Texas Water Development Board Report XXX

Brackish Groundwater in the Blaine Aquifer System, North-Central Texas

by

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The contents of this report (including figures and tables) document the work of the following licensed Texas geoscientists:

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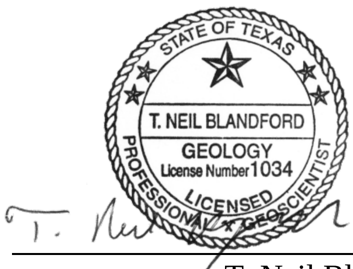

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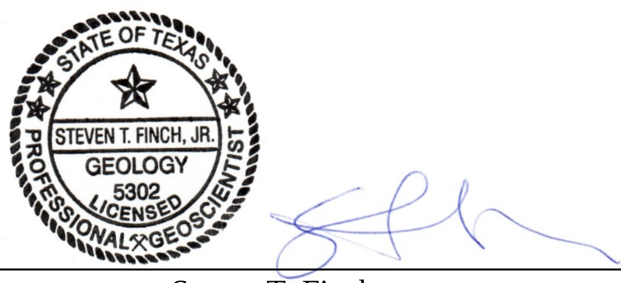

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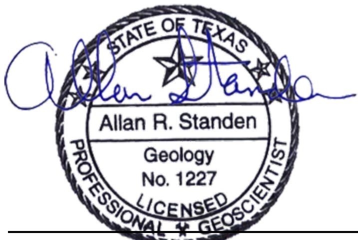
Mr. Standen was responsible for well log and associated stratigraphic analysis, and the determination of exclusion areas and potential production areas.



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1. Executive summary

The 84th Texas Legislature passed House Bill 30 (HB-30) in 2015 directing the Texas Water Development Board (TWDB) to conduct studies of the brackish groundwater resources of four aquifers by December 1, 2016, and the remaining aquifers in the state by December 1, 2022. The four aquifers are the Carrizo-Wilcox Aquifer located between the Colorado River and the Rio Grande, the Gulf Coast Aquifers and sediments bordering that aquifer, and the Blaine and Rustler Aquifers. The mandated studies are a continuation of the Brackish Resources Aquifer Characterization System (BRACS) program established in 2009. The goal of the BRACS program is to map and characterize the brackish portions of aquifers in Texas in sufficient detail to provide useful information to regional water planning groups and other interested parties.

The Blaine Aquifer is one of the first four aquifers required to be studied prior to December 1, 2016. The Daniel B. Stephens & Associates Inc. (DBS&A) team was selected by the TWDB to complete the brackish groundwater study of the Blaine Aquifer. As part of this study, significant effort was devoted to the compilation of basic hydrogeologic data such as geologic structure, water levels, spring locations, water quality, and aquifer properties. These data were necessary to construct a complete hydrogeologic conceptual model of the aquifer system so that the potential effects of brackish groundwater development could be reasonably assessed.

The project area includes approximately 10,400 square miles in all or portions of 20 counties in what is called the Rolling Plains region of north-central Texas. The study area includes the Blaine Aquifer, as defined by the TWDB, and a significant region to the west of the Blaine Aquifer where slightly to moderately saline groundwater occurs in the Whitehorse Group, which is not currently designated as a major or minor aquifer by the TWDB. The Whitehorse Group and the Blaine Aquifer are hydraulically connected and constitute a single groundwater flow system in north-central Texas and southwestern Oklahoma. Both aquifers, therefore, were considered together in what is called in this report the Blaine Aquifer system.

The region is predominantly rural, and the economy is based on ranching, irrigated agriculture, and energy production (oil, gas, and wind). The study area is covered by Regional Water Planning Areas A, O, B, G, and F and Groundwater Management Areas (GMAs) 1, 2, 6, and 7, although the majority of the study area occurs within GMA 6. All or portions of five groundwater conservation districts (GCDs) are within the study area.

Available information from water wells and oil and gas wells was used to develop Blaine Aquifer system stratigraphy and hydraulic characteristics. Data sources include the existing TWDB groundwater and BRACS databases, the Texas Bureau of Economic Geology Geophysical Log Facility historical well drillers' reports (cable tool) and scout tickets, the Texas Department of Licensing and Regulation database of submitted drillers' reports, information from the U.S. Geological Survey (USGS) Texas Water Science Center, and multiple publications by the TWDB, the USGS, and others.

The Blaine Aquifer system is a recharge-driven system, where the thickness of fresh to moderately saline water ranges from less than 100 to several hundred feet. The region has long been known as a discharge zone of high-salinity water derived from both local, relatively shallow groundwater flow through the aquifer system and discharge of brines derived through deeper, regional groundwater flow paths. Brine exists beneath the entire aquifer system, but in much of the southern two-thirds of the aquifer system the brine interface occurs above the base of the Blaine Formation. Where this occurs, the brine surface functions as the base of the aquifer system.

The Blaine Aquifer system is also predominantly a karst aquifer, where the aquifer permeability is the result of solutioning, collapse, and disruption of soluble rocks such as gypsum. As is typical of karst aquifer systems, well yields and production zones are highly variable, with low-yield wells located close to high-yield wells. Water quality is also variable, with numerous slightly saline wells adjacent to moderately saline wells. Fresh water does occur over limited portions of the aquifer system in topographically high regions, which are the zones of groundwater recharge. Based on the limited existing information, water quality appears to be relatively consistent with depth above the brine interface, with abrupt degradation of water quality at the brine interface.

HB-30 requires that brackish groundwater production zones be identified and the amount of brackish groundwater within each zone that can be produced over a 30- and 50-year period be determined. Brackish groundwater production is not supposed to have a significant impact on water availability or quality relative to significant sources of water supply already being used for municipal, domestic, or agricultural purposes. In this report potential production areas (PPAs), not “production zones” as referred to in HB-30, are evaluated. Whether or not one or more of the PPAs will be considered a production zone will be determined at a later date, based in part on stakeholder input.

The first step in determining the PPAs was to define exclusion areas based on known regions of significant municipal, domestic, and agricultural groundwater use. Exclusion areas were also determined for regions where injection wells are relatively shallow and for protected wildlife areas.

Based on existing information, three PPAs were identified outside the evaluated exclusion areas in areas expected to produce useable quantities of water. The effects of future groundwater pumping in these PPAs were analyzed at assumed well field production rates of 1,000, 2,000, and 3,000 acre-feet per year. Based on assumed aquifer properties, each PPA should be able to sustain the maximum amount of pumping for both 30- and 50-year periods. These PPAs or others considered for groundwater development would need to be investigated in detail through field studies prior to actual development. There are likely many other areas that could be developed to produce these general quantities of water.

Local stakeholders at a meeting held on August 18, 2016 unanimously opposed the designation of any PPAs within the Blaine Aquifer system because of, among other things, the limited thickness of the aquifer system and limited yields experienced by some water users, particularly during periods of drought and near the end of irrigation seasons.

Because the Blaine Aquifer system is shallow, relatively thin, and dependent on groundwater recharge within the outcrop area, and because target groundwater zones with slightly to moderately saline water occur adjacent to brine at depth, any brackish groundwater development project would need to be carefully planned and operated in order to be sustainable and avoid adverse impacts to adjacent water users.

2. Introduction

The 84th Texas Legislature passed House Bill 30 (HB-30) in 2015 directing the Texas Water Development Board (TWDB) to conduct studies of the brackish groundwater resources of four aquifers by December 1, 2016, and the remaining aquifers in the state by December 1, 2022. The four aquifers are the Carrizo-Wilcox Aquifer located between the Colorado River and the Rio Grande, the Gulf Coast Aquifers and sediments bordering that aquifer, and the Blaine and Rustler Aquifers. The mandated studies are a continuation of the Brackish Resources Aquifer Characterization System (BRACS) program established in 2009. The goal of the BRACS program is to map and characterize the brackish portions of aquifers in Texas in sufficient detail to provide useful information to regional water planning groups and others interested in using brackish groundwater.

The Blaine Aquifer is one of the first four aquifers required to be studied prior to December 1, 2016. The Daniel B. Stephens & Associates Inc. (DBS&A) team was selected by the TWDB to complete the brackish groundwater study of the Blaine Aquifer. DBS&A team members include John Shomaker & Associates, Inc. (JSAI), Allan R. Standen, LLC (ARS), and Michelle A. Sutherland, LLC. The project study area is shown in Figure 2-1.

3. Project deliverables

Unlike some previous BRACS reports completed to date, there has not been a comprehensive groundwater availability model (GAM) or geologic structure project completed for the Blaine Aquifer system. As part of this study, therefore, significant effort was devoted to the compilation of basic hydrogeologic data such as geologic structure, water levels, spring locations, water quality, and aquifer properties. These data were necessary to construct a complete hydrogeologic conceptual model so that the potential effects of brackish groundwater development could be reasonably assessed. The results of this work are documented in this peer-reviewed report, which is available for download from the TWDB website.

In addition to the project completion report, associated electronic data are available through the BRACS database or GIS files developed as part of this project and available from the TWDB. Key geologic and hydrologic surfaces and associated data were also implemented in the three-dimensional visualization and analysis software Leapfrog; these files can be viewed using a free viewer also available for download from the Leapfrog website (http://www.leapfrog3d.com/products/Leapfrog-Viewer/downloads).

4. Project area

The project area includes approximately 10,400 square miles in all or portions of 20 counties in what is called the Rolling Plains region of north-central Texas (Figure 2-1). The region of interest extends approximately from near the base of the High Plains caprock escarpment in the west to the eastern extent of Blaine Formation outcrop. Land surface elevation ranges from about 1,360 to 3,100 feet above mean sea level. The topography is dissected by numerous intermittent and in some cases perennial stream reaches that feed either the Red or Brazos Rivers. Average annual precipitation ranges from about 20 inches per year in the west to 25 inches per year in the east (OSU, 2016).

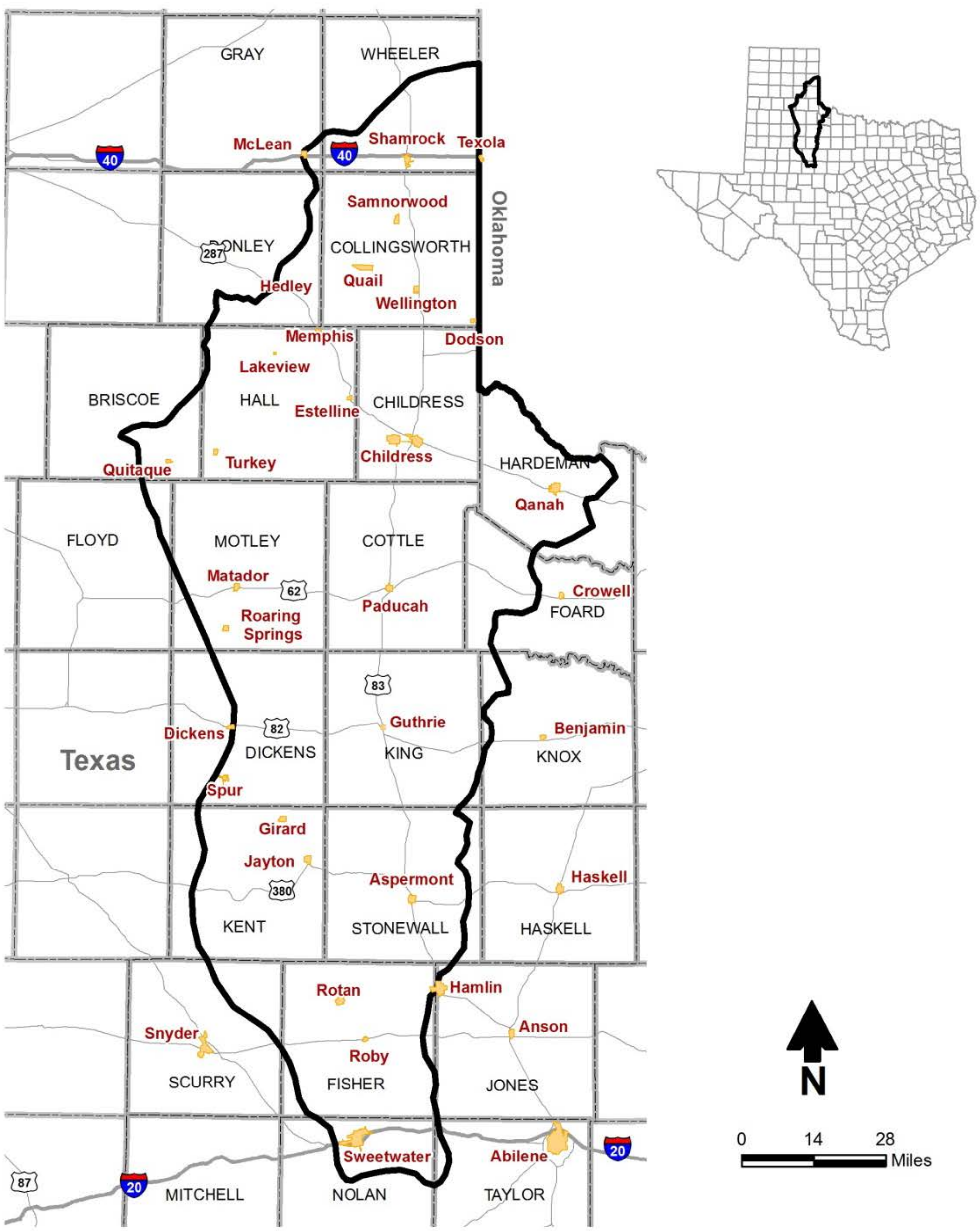

Figure 2-1. Study area.

The region is predominantly rural, and the economy is based on ranching, irrigated agriculture, and energy production (oil, gas, and wind). The largest town in the northern portion of the study area is Childress, with a population of about 6,000. The largest town in the southern portion of the study area is Sweetwater, with a population of about 11,000.

The study area is covered by Regional Water Planning Areas A, O, B, G, and F (Figure 4-1) and Groundwater Management Areas (GMAs) 1, 2, 6, and 7, although the majority of the study area occurs within GMA 6 (Figure 4-2). All or portions of five groundwater conservation districts (GCDs) are within the study area (Figure 4-3). As described in Section 5, the study area includes a significant region west of the Blaine Aquifer as currently delineated by the TWDB.

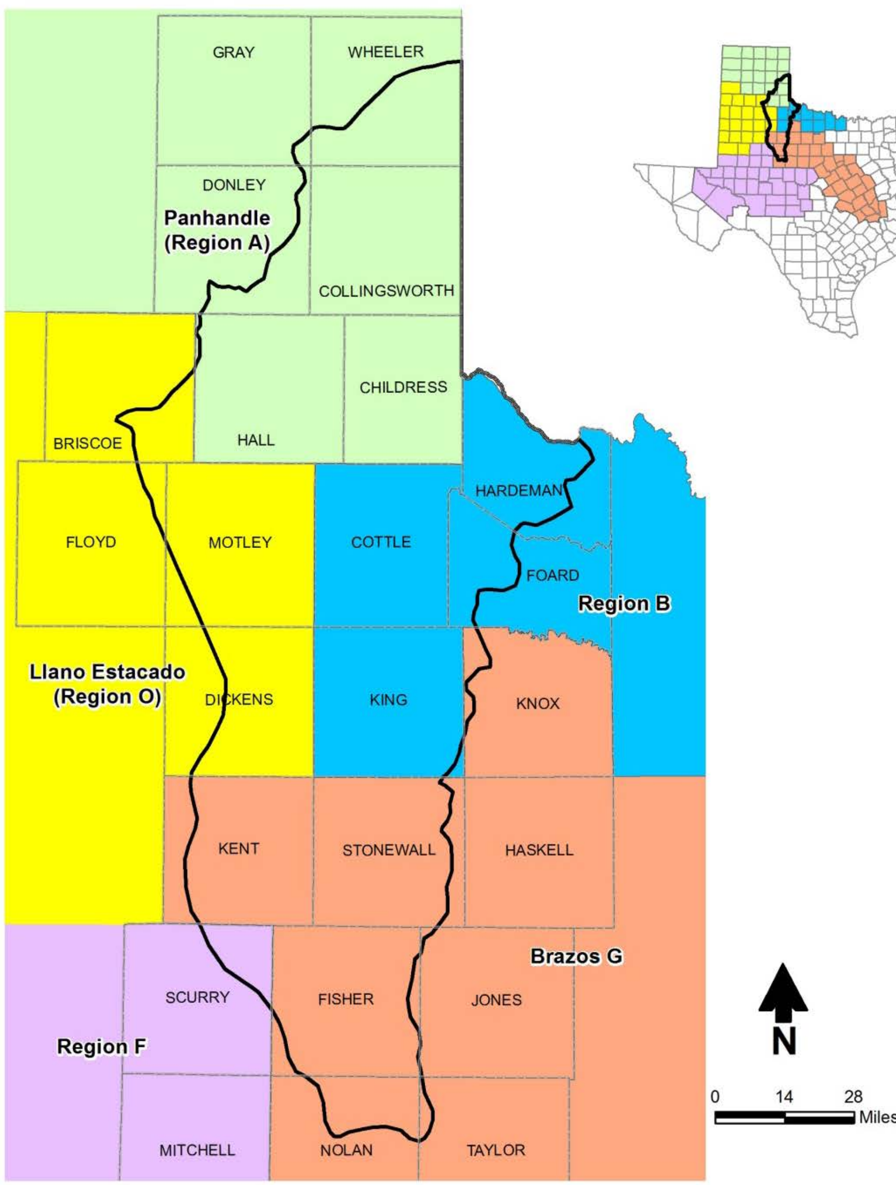

Figure 4-1. Regional water planning areas.

