amount of water passes into the deeper part of the basin beyond the zone of freshwater. Increased concentrations of dissolved solids occurs along flow paths from the outcrop and are a result of ion exchange, dissolution of the mineral grains that make up the formation, and diffusion of residual salts out of low-permeability claystone and siltstone beds.
- Faults in the Karnes-Milano-Mexia Fault Zone disrupt the hydrologic continuity of the aquifers, probably affecting the extent of downdip, movement of groundwater, and width of the freshwater zone in the aquifers (fig. 27).
- At depths of more than 8,000 ft in the Wilcox Group there is a transition from normally pressured to geopressured conditions. The Wilcox Growth Fault Zone coincides approximately with the updip boundary of the geopressured zone. There has been a small amount of leakage of fluids upward and out of the geopressured zone into the deep part of the Carrizo–Wilcox aquifer downdip of the base of freshwater. Between the base of freshwater and the Wilcox Growth Fault Zone is a broad zone of convergence of the two flow systems where lateral flow may be very slow and where vertical flow may predominate.
- Pumping rate increased only slightly between 1950 and 1980. Total pumping rate has accelerated during the past 20 years (fig. 52). Part of the growth in groundwater withdrawal has been related to operations at lignite mines.
- Pumping rate is expected to continue to increase between 2000 and 2050, but at a slower rate than that of the past decade. Pumping will increase from the

Bryan-College Station well field but will be fairly steady from the Lufkin-Angelina County well field. Additional well fields will be established or grow because many municipalities and industries will meet future needs by drilling new wells and increasing their withdrawal from the Carrizo–Wilcox aquifer. Mining will continue to extract a significant volume of groundwater for mining operations, but after increasing in withdrawal rate during the period from 1990 through 2010, production of groundwater is expected to remain steady or to decrease.