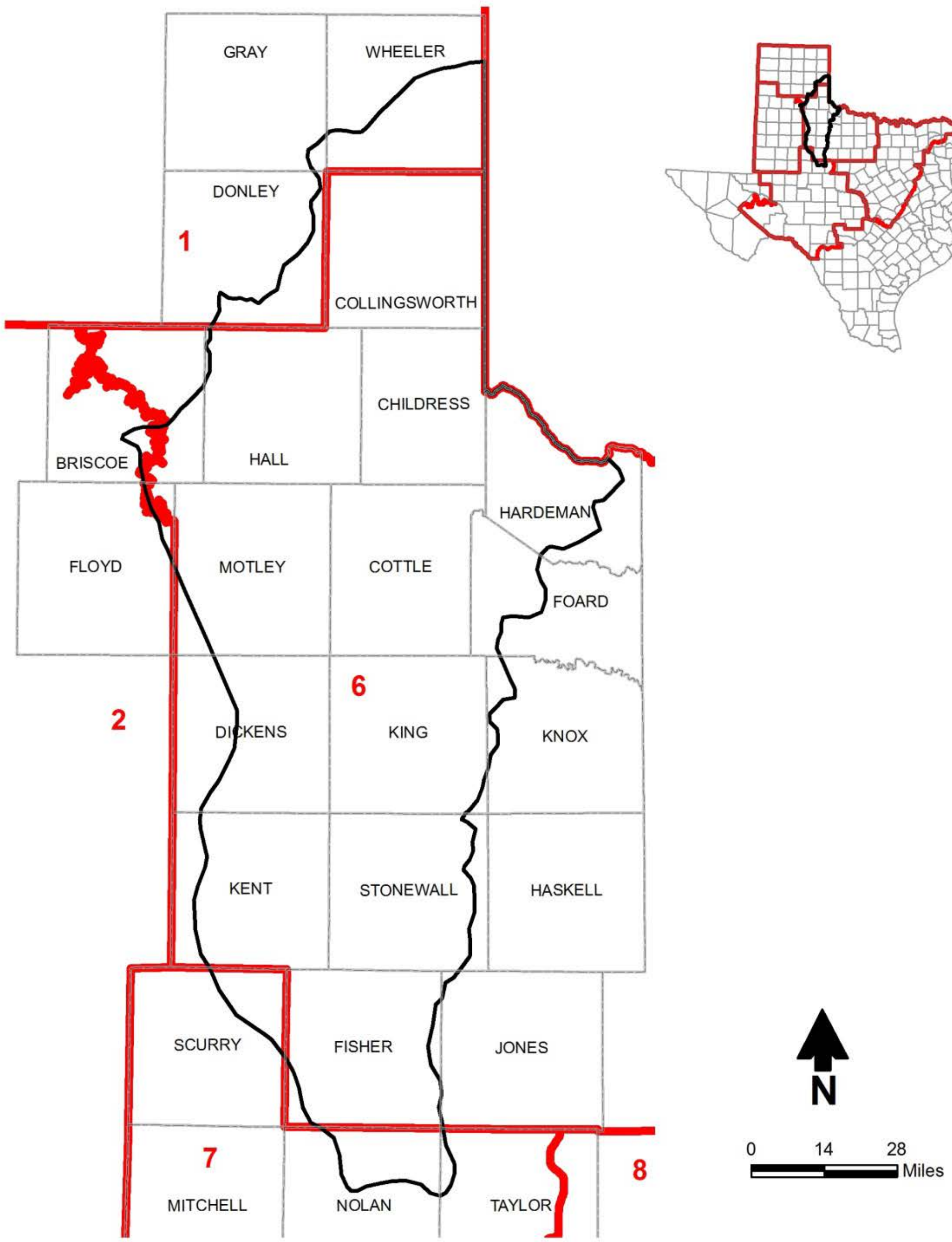

Figure 4-2. Groundwater management areas.

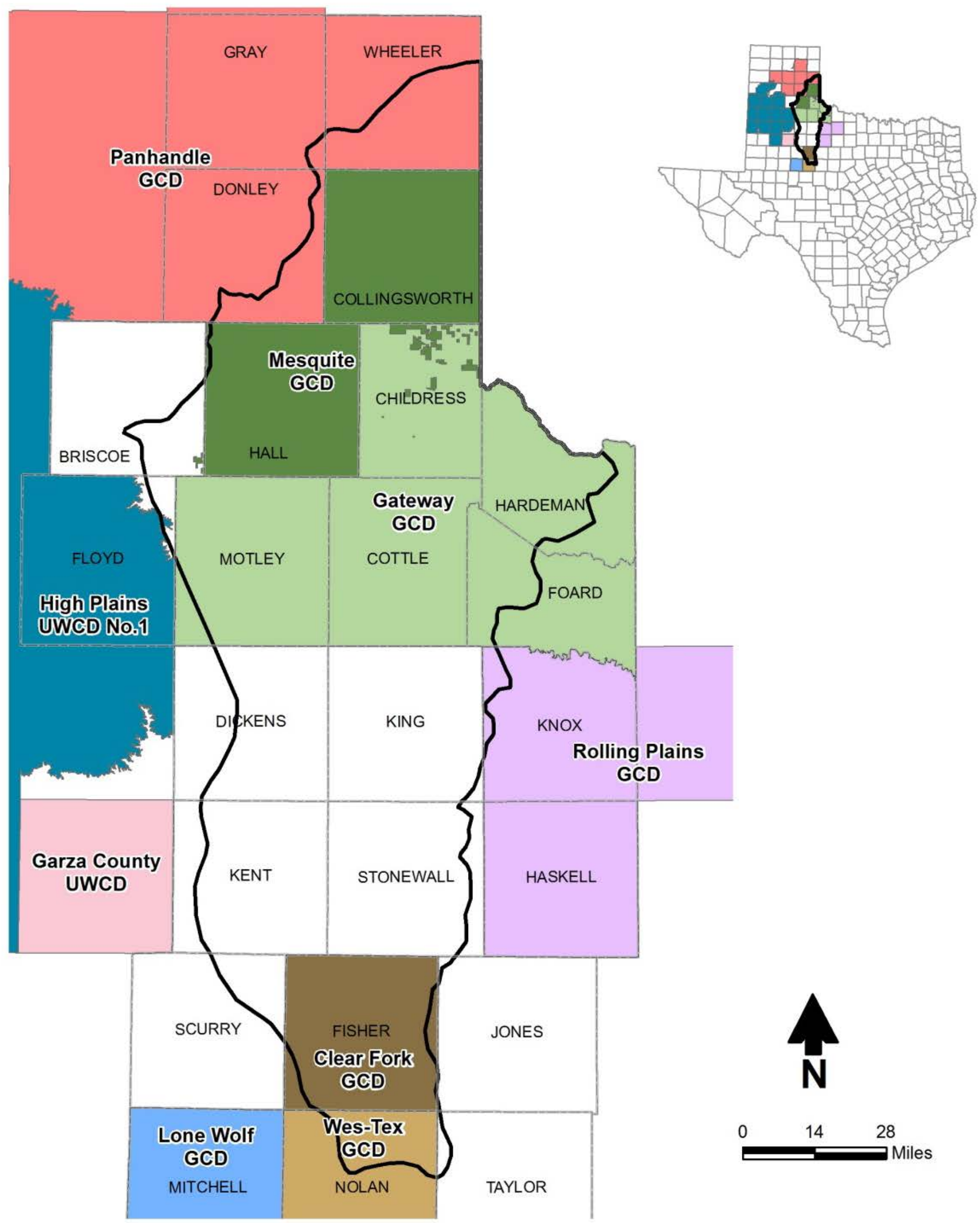

Figure 4-3. Groundwater conservation districts.

5. Hydrogeologic setting

The extents of the major and minor aquifers within the study area as defined by the TWDB are illustrated in Figure 5-1, and geologic formation outcrops and structure are illustrated in Figure 5-2. Comparison of the two figures shows that the region west of the Blaine Aquifer outcrop and subcrop (Figure 5-1) is characterized by outcrop of the Whitehorse Group and, to a lesser extent, the Quartermaster Formation (Figure 5-2). The Whitehorse Group is a known aquifer unit, although it is not officially designated as a major or minor aquifer by the TWDB. Furthermore, as discussed in Section 7, the Whitehorse Group and the Blaine Aquifer are hydraulically connected and constitute a single groundwater flow system in north-central Texas and southwestern Oklahoma. Consequently, the current study was completed for what is called the Blaine Aquifer system, composed of the Whitehorse Group and the Blaine Formation.

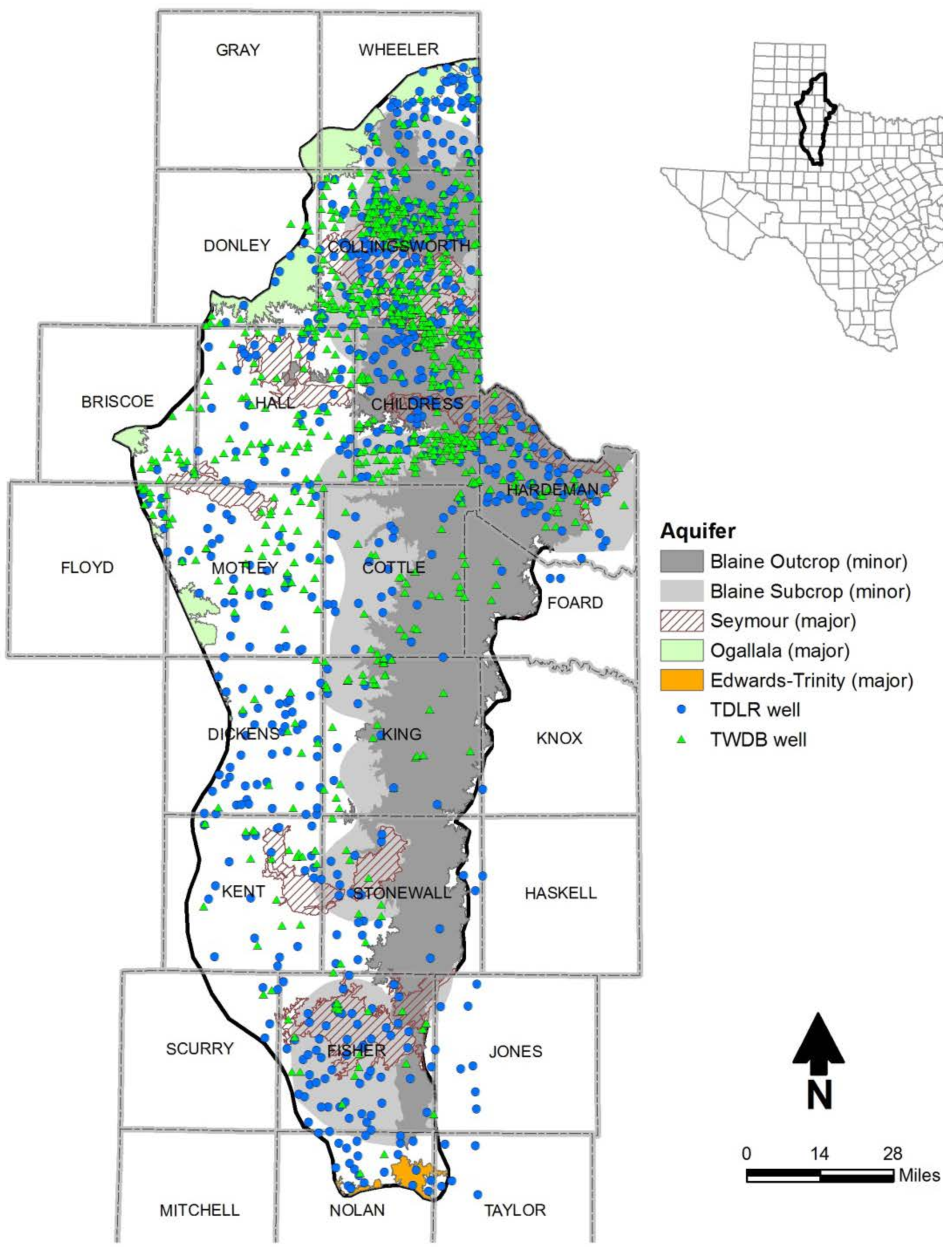

Figure 5-1. Major and minor aquifers as designated by the TWDB within the study area.

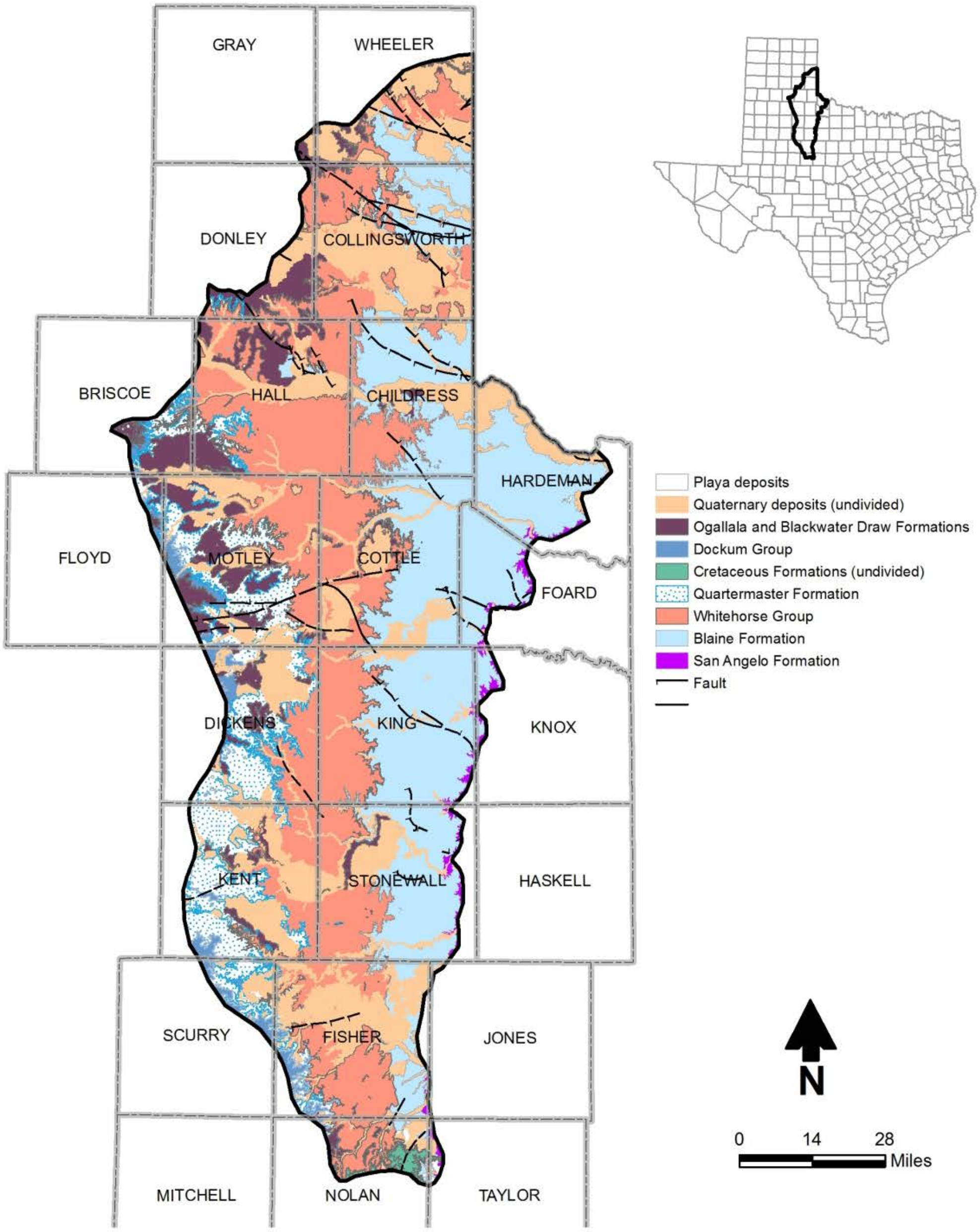

Figure 5-2. Study area surface geology from Geologic Atlas of Texas (Barnes, 1974, Amarillo, Plainview, Lubbock, Big Spring, Wichita Falls-Lawton and Abilene sheets) and structure from Ewing (1991).

The Whitehorse Group is assumed to include the Whitehorse Sandstone and the Cloud Chief Gypsum where it is present. Both the Blaine Formation and the Whitehorse Group are late Permian-age rocks that formed along the eastern shelf of the Permian Basin. A general stratigraphic chart for the Blaine Aquifer system is presented as Figure 5-3.

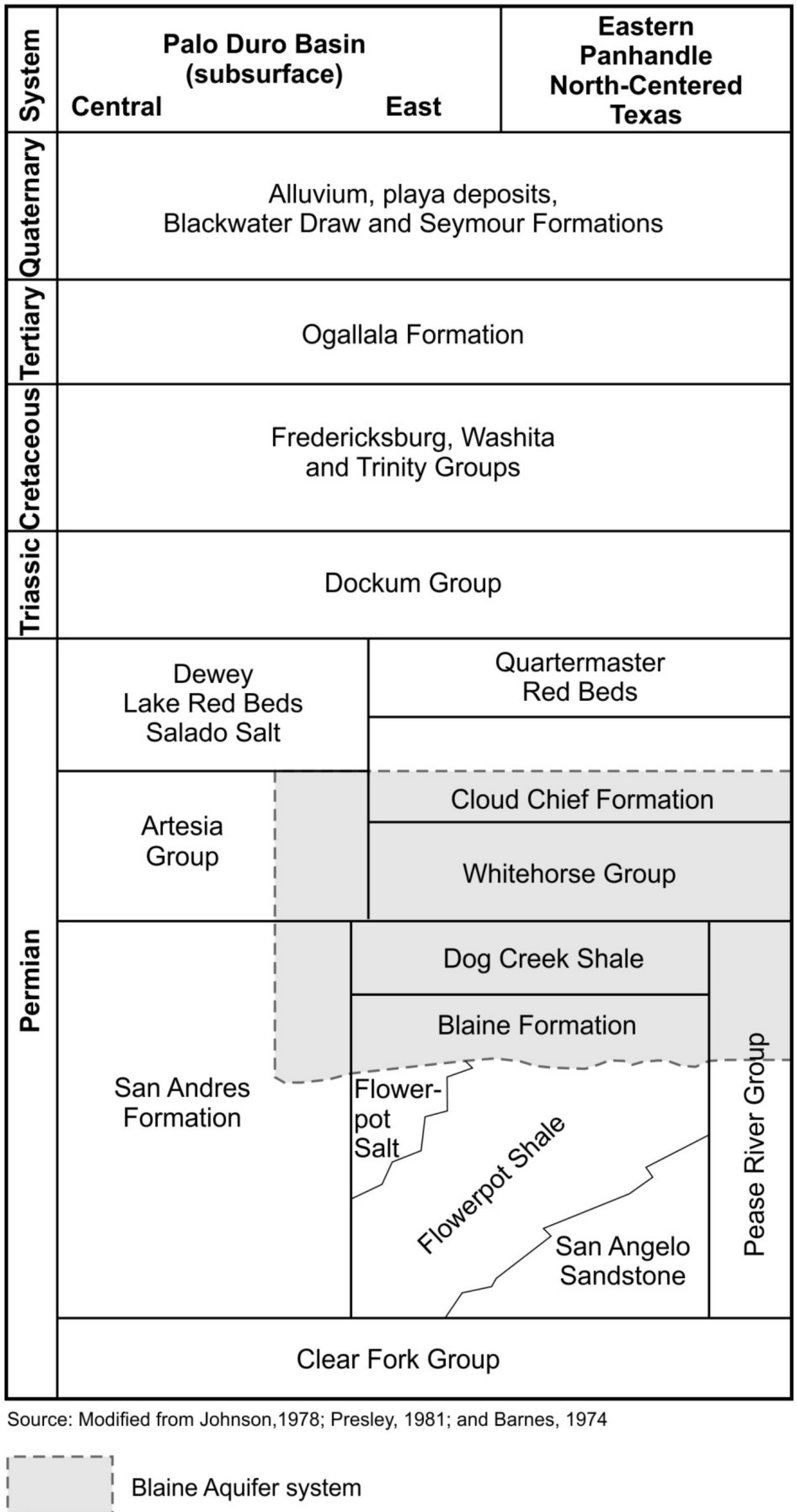

Figure 5-3. Generalized stratigraphic chart for the Blaine Aquifer system and adjacent geologic units.

The Blaine Formation is composed primarily of gypsum and anhydrite beds with interbedded dolomite and shale. Based on review of drillers' logs across the study area, the dolomite beds are more prominent in the northern part of the study area, and the net thickness of shale beds in the Blaine Formation increases to the south. The Blaine Formation contains very few sand beds. The Whitehorse Group contains gypsum, dolomite, and shale beds, but has numerous red sand beds.

In the southern two-thirds of the aquifer system, rocks of the Whitehorse Group and Blaine Formation crop out to the east and dip westward at an average rate of about 25 feet per mile (Cronin, 1972). The bottom elevation of the Blaine Formation is illustrated in Figure 5-4, and the depth to the base of the Blaine Formation from land surface is illustrated in Figure 5-5.

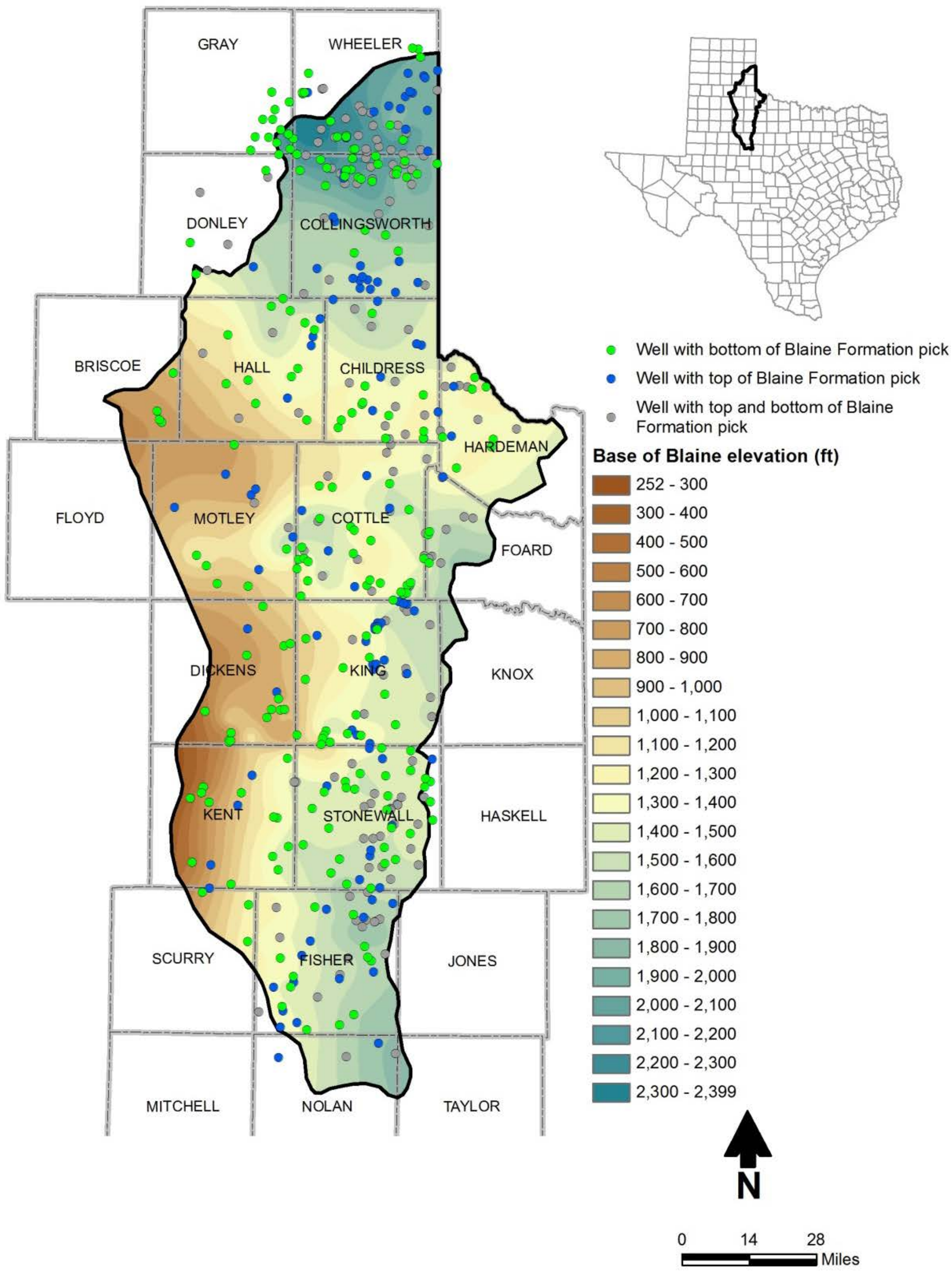

Figure 5-4. **Bottom elevation of the Blaine Formation.**

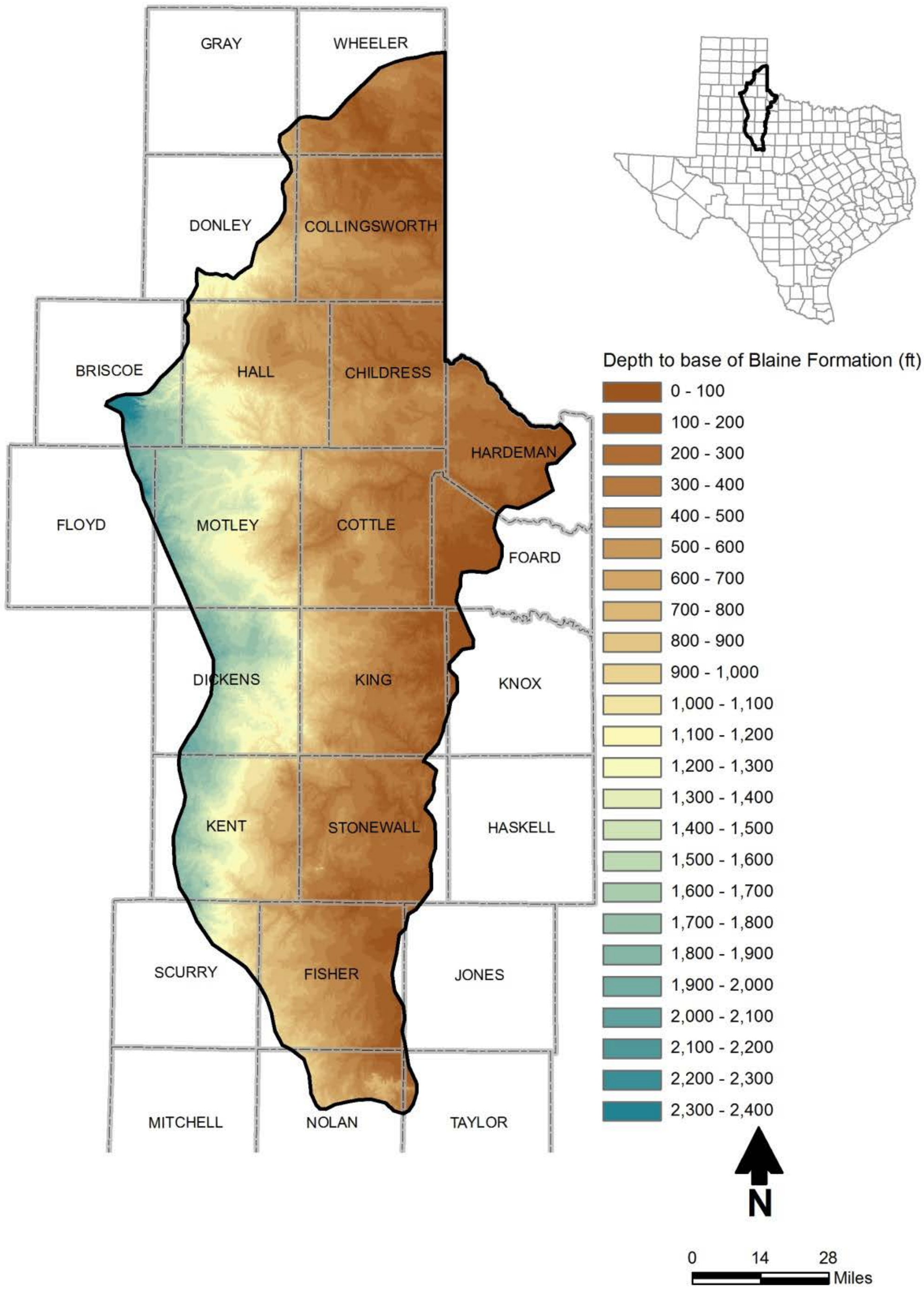

Figure 5-5. Depth to bottom of the Blaine Formation from land surface.

6. Groundwater salinity zones

The groundwater salinity classification developed by Winslow and Kister (1956) for TWDB brackish aquifer studies were used for the Blaine Aquifer system analysis. Table 6-1 is a summary of groundwater salinity classifications and representative ranges in total dissolved solids (TDS) content.

Table 6-1. Groundwater salinity classification summary

Groundwater salinity classification	Salinity zone code	Range in TDS content (mg/L)
Fresh	FR	0 to 1,000
Slightly saline	SS	1,000 to 3,000
Moderately saline	MS	3,000 to 10,000
Very saline	VS	10,000 to 35,000
Brine	BR	greater than 35,000

TDS = total dissolved solids
mg/L = milligrams per liter

The TWDB aquifer codes and the available water quality data obtained from the TWDB database are summarized in Table 6-2, and the distribution of water quality data is shown in Figure 6-1.

Table 6-2. Summary of Blaine Aquifer system aquifer water quality data

TWDB aquifer code	Name	Number of water-quality analyses	Average well depth (feet)	Maximum well depth (feet)
313ARTS	Artesia Group	40	143	327
313WTRS	Whitehorse Group	106	105	420
313WDCB	Whitehorse, Dog Creek, and Blaine	14	139	233
313DCKB	Dog Creek Shale and Blaine Gypsum	10	94	296
313DCBF	Dog Creek Shale, Blaine Gypsum, and Flowerpot Shale	1	105	105
313BLIN	Blaine Gypsum	254	129	360

6.1. Fresh to moderately saline zones

As shown in Figure 6-1, the northern half of the study area has better water well data coverage than the southern half of the study area, but overall the entire area has a fair distribution of water quality data points. Initial analysis of the water quality data indicates that the primary water quality data gap from the water well data set is the vertical distribution of water quality within the aquifer system. The average depth of water wells with water quality data is 129 feet

(Table 6-2); only a handful of data points are available for the depth range of 129 to 420 feet. Most of the eastern half of the aquifer system is less than 500 feet in depth (Figure 5-3) and is probably reasonably represented by water quality data from water wells. The western half of the aquifer has significant data gaps with respect to water quality versus depth.

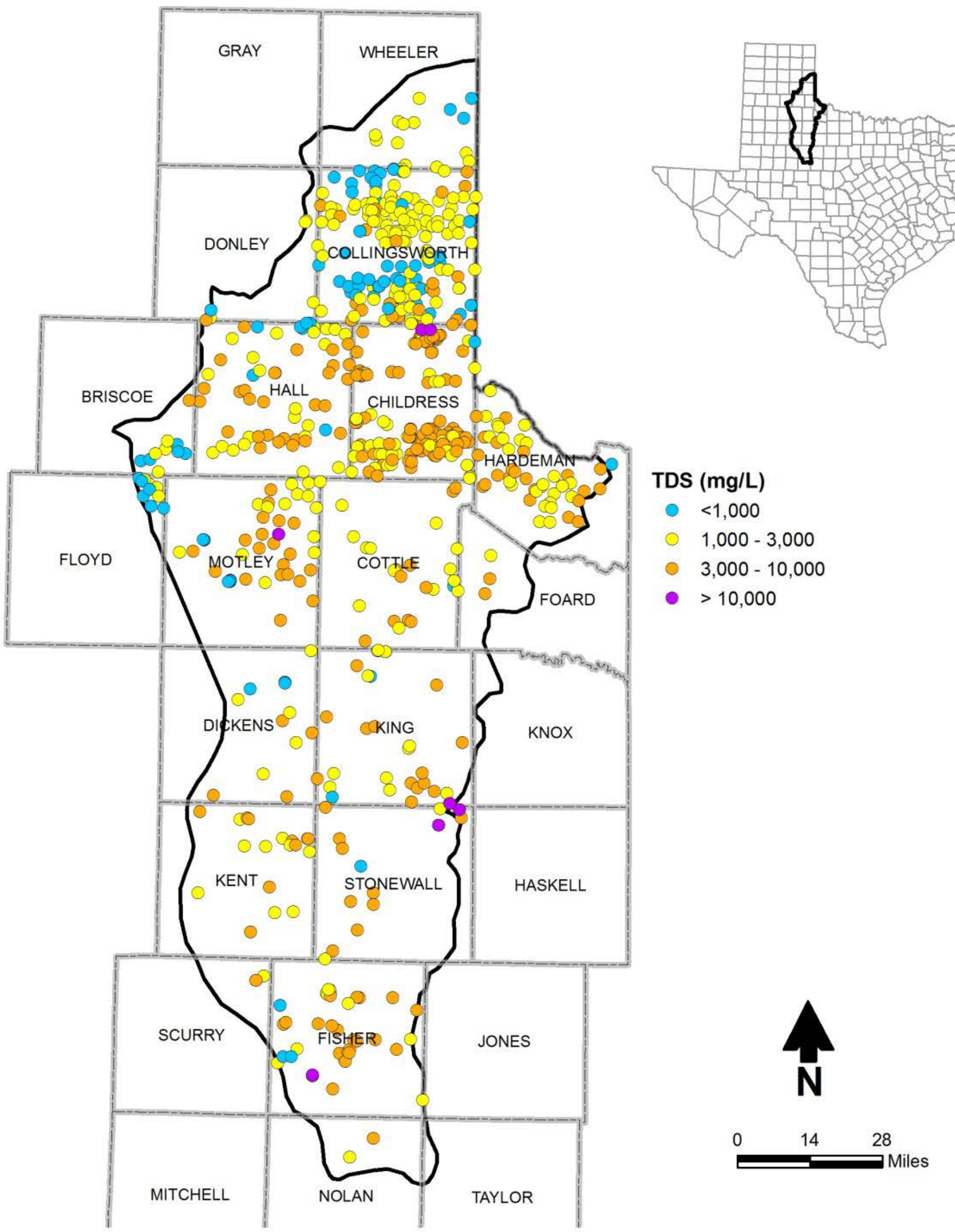

Figure 6-1. Blaine Aquifer system TDS from water wells.

Water-quality data from water wells do not show a significant trend of TDS versus depth (Figure 6-2), indicating that groundwater above the brine surface does not have a significant vertical gradient in salinity (i.e., the groundwater TDS from the top of the aquifer to the brine interface is relatively homogeneous). Most of the water well data plot in the slightly to moderately saline classification, although a fair number of fresh water values are evident (Figure 6-2).

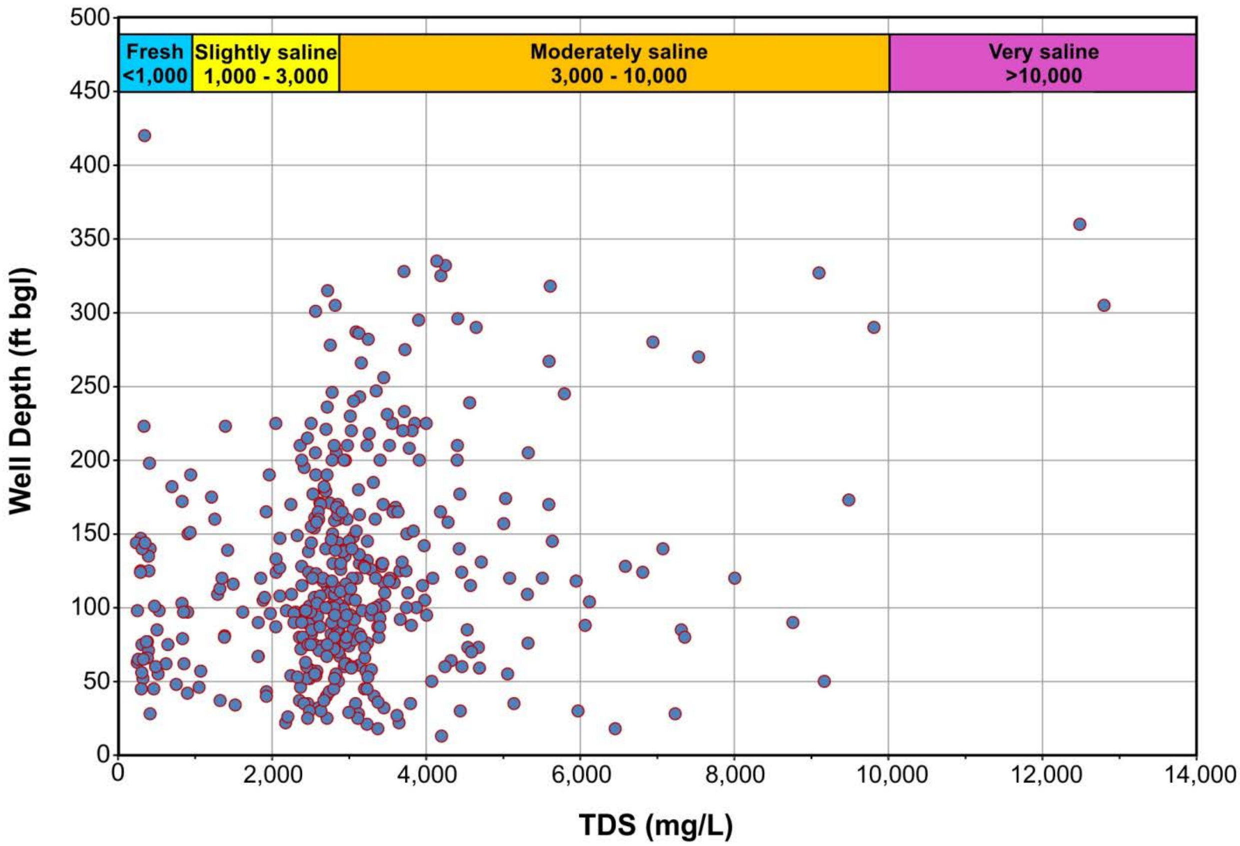

Figure 6-2. Well depth versus TDS for wells completed in the Blaine Aquifer system.

6.2. Very saline and brine zones

It appears that one of the primary reasons for the lack of water quality data from deeper water wells within the study area is the presence of a brine interface that occurs throughout much of the Blaine Aquifer system at relatively shallow depths. The brine interface is characterized by a sharp transition from slightly or moderately saline water to brine (TDS 35,000 mg/L or higher). Above the brine interface there is undoubtedly a limited thickness of very saline water, but the thickness cannot be delineated based on existing information. Figure 6-2 shows only two water quality samples in the very saline category.

Brine emission areas were identified in the Blaine Aquifer by the Texas Water Commission (1989) based on multiple data sources; a modified version of the Texas Water Commission

(1989) map provided by Duffin and Beynon (1992) is provided as Figure 6-3. The brine interface has been mapped in detail by the U.S. Geological Survey (USGS) (Stevens and Hardt, 1965; Keys and MacCary, 1973; Garza, 1982) around the intersection of Dickens, King, Kent, and Stonewall Counties. The brine surface in this area is relatively shallow (less than 200 feet below land surface), and the transition from fresh or brackish groundwater to brine is abrupt.

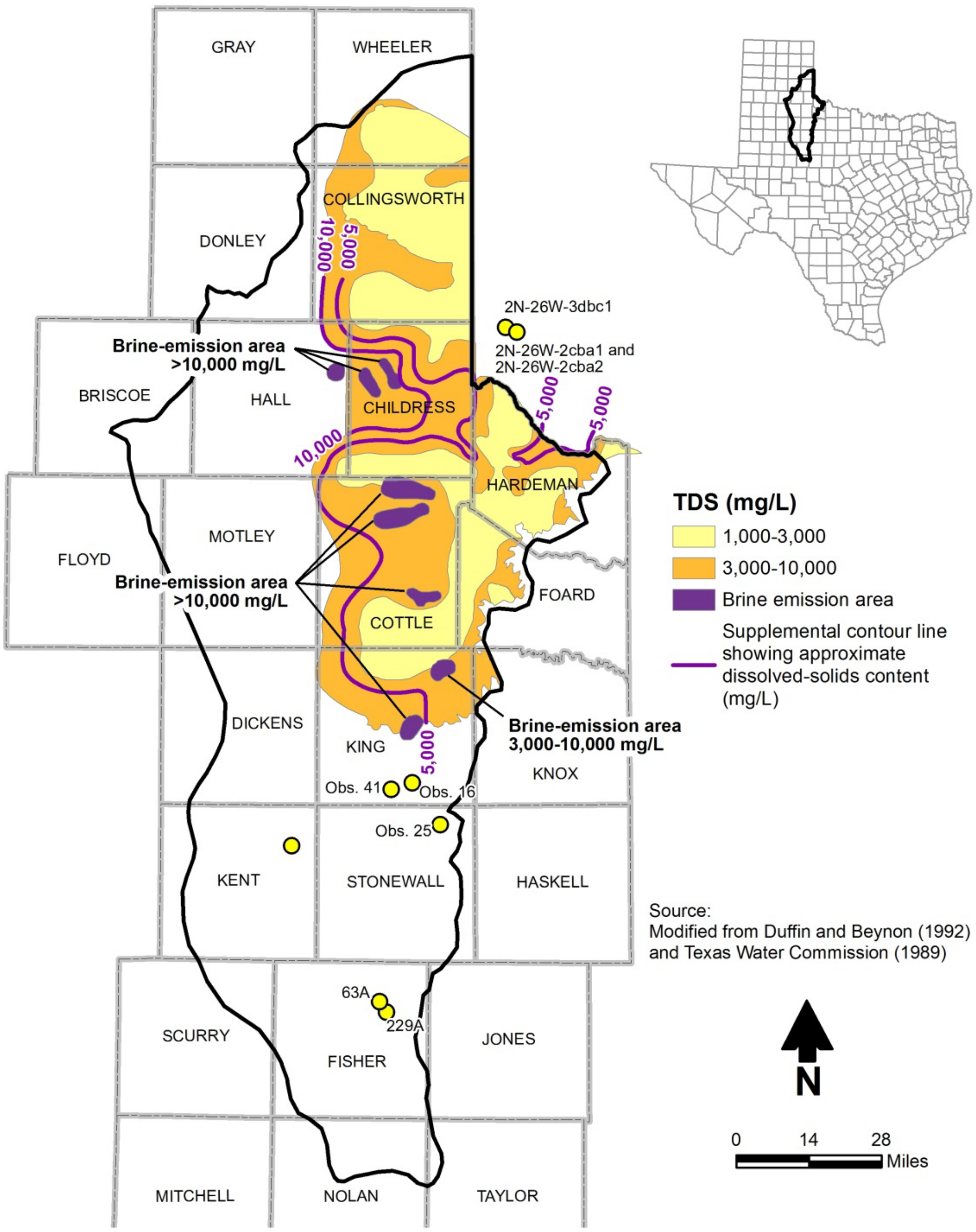

Figure 6-3. Map of Blaine aquifer salinity distribution and brine emission areas and location of Table 6-3 data points.

Figure 6-4 shows a cross section taken from McMillion (1958) for a region in northeastern Kent County. The cross section illustrates lower TDS water on top of the brine interface and the two waters mixing within zones of discharge.

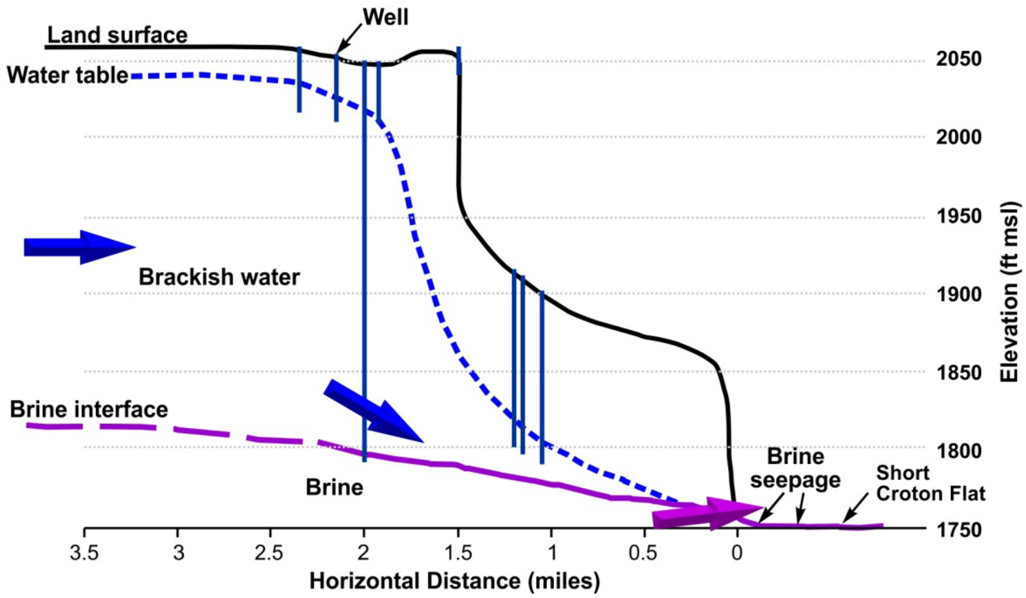

Figure 6-4. Cross section of brine interface and overlying brackish groundwater illustrating groundwater flow and mixing of brine with brackish groundwater at discahrge areas. Modified from McMillion, 1958.

Several researchers (e.g., Duffin and Beynon, 1992) have described the fresh and brackish groundwater zones:

- The fresh to very saline groundwater is a shallow upper aquifer that receives recharge within the High Plains and the Rolling Plains, flows eastward, and dissolves up-dip sections of evaporate layers.
- The underlying brine is a lower deep-basin aquifer that receives recharge in central New Mexico (e.g., Richter and Kreitler, 1986), traverses the High Plains below or through the Permian salt section, and flows generally to the east and northeast.

The brine interface is found at variable depth throughout the study area and does not coincide with specific geologic formations or surfaces. For example, in much of the south-central portion of the study area, the brine interface occurs above (shallower than) the base of the Blaine Formation, while in the northern part of the study area the brine surface occurs below the base of the Blaine Formation (Section 13.3).

Available water quality data were reviewed to determine if the brine surface could be identified in other areas of the Blaine Aquifer system. The data are limited (Table 6-3), but it appears that the brine surface exists throughout the study area and the transition from moderately or very saline water to brine is abrupt in all cases. The locations of data points listed in Table 6-3 are illustrated in Figure 6-3.

Table 6-3. Summary of vertical profile water-quality data for the Blaine Aquifer system.

Well ID	Sample depth (ft bgl)	Formation	TDS (mg/L)	Source
Harmon County, Oklahoma (5 miles east of Childress County, Texas)				
2N-26W-2cba1	102	Blaine Gypsum	3,220	Steele and Barclay (1965)
2N-26W-2cba2	189	Blaine Gypsum	3,050	Steele and Barclay (1965)
2N-26W-3dbc1	450	Blaine Gypsum	144,000	Steele and Barclay (1965)
King County, Texas				
OBS-16	63 80 94	Blaine Gypsum Blaine Gypsum Blaine Gypsum	4,850 16,300 69,500	Garza (1982)
OBS-41	35 85	Blaine Gypsum Blaine Gypsum	2,100 163,000	Garza (1982)
Stonewall County, Texas				
OBS-25	42 52	Blaine Gypsum Blaine Gypsum	13,600 41,300	Garza (1982)
Fisher County, Texas				
63A	100	Blaine Gypsum	3,740	Core Laboratories, Inc., (1972)
229A	494	Permian	34,000	Core Laboratories, Inc., (1972)

ft bgl = feet below ground level
TDS = total dissolved solids
mg/L = milligrams per liter

7. Previous investigations

Previous hydrogeological studies have been conducted for regional assessment of saline groundwater resources for the north-central Texas region, and for local and county-wide water resource assessments. The saline groundwater resources of the Blaine Aquifer system were first assessed by Winslow and Kister (1956), who identified the Blaine Formation as a significant source of brackish groundwater. Core Laboratories (1972) performed a more detailed assessment of the saline groundwater resources of Texas using available water quality data from wells and interpretation of geophysical logs, although this assessment only considered the upper undifferentiated Permian rocks for the north-central Texas region. Richter and Kreitler (1986) analyzed the geochemistry and isotopic composition of groundwater in north-central Texas to distinguish the origin of brines. The Texas Water Commission (1989) provided an overview of naturally occurring and anthropogenic groundwater quality conditions for all designated aquifers in Texas, including the Blaine Aquifer. Duffin and Beynon (1992) compiled a summary of brackish and saline groundwater of the Permian rocks in north-central Texas. LBG-Guyton (2003) prepared a summary of brackish groundwater resources for Texas and provided descriptions of the Whitehorse-Artesia and Blaine as separate aquifers. More recently the Blaine Aquifer was assessed by Hopkins and Muller (2011) to describe water quality.

The areas covered by some of the more pertinent hydrogeologic studies are illustrated in Figure 7-1. Selected hydrogeologic cross sections from these studies are presented in Figures 7-2 through 7-4. These cross sections illustrate the conceptual hydrogeologic model of the Blaine Aquifer system, where groundwater flow in the aquifer system occurs either above the Flowerpot Shale (base of aquifer in the north, Figure 7-2) or the brine interface in the central and southern regions (Figures 7-3 and 7-4). Groundwater that originates in the Whitehorse Group is interconnected with groundwater in the Blaine Formation (Figures 7-2 and 7-3), and groundwater flow is generally from west to east on a regional scale.

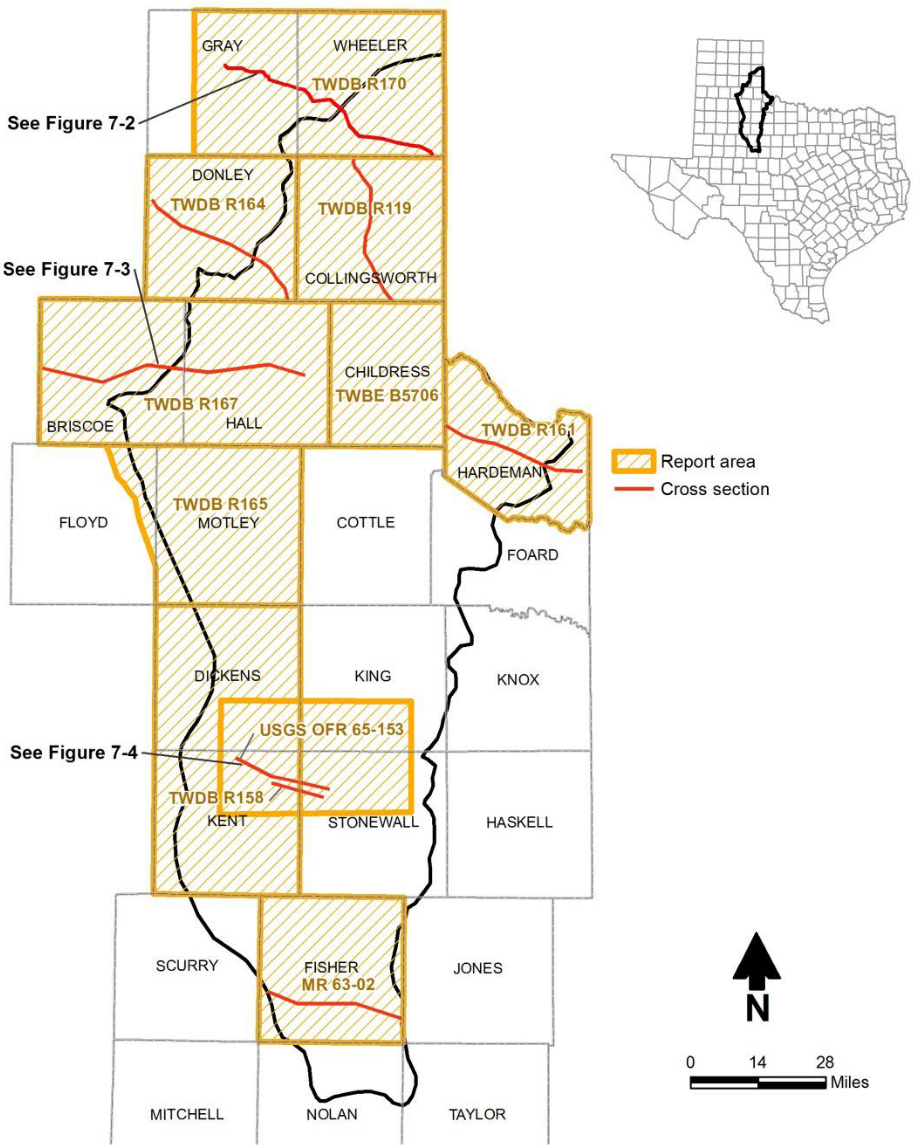

Figure 7-1. Regions covered by selected historical reports.
R=Report, MR = Memorandum report, OFR = Open-File report, B= Bulletin,
TWDB = Texas Water Development Board, TWBE = Texas Water Board of Engineers,
USGS = U.S. Geological Survey.

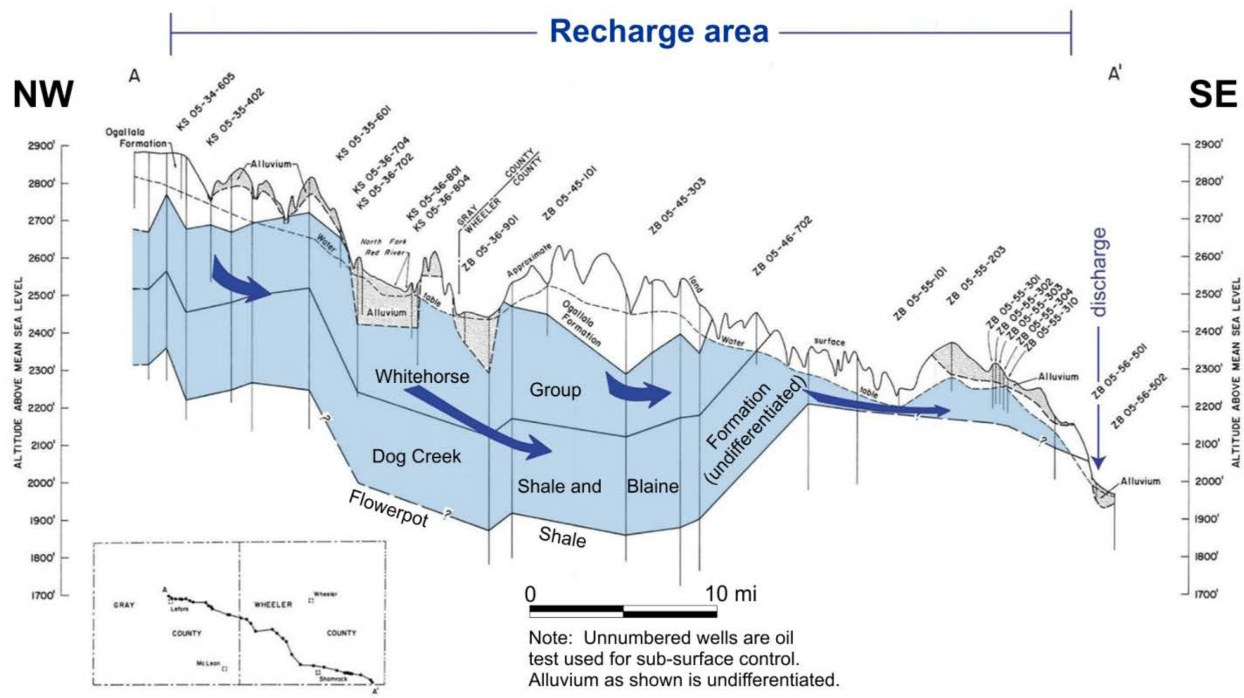

Figure 7-2. Hydrogeologic cross section through Gray and Wheeler Counties from Maderak (1973). Features in blue were added to illustrate the conceptual model of gorundwater flow.

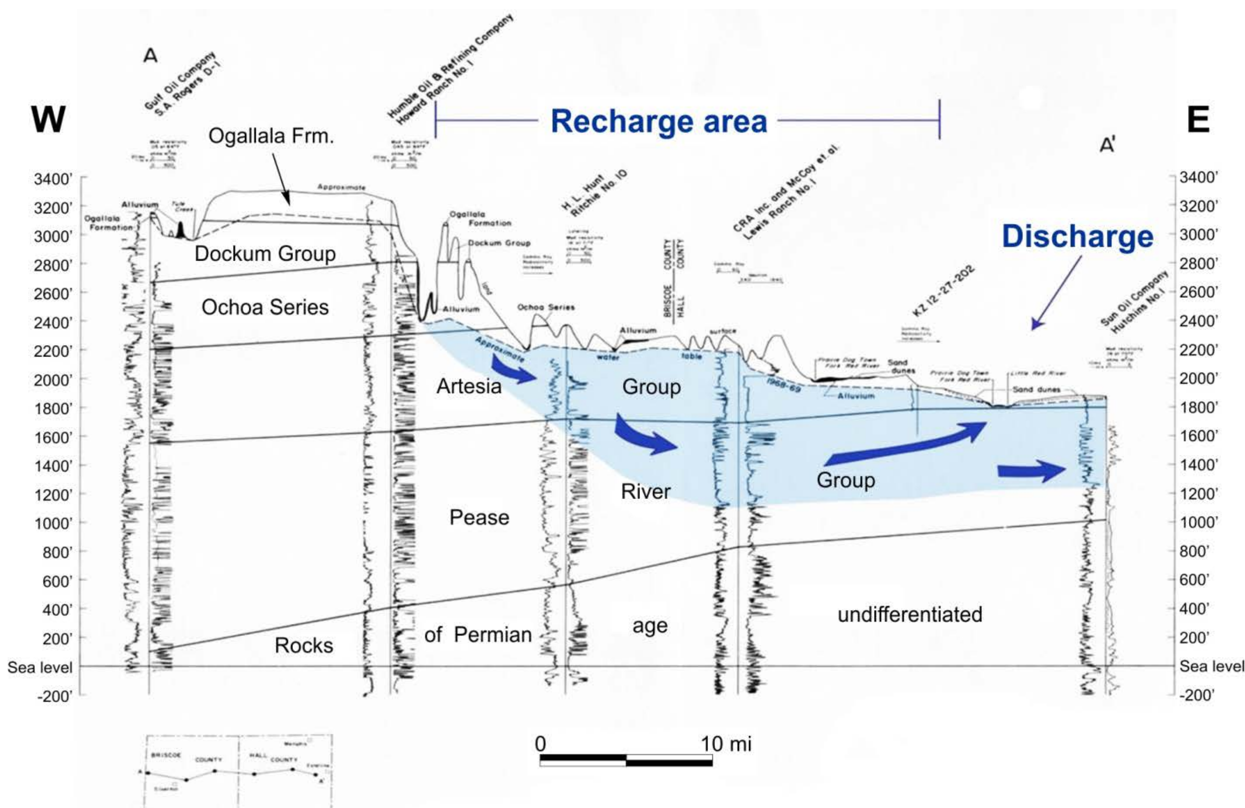

Figure 7-3. Hydrogeologic cross section through Briscoe and Hall Counties from Popkin (1973b). Features in blue were added to illustrate the conceptual model of gorundwater flow.

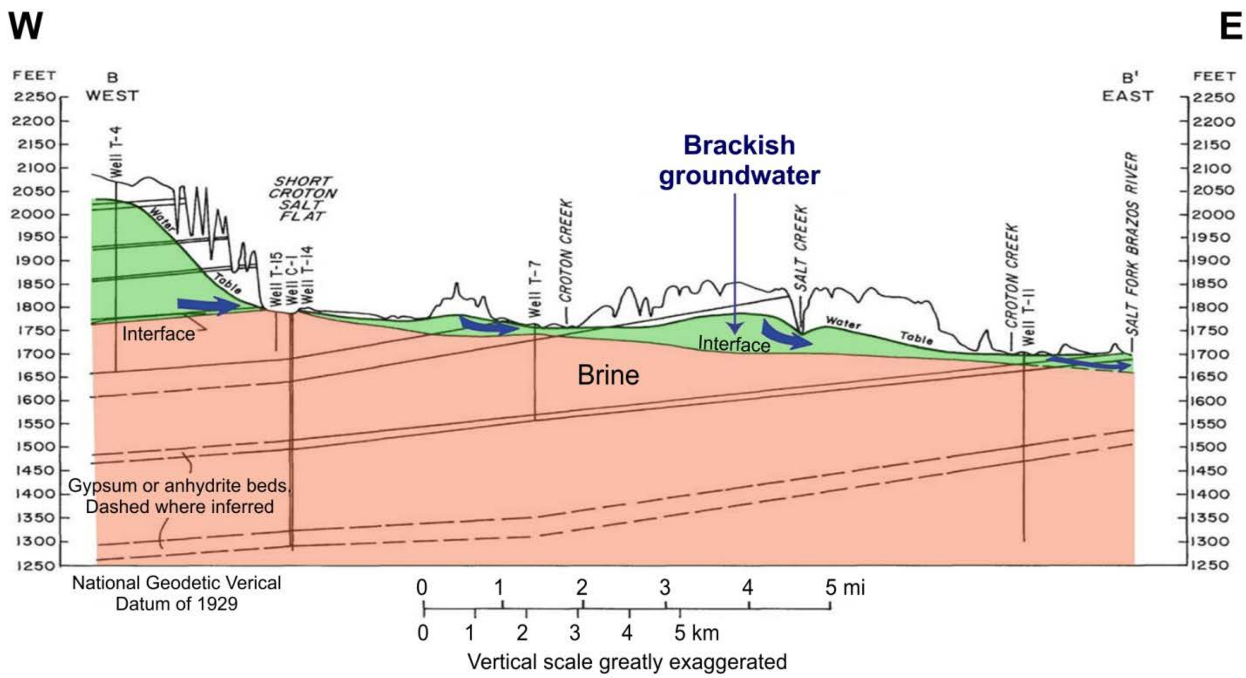

Figure 7-4. Hydrogeologic cross section through Kent and Stonewall Counties from Stevens and Hardt (1965). Features in blue were added to illustrate the conceptual model of gorundwater flow.

The northern half of the aquifer, where irrigation wells were established, has been studied from a perspective of general water resource assessment (Shafer, 1957; Smith, 1970; Cronin, 1972; Maderak, 1972, 1973; Popkin, 1973a, 1973b; Smith, 1973). These studies provide basic geologic descriptions, reported well yields, water table contour maps, and water quality data, but little to no analysis of the water quality distribution and hydraulic properties of the aquifer.

Portions of the southern part of the Blaine Aquifer system have been evaluated by the USGS (Stevens and Hardt, 1965; Zohdy and Jackson, 1973; Garza, 1982) and the Texas Water Commission (Burnitt, 1963) to identify sources of saline groundwater discharge to streams and agricultural lands. Other studies have been completed to investigate salinity control projects for the Brazos River watershed, where brine emission areas are largely responsible for contributing salinity to streams. Stevens and Hardt (1965) and Cronin (1972) described and mapped out the fresh groundwater-brine interface identified in the central portion of the Blaine Aquifer system.

The Seymour Aquifer GAM (Ewing and others, 2004) included the Permian rocks as a model layer underlying the Quaternary alluvium of the Seymour Aquifer, although little effort was devoted to defining the structure, hydraulic properties, and water quality distribution in the Permian units.

The occurrence of salt-karst in the Blaine Aquifer system has been recognized by Gustavson and others (1981) and Johnson (2013), but studies characterizing the Blaine Aquifer karst system in Texas are limited. Johnson (2013) refers to salt dissolution by groundwater as salt karst, where partial or total dissolution of the shallowest salt in some areas has resulted in subsidence and collapse of overlying strata. Areas with karst features include salt-dissolution cavities in the formation, collapse features, and sinkholes reported in overlying strata.

8. Data collection and analysis

This section provides an overview of the data collection and analysis completed for geologic, hydrologic, and water quality interpretations.

8.1. Geologic data for stratigraphic analysis

Available information from water wells and oil and gas wells was used to develop Blaine Aquifer system stratigraphy and hydraulic characteristics. Data sources include:

- The Texas Bureau of Economic Geology (BEG) Geophysical Log Facility (GLF) historical well driller's reports (cable tool) and scout tickets
- The TWDB's groundwater database, accessed in November 2015
- The Texas Department of Licensing and Regulation (TDLR) database of submitted drillers' reports, accessed in November 2015
- USGS Texas Water Science Center, visited in July 2016
- The TWDB Q-log database, accessed in July 2016
- Geophysical logs collected and considered for the evaluation of groundwater quality

Water well data obtained from the TDLR and TWDB water well databases provided shallow geology and aquifer hydraulic property data. Oil and gas well data obtained from the BEG was essential in the development of the study area stratigraphy, in particular development of the Blaine Formation top and base elevations. The USGS water well data archive at the Texas Water Science Center was reviewed for information in Motley, Cottle, and Childress Counties, but useful additional data were not found. The TWDB provided Q-logs from Motley County to supplement the project's existing geophysical log coverage. The geophysical logs evaluated to assess water quality and base of the Blaine Formation are discussed in Section 13.

There are five active GCDs within or partially within the study area (Figure 4-3). The manager of each GCD was contacted in April 2016 to provide them with a general overview and purpose of the project and ask them to provide water quality and/or water level data not reported in the TWDB database. Water level data were provided by the Panhandle, Mesquite, and Rolling Plains GCDs. None of the GCDs had additional Blaine Aquifer system water quality data.

8.1.1. Data screening criteria

Information from the data sources outlined above was screened to identify the most useful and accurate data for utilization during the project. The data screening was conducted in two phases: (1) review of well location information, well depth interval, water properties, and geologic descriptions and (2) review of data point distribution throughout the study area and removal of redundant data points. The data screening process is described below.

BEG drillers' reports and scout tickets were first reviewed to determine if the well location was in the study area and if the record contained pertinent geological information. The BEG's paper oil, gas, and water cable tool drillers' reports and scout tickets were located using The Subsurface Library (Austin location), which provided American Petroleum Institute (API) and location information for each well of interest. Location data were obtained in North American Datum (NAD) 83 geographic coordinates. The location coordinates were compared with Texas land survey data on each well record to confirm that each well location was accurate. The geologic information provided on each well record was also reviewed to identify wells suitable for this study. Drillers' reports that did not provide geologic data starting at or near land surface, or that contained ambiguous or coarse lithology interval descriptions, were not considered further. Scout ticket data were reviewed to identify records that contained formation picks pertaining to the Blaine Formation, the Flowerpot Shale, the Dog Creek Shale, the San Andres Formation (equivalent to the Blaine Formation in the west), and the Clear Fork Group or the Merkel Dolomite, which is the upper member of the Clear Fork Group. Several thousand BEG drillers' reports and scout tickets were reviewed.

The TWDB and TDLR databases provide location coordinates for each well record. It was assumed that these coordinates were accurate. If a well's latitude and longitude location were inconsistent with its listed state well grid or county, the well report was reviewed further to determine the validity of the location. If the well location could not be reasonably confirmed from the existing information it was not used. Figure 5-1 illustrates the TDLR and TWDB wells used during this study.

The TDLR drillers' reports were reviewed to identify wells with descriptive lithology logs and/or water quality information that would be of value to the study. TDLR wells less than 40 feet deep were not considered because they were unlikely to provide meaningful information and wells of this depth interval in the study area are predominantly classified as environmental wells. TWDB wells were used to evaluate assigned aquifer codes and to obtain well yield and water quality information.

Once the set of wells that had accurate locations and useful geologic information was identified, each well location was reviewed to determine its proximity to nearby wells with similar data. This process was completed to remove redundancy and unnecessary clustering of well data. When removing wells in close proximity, preference was given to TWDB well data over TDLR well data. There were many instances where multiple TDLR wells occupied the same location or were in very close proximity to one another; where this occurred, all but one of the representative wells were removed from the data set.

8.1.2. Stratigraphic analysis

Stratigraphic analysis was conducted to estimate the top and bottom of the Blaine Formation and the top of the Clear Fork Group throughout the study area. The top of Clear Fork Group surface provided a reference for deeper structural features that extend into the shallower Permian formations, which was particularly useful in developing a relationship between the Wichita

Uplift and base of the Blaine Formation. These formation surfaces were developed using BEG and TDLR drillers' reports lithologic descriptions and BEG scout tickets (Figures 8-1 and 5-4). Where the Seymour or Ogallala Formation overlies the Blaine Formation or the Whitehorse Group, the top of the Blaine Formation was taken from raster files obtained from the Seymour and Ogallala GAMs.

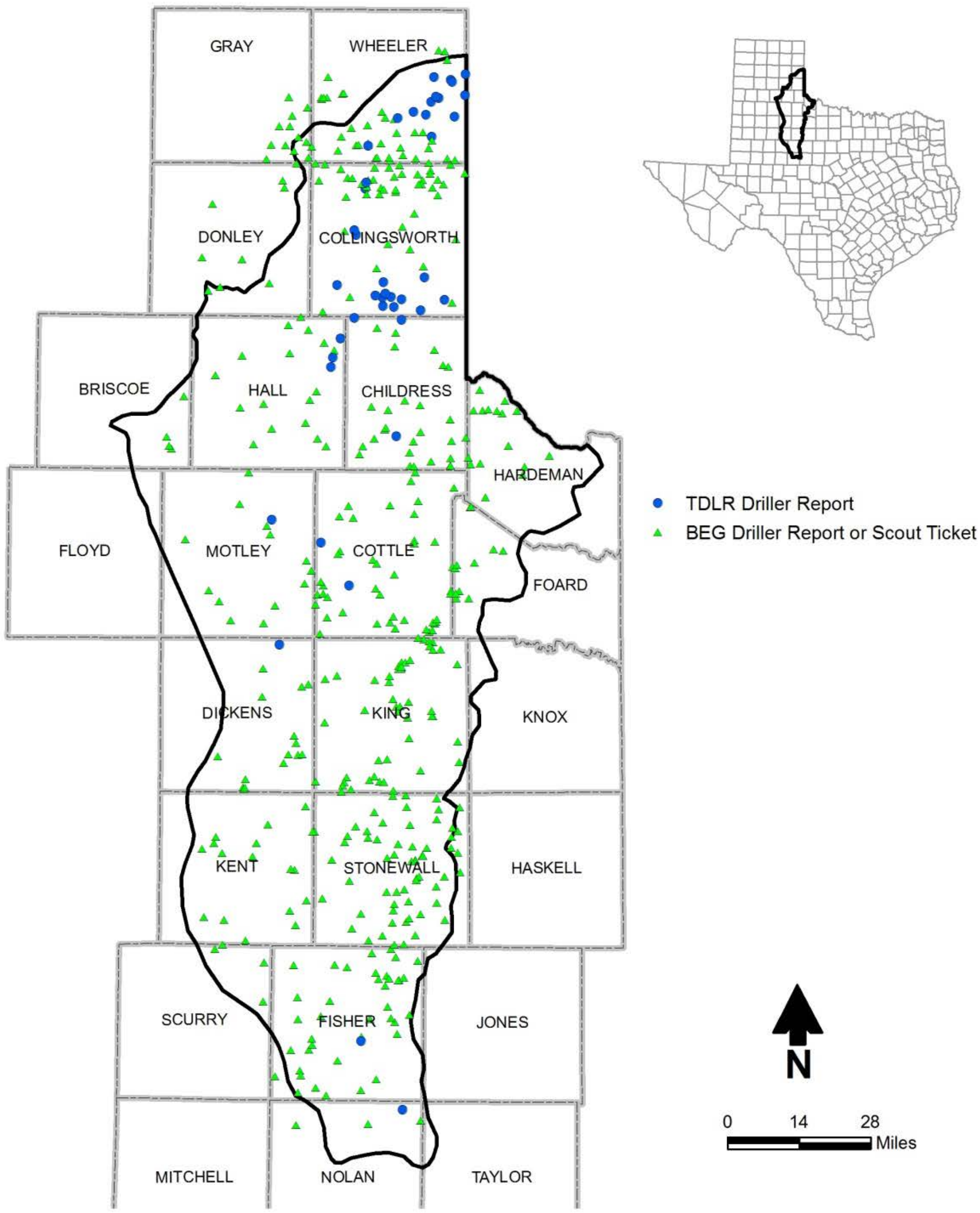

Figure 8-1. BEG and TDLR wells used for stratigraphic analysis.

The top of the Blaine Formation (base of the Whitehorse Group) was identified west of its outcrop area by the presence of more than 10 feet of gypsum or anhydrite, followed by additional gypsum or anhydrite layers. In some cases the gypsum was interbedded with layers of shale, sandstone, or limestone. The gypsum or anhydrite at the top of the Blaine Formation could usually be distinguished from gypsum and anhydrite within the Whitehorse Group, which is typically only a couple feet thick and occurs at shallow depths. In the western portion of the study area (west of the Blaine Formation outcrop), many TDLR wells are completed only in the Whitehorse Group. Where gypsum was not present on a driller's report or where Blaine Formation gypsum could not be discerned from gypsum in the overlying Whitehorse Group, a Blaine Formation pick was not made. Scout ticket references to the San Andres Formation, a lateral equivalent to the Blaine Formation that occurs in the western portion of the study area (Figure 5-3), were also used to construct the top of Blaine Formation surface. Because the Dog Creek Shale was not mapable in the study area, the top of Blaine Formation surface may include portions of the Dog Creek Shale.

BEG and TDLR drillers' reports and BEG scout tickets were also used to identify the base of the Blaine Formation, although very few TDLR wells were drilled deep enough to provide this information. The base of the Blaine Formation was identified by a facies change to the Flowerpot Shale, a predominantly blue to varicolored shale. Within the study area, the Flowerpot Shale was primarily blue with thin gypsum layers interbedded in the upper section at some locations. Along the western margin of the study area, identification of the Flowerpot Shale was less obvious. Scout tickets that identified the base of the Blaine Formation and the top of Flowerpot Shale were also used to define this surface.

The primary information source used to construct the top of the Clear Fork Group was the BEG scout tickets. In several instances the upper member of the Clear Fork Group, the Merkel Dolomite, was used as a top of Clear Fork Group pick. Formation picks on the scout tickets were not used if they were inconsistent with adjacent formation data or regional geologic structure interpretations.

Once the initial surfaces were constructed, a surface anomaly analysis was conducted using the Kriging and Topo to Raster tools in GIS. These tools generated formation surfaces that were used to identify high/low and low/high data points, regional trends, and structural features. Where a well location had a formation elevation significantly above or below that of surrounding wells, the well location and formation picks were reviewed and data entry was confirmed for accuracy. If the apparently anomalous value appeared to be correct but no other wells or structural features in the vicinity supported the observed anomaly, the well was considered to be an outlier and was deleted from the study dataset. If other wells or structural features in the vicinity provided some corroboration, such as similar or trending values, then the well was maintained as a data point.

In addition to the above analysis, the formation surfaces (e.g., Figures 7-2 through 7-4) were also compared to cross sections in published reports, including Smith (1970), Cronin (1972), Maderak (1972, 1973), and Popkin (1973a, 1973b). In general, the generated geologic surfaces compared very favorably with published cross sections. A discrepancy was observed in a limited segment of a cross section in northwestern Wheeler County, along the study area boundary, from Maderak (1973). Based on the well control obtained for this study and the structural features in the area, the formation elevations presented herein are believed to be accurate.

8.1.3. *Confidence rankings*

Each well used for stratigraphic analysis was assigned a location and formation pick confidence value to assist with the reliability of interpretations. A confidence ranking of 1 (highest confidence) or 2 (less confidence) was assigned to well locations. TDLR and TWDB wells were assigned a location confidence value of 1, while BEG drillers' reports and scout tickets were assigned a confidence value of 2 due to the age of some of the reports. Stratigraphic picks were assigned a confidence value of 1 to 4 as described below. The interpretation reliability attribute for a well location should be considered when reviewing or using the data.

- Confidence Level 1: Excellent description, easy stratigraphic picks. Good local well control that confirmed observations. These wells normally have highly detailed lithology descriptions. Marker beds are easily identifiable.
- Confidence Level 2: Good descriptions, relatively easy stratigraphic picks. Additional wells in proximity that correlate well. Wells in this category normally have highly detailed lithologic descriptions. Marker beds may not be easily identifiable, and/or formation contacts may not be obvious.
- Confidence Level 3: Generally acceptable descriptions, but stratigraphic picks are less apparent. Few nearby wells to confirm observations. Lithologic descriptions for wells in this category normally have less detail and/or may lump multiple lithologies. Marker beds are not easily identifiable. All scout ticket data points were assigned a confidence rating of 3 since they provide only formation picks, not lithology.
- Confidence Level 4: Generally acceptable descriptions, but stratigraphic picks were challenging with few nearby wells to confirm observations. Wells in this category usually have lithology descriptions that lump multiple lithologies or do not adequately describe marker beds. Wells in this category were only considered because they occur in areas with limited data.

8.2. Groundwater levels

A groundwater level elevation surface was required to define the top of the Blaine Aquifer system. Construction of this surface was completed in three steps:

1. Published water level elevation contour maps were compiled and georeferenced from Stevens and Hardt (1965), Garza (1982), Smith (1970), Cronin (1972), Maderak (1972, 1973), and Popkin (1973, 1973a).
2. Water level data from the TWDB Groundwater Database were obtained on October 18, 2015. Water level data and corresponding information for wells with a "313" aquifer code (Blaine Formation, Whitehorse Group, Artesia Group) were culled. The available time-series water level data were reviewed for trends, and it was determined that there were no significant long-term water level declines or recovery evident in the dataset (Figure 8-2). Because long-term water level trends are not evident for the Blaine Aquifer system, it is reasonable to use water level elevations for all locations where they are available, regardless of the date of measurement. Water levels from TDLR wells were not used to map the Blaine Aquifer system potentiometric surface because the other sources of water level data provided adequate data coverage for the regional-scale map.

3. The water level data and the published water level elevation contours were plotted on a topographic base (ESRI - National Geographic TOPO!) scaled to 1:24,000. For wells with multiple measurements the most recently measured water level was used. Water level elevation contours were constructed and digitized using a 50-foot contour interval. Contours were adjusted to best match available water level data, known perennial streams, springs, and other water bodies. Water level elevation contours were checked against the land surface elevation contours to correct for values above land surface outside of groundwater discharge zones.

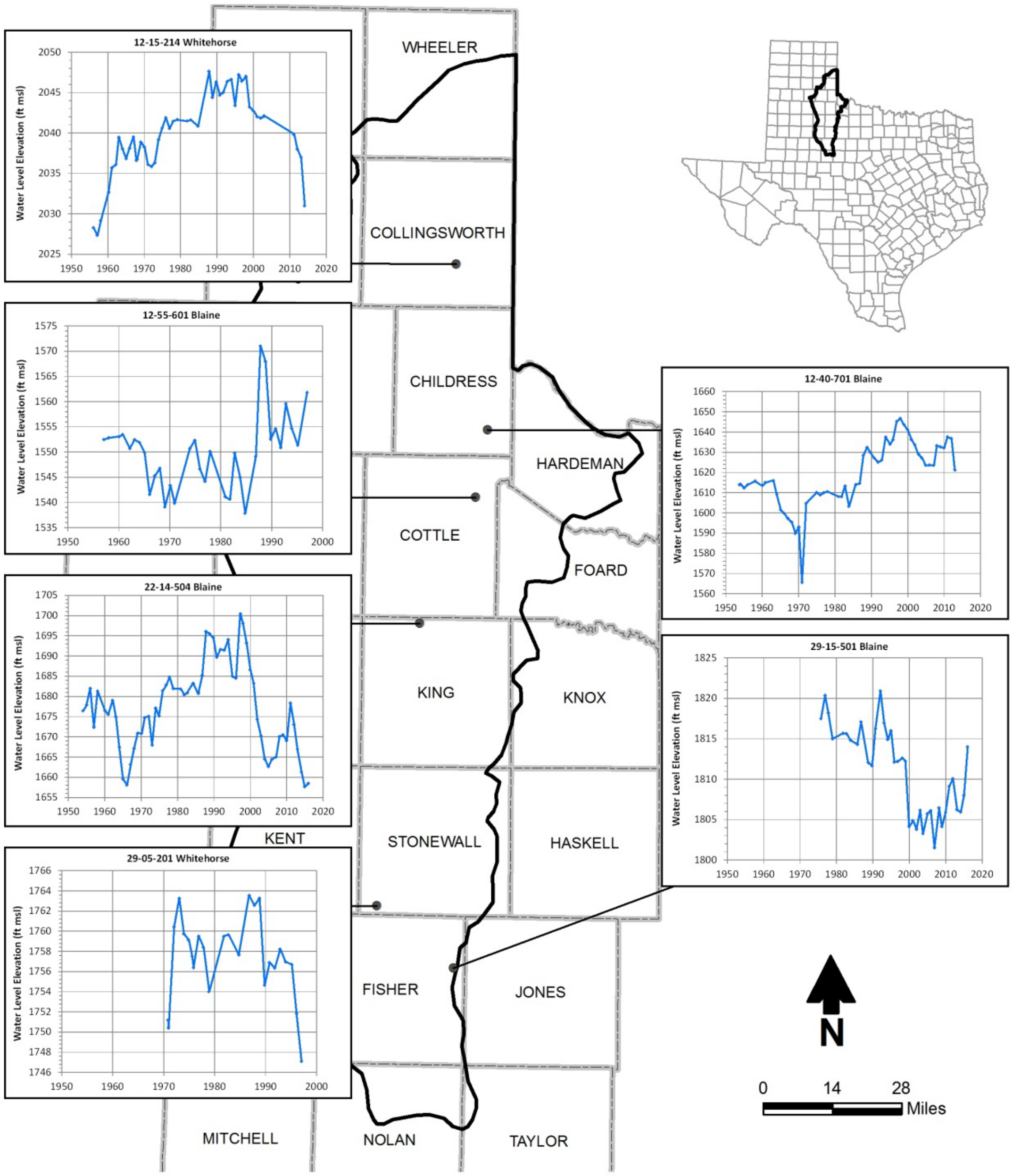

Figure 8-2. Example Blaine Aquifer system hydrographs.

The compiled Blaine Aquifer system water level elevations are presented in Figure 8-3. Figure 8-4 presents the depth to water from land surface.

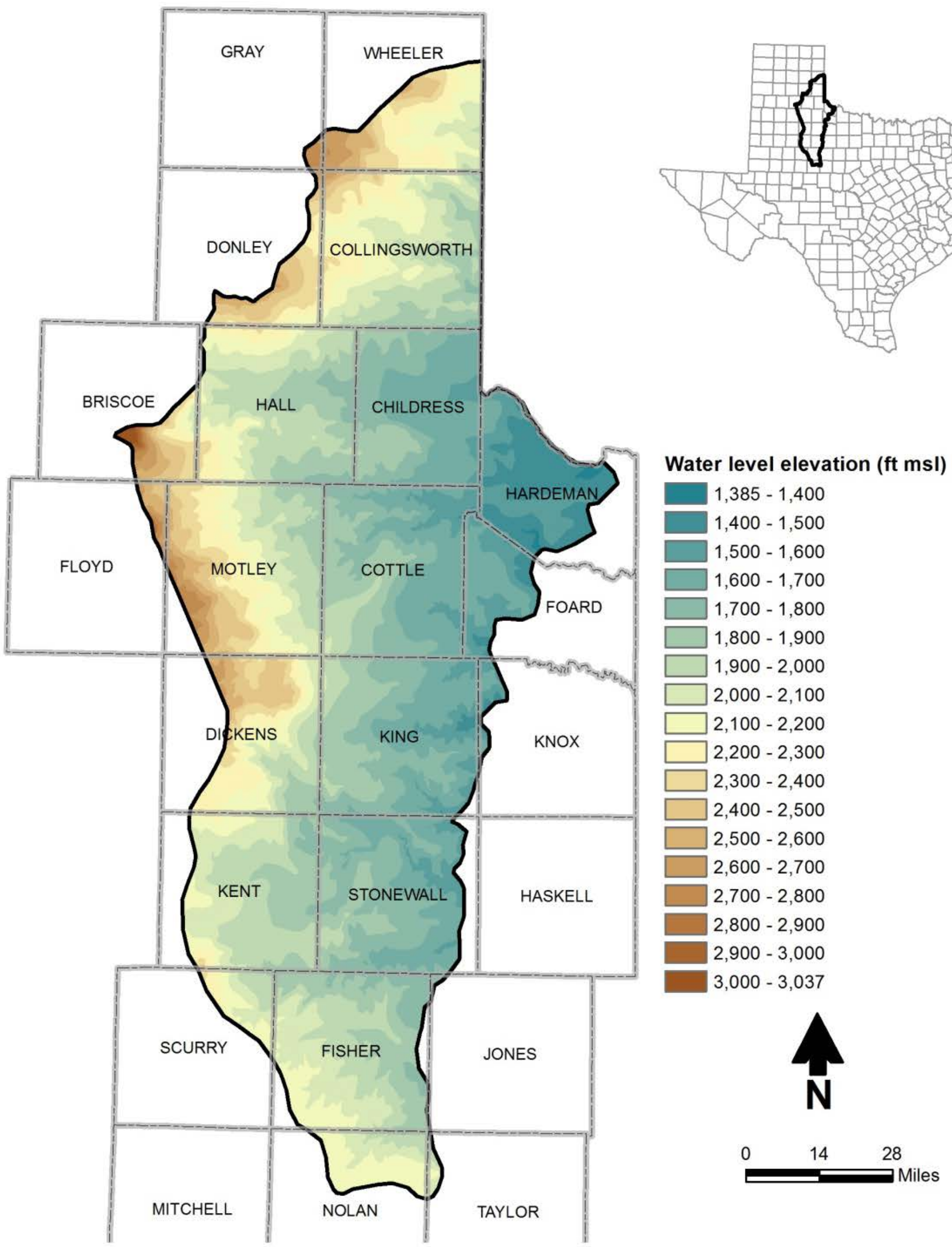

Figure 8-3. Blaine Aquifer system potentiometric surface based on static water level elevations, spring elevations, and published potentiometric surface maps from multiple time periods.

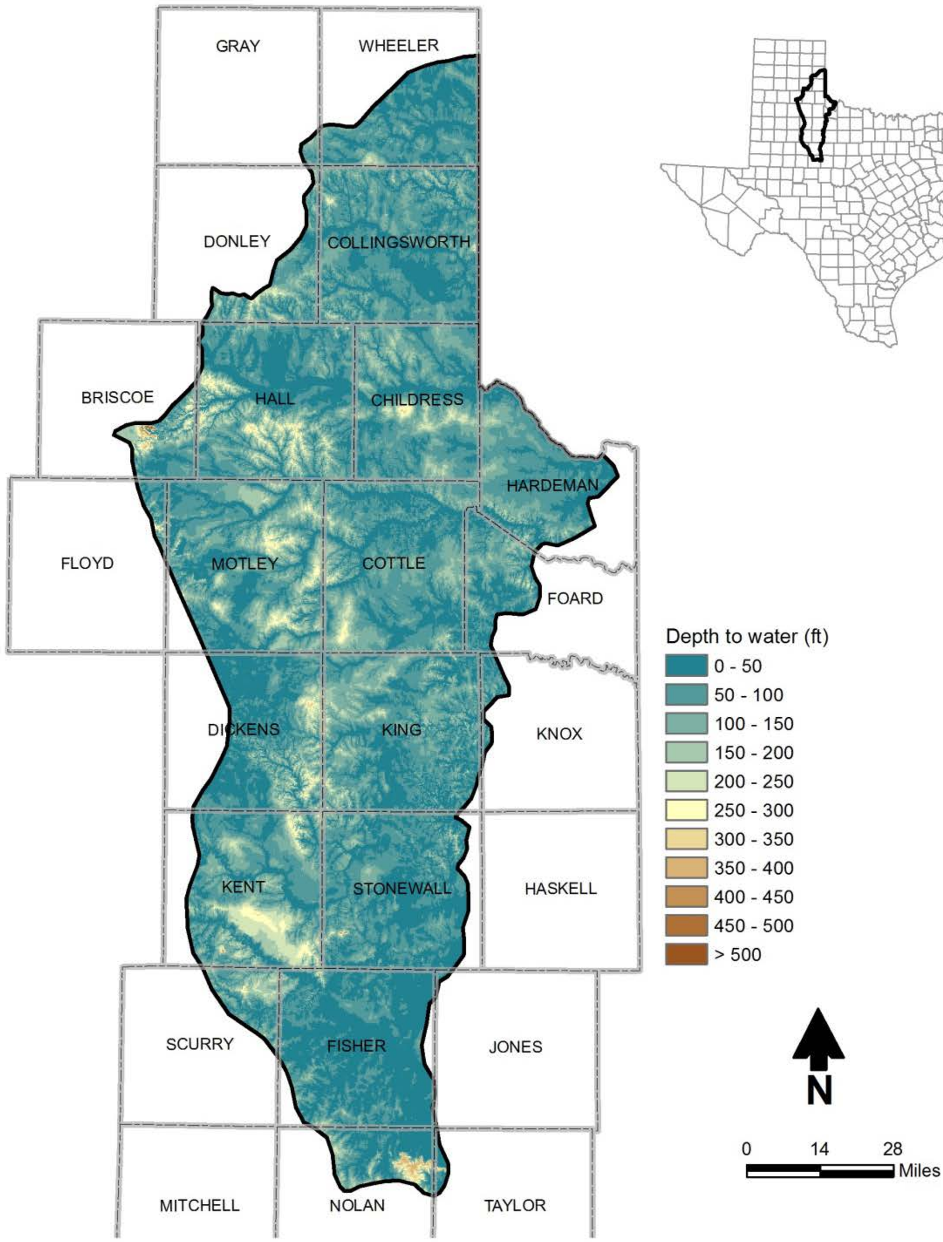

Figure 8-4. Blaine Aquifer system depth to water from land surface.

8.3. Springs and streams

Data regarding springs was obtained from Texas Parks and Wildlife GIS laboratory (tpwd.texas.gov/gis/data) and the TWDB Groundwater Database. Duplicate data points were identified and removed from the data set. The streams coverage was obtained from the Center for Geospatial Technology, Texas Tech University, USGS National Hydrography Dataset (http://www.gis.ttu.edu/center/TexasGISData.html, file name: Rivers-high resolution). The springs and perennial reaches are discussed further in Section 10.

8.4. Geophysical logs for water quality analysis

Geophysical logs were used to evaluate the stratigraphic character of the Blaine Aquifer system and to evaluate water quality characteristics where water quality data from water wells were limited or absent. An initial listing of all geophysical logs in the study area from the TWDB BRACS Database was obtained in Excel database format; this list included 1,634 logs. An additional 24 geophysical logs were obtained from the Railroad Commission of Texas (RRC) online database (www.rrc.state.tx.us) using the public GIS viewer. The distribution of available geophysical logs in the study area was plotted to determine if significant data gaps existed in the study area (Figure 8-5).

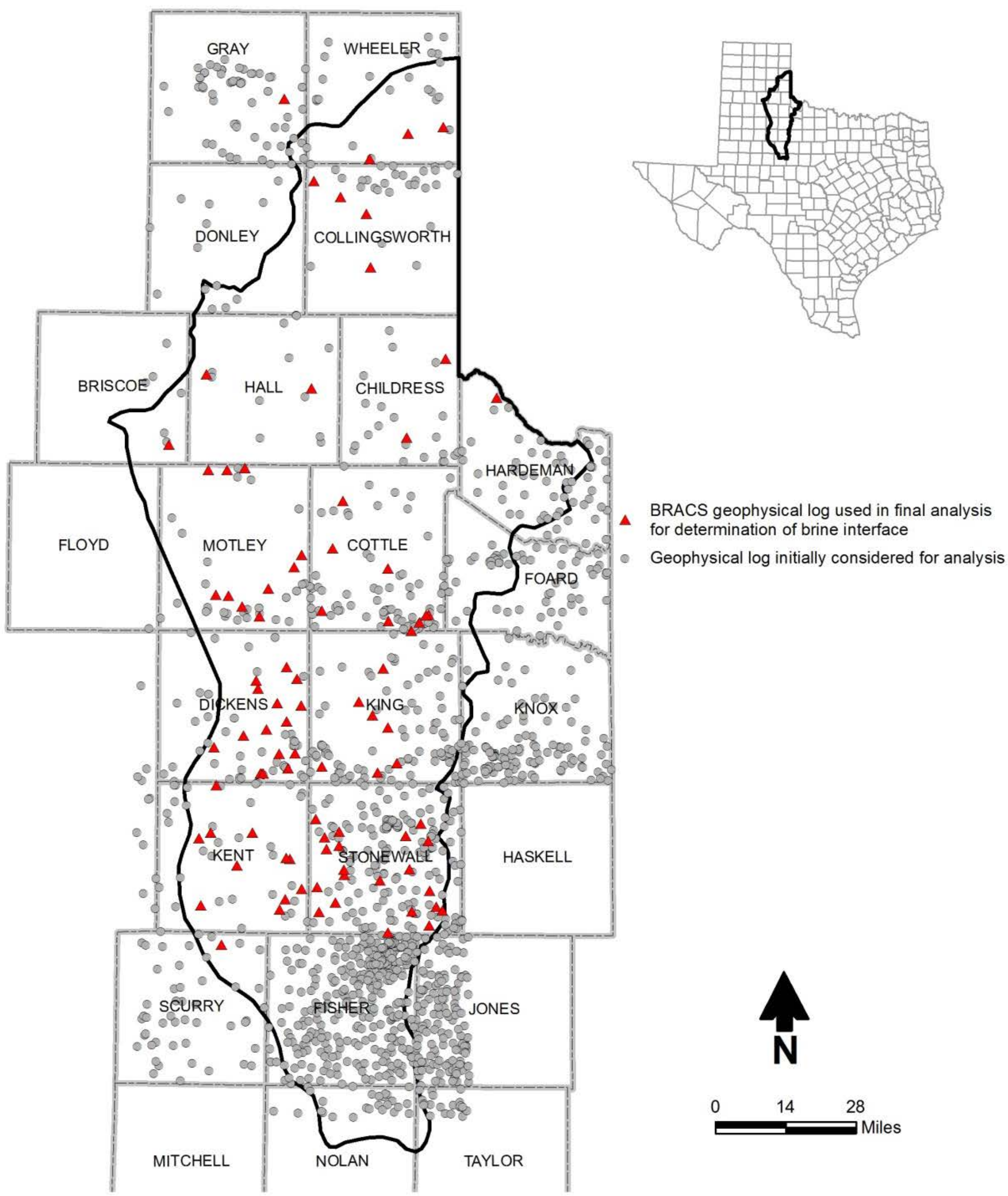

Figure 8-5. Distribution of geophysical logs initially considered for data analysis.

Geophysical log image data files (*.tif) were organized by county and by BRACS ID. Additional Headers (fields) were added to the database for logs evaluated in detail, which included inputs for the following:

- Log type (e.g., electric, gamma-neutron, dual induction)
- Mud type (e.g., fresh gel, salt gel, natural formation fluids, diesel, air)
- Top log interval (depth to top of geophysical logging survey)
- Depth of surface casing reported by logger (feet)
- Top of electric log (spontaneous potential [SP], resistivity) reported by logger (feet)
- Suitable for determining water quality? (yes or no)
- Suitable for determining brine interface? (yes or no)
- Brine interface reason (log used for interpretation)
- Top of Flowerpot Shale (depth, in feet, interpreted from log)
- Ground level elevation (from log header)
- Depth to brine interface (feet)
- Elevation of brine interface (feet above mean sea level)
- Additional notes

Individual geophysical log image files were viewed and analyzed using Haliburton LogView Pro version 9.7.5. Geophysical logs were omitted from detailed analysis for any combination of the following conditions:

- Header information was incomplete.
- Log interval did not include the Blaine Aquifer system.
- Quality of the log was poor.
- Log type was not applicable to analysis (e.g., cement bond log).

After the initial geophysical log screening process, over 300 of the 1,634 geophysical logs remained for more detailed review and analysis. The methods used to analyze these geophysical logs are described in Section 13.

9. Aquifer hydraulic properties

The yields of the wells completed in karst formations, such as the Blaine Aquifer system, may vary widely because they are dependent upon the size, number, and interconnectedness of solution openings and fractures encountered by the well. Hydraulic properties of the Blaine Aquifer system are largely absent from published reports. Existing data and estimates for aquifer permeability and storage coefficient are summarized in Sections 9.1 and 9.2.

9.1. Aquifer permeability and well yield

In his study of groundwater resources of Wheeler and eastern Gray Counties in Texas, Maderak (1973) reported an average specific capacity of 8 wells in the Blaine to be 15.7 gallons per minute per foot of drawdown (gpm/ft). Assuming semiconfined conditions, this corresponds to an average aquifer transmissivity of 3,675 square feet per day (ft^2/d).

Shafer (1957) states that the dolomite and gypsum beds of the Blaine Aquifer had proven to be the most prolific aquifers in Childress County and that probably all the water used for irrigation in the county was obtained from the Blaine Aquifer. He reported well yields ranging from 178 up to 1,500 gallons per minute (gpm), although most well yields were between 600 and 900 gpm.

In Hardeman County, Maderak (1972) reported that the highest well yield was 1,000 gpm, but that the average yield of 108 wells completed in the Blaine Aquifer was 275 gpm. Maderak (1972) also reported the average specific capacity of 29 wells in Blaine Aquifer to be 4.6 gpm/ft.

Steele and Barclay (1965) studied the Dog Creek Shale and the Blaine Formation in Harmon and parts of Greer and Jackson Counties in Oklahoma; their study area borders Collingsworth, Childress, and Hardeman Counties. Steele and Barclay reported that some well yields exceed 1,000 gpm, but many well yields were between 500 and 1,000 gpm and many others yielded less than 10 gpm. They estimated an average transmissivity of the aquifer in an area where solution channels are best developed to be 34,750 ft^2/d, and an average aquifer thickness of 80 feet. This transmissivity and aquifer thickness is equivalent to a hydraulic conductivity greater than 400 feet per day (ft/d). Steele and Barclay (1965) caution that this permeability would be much higher than that expected to apply to the aquifer as a whole. Similarly, the transmissivity of the Blaine Aquifer in southwestern Oklahoma is reported by Johnson (1990) to range from 5,450 to 43,353 ft^2/d based on pumping test data. The corresponding hydraulic conductivity would be about 368 ft/d.

Popkin (1973b) provides specific capacity information for 8 wells in the Artesia Group (Whitehorse Group equivalent, Figure 5-2) in Hall and eastern Briscoe Counties. The estimated aquifer hydraulic conductivity based on these tests is approximately 35 to 45 ft/d. Popkin (1973a) studied the groundwater resources in Donley County and reported that the Blaine Aquifer was not used within the county. Smith (1973) reported small to moderate quantities of water, usually less than 100 gpm, obtained from wells tapping the Artesia Group in Motley and northeastern Floyd Counties. Cronin (1972) acknowledged that very little information is available concerning the hydrologic properties of the Permian rocks in Dickens and Kent Counties, but noted that the known yields from these units are usually small, suggesting low hydraulic conductivity.

For the southern portion of the study area, Garza (1982) reported that the Whitehorse Group has an average hydraulic conductivity of 0.5 ft/d, the shale beds in the Blaine Formation have a hydraulic conductivity less than 0.000001 ft/d, and other parts of the Blaine Formation have a hydraulic conductivity averaging 1 to 2 ft/d. Garza (1982) did not provide hydraulic properties for the portions of the aquifer with karst features.

9.2. Estimation of aquifer transmissivity from specific capacity

In the absence of pumping test data, transmissivity can be estimated from specific capacity data using a rewritten form of the Cooper-Jacob solution for drawdown in a pumping well (Walton, 1970; Mace, 2001). The Cooper-Jacob solution for drawdown in a pumping well (Cooper and Jacob, 1946) can be written assuming any consistent set of units as follows:

$$s = (Q/(4\pi T)) * \ln(2.25Tt/r2S) \qquad \text{Eq. 9-1}$$

where
- s = drawdown in the well
- Q = pumping rate of the well
- T = aquifer transmissivity
- t = time since pumping began
- r = radius of the well
- S = aquifer storage coefficient

Equation 9-1 can be rearranged to solve for theoretical specific capacity as follows:

$$Q/s = 4\pi T/(\ln((2.25Tt/r2S)) \qquad \text{Eq. 9-2}$$

For a given specific capacity, transmissivity can be solved for iteratively. Hydraulic conductivity can then be calculated by dividing the estimated transmissivity by the aquifer thickness tapped by the well (i.e., the total well depth less the non-pumping water level). The non-pumping water level was estimated from nearby wells if it was missing from TWDB database.

Specific capacity data from wells completed in the Blaine Aquifer system were compiled and used to estimate aquifer transmissivity and corresponding average hydraulic conductivity values. Approximately 60 specific capacity values for wells completed in the Blaine Formation, the Whitehorse Group, or equivalent strata were obtained from the TWDB database (Appendix A).

The following assumptions were made to calculate aquifer transmissivity from specific capacity data using the Cooper-Jacob solution:

- The storage coefficient was assumed to equal 0.05.
- The well efficiency was assumed to be 80 percent.
- Pumping duration from the TWDB database was used; if pumping duration was not recorded a value of 60 minutes was assumed.

The well casing diameter was obtained from TWDB database. An example calculation where aquifer transmissivity has already been solved for iteratively is illustrated below.

Specific capacity and transmissivity slide rule

T, gpd/ft	6,600	TWDB Well ID:	562419
S, fraction	0.05	well diameter:	16 inches
rw, ft	0.67	aquifer thickness:	50 ft
t, minutes	240	pumping duration:	60 min
		Q/s obs =	4.80 gpm/ft
Q/s, gpm/ft =	6.0	Q/s obs corrected =	6.0 gpm/ft
		(corrected for assumed 80 percent efficiency)	

formula:

Q/s=+(C3)/((264*LOG(((C3)*(C6))/(2693*(C5^2)*C4))-65.5))

Results:

Transmissivity =	882 ft2/day
thickness of aquifer tapped by well =	50.0 ft
average horizontal hydraulic conductivity =	17.6 ft/day

The estimated hydraulic conductivity obtained using this approach ranges from 0.02 ft/d to more than 1,000 ft/d. A histogram showing distribution of estimated hydraulic conductivity values is presented as Figure 9-1. The calculated distribution is skewed to the right (higher values), as would be expected for a karst aquifer system due to the very large local aquifer permeabilities that may occur. The mean hydraulic conductivity of the dataset is 101 ft/d, and the median of the dataset is 14 ft/d. Estimated hydraulic conductivity values for wells completed in the Whitehorse Group range from 0.02 to 32.4 ft/d, and estimated hydraulic conductivity values for wells completed in the Blaine Formation range from 0.03 to 1,290 ft/d. The higher hydraulic conductivity values (those greater than about 10 ft/d) are likely representative of portions of the aquifer with karst features. Hydraulic conductivity values less than about 1 ft/d are likely representative of areas with little to no karst development or secondary permeability.

9.3. Aquifer storage coefficient

Specific yield values for the Blaine Aquifer system are reported by Garza (1982) to range from 0.15 to 0.20 (unconfined aquifer conditions). Johnson (1990) estimated that storage coefficients for the Blaine Aquifer range from about 0.0004 to 0.03 and averaged about 0.016. Steele and Barclay (1965) estimated a storage coefficient of 0.01. The shallow Blaine Aquifer system is likely unconfined where no clay or shale layers are present at the water table surface and confined where clay or shale layers exist at the water table surface.

10. Water quality data

A total of 563 TWDB groundwater database water wells with a Permian aquifer code (310QRMW – 318PRVR) had TDS and the associated cation (silicon, calcium, magnesium, sodium, potassium) and anion (chloride, bicarbonate, sulfate, and nitrate) chemical analyses. Wells completed in the overlying Ogallala or Seymour Formations were removed from the working data set based on driller's report geologic descriptions, the base of the Ogallala or Seymour Formations obtained from the GAMs, or the mapped geologic outcrop. For wells with multiple sample results the most recent water quality sample was used.

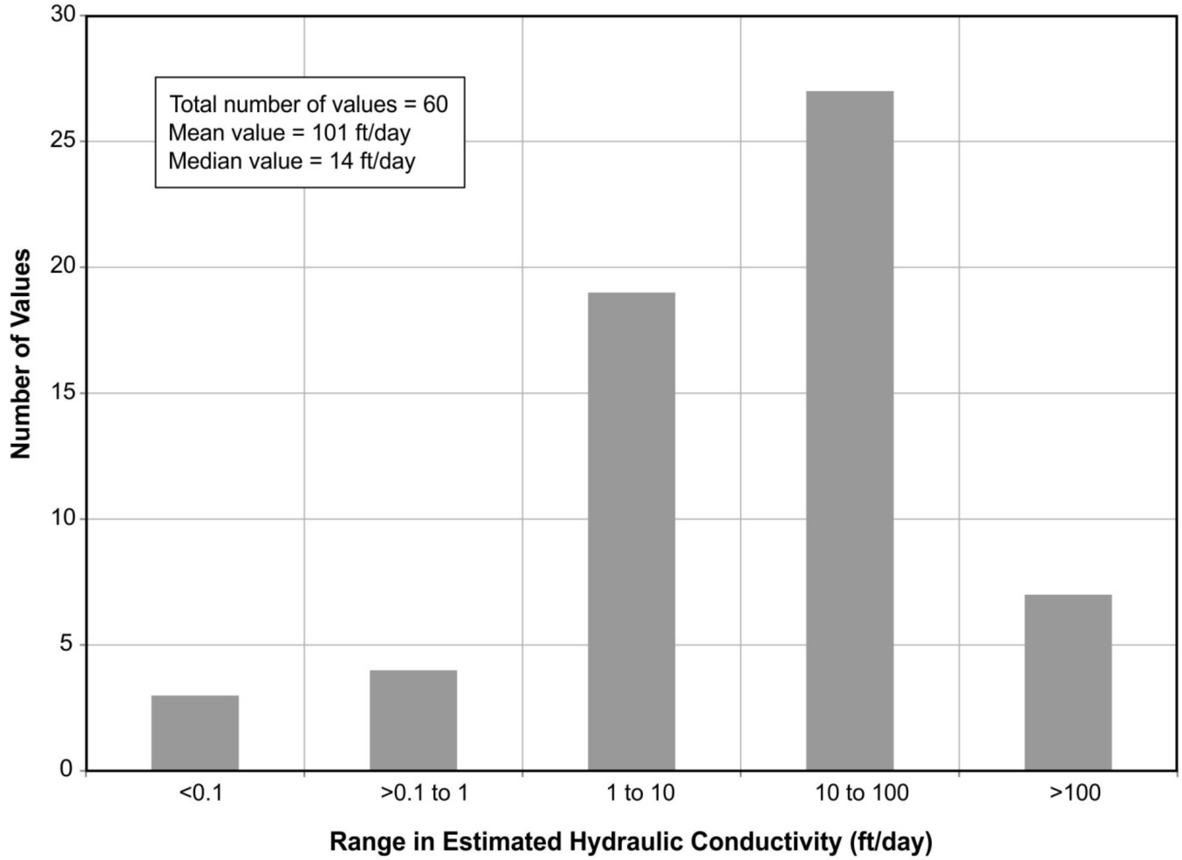

Figure 9-1. Histogram of Blaine Aquifer system hydraulic conductivity determined from specific capacity data.

Of the 563 TWDB water wells, 82 had a driller's report with identified screen intervals that could be used to determine the specific water quality sampling interval. It was assumed that the remaining 461 TWDB wells with water quality analyses were completed to depths near the well's total depth. The TDS in these wells ranged from 239 to 33,969 mg/L, chloride ranged from 5 to 17,000 mg/L, and sulfate ranged from 12 to 4,330 mg/L.

The TWDB data were plotted to identify data gap areas. Initial data gap areas included parts of Cottle, King, Stonewall, and Fisher Counties. Water quality data from USGS studies (Stevens and Hardt, 1965; Garza, 1982) were added to the project database to fill in data gaps for King and Stonewall Counties, and water quality data from Burnitt (1963) were used to fill in data gaps for Fisher County.

10.1. Dissolved minerals

The correlation between specific conductance and TDS is established graphically in Figure 10-1 and is affected by the composition of dissolved minerals. Two trends are apparent in the figure. One trend relates to specific conductance values derived from laboratory analysis (diluted electrical conductivities), and the other trend is derived from temperature-corrected field measurements. The correlation between field-measured specific conductance and TDS should be used for calculating TDS from specific conductance values.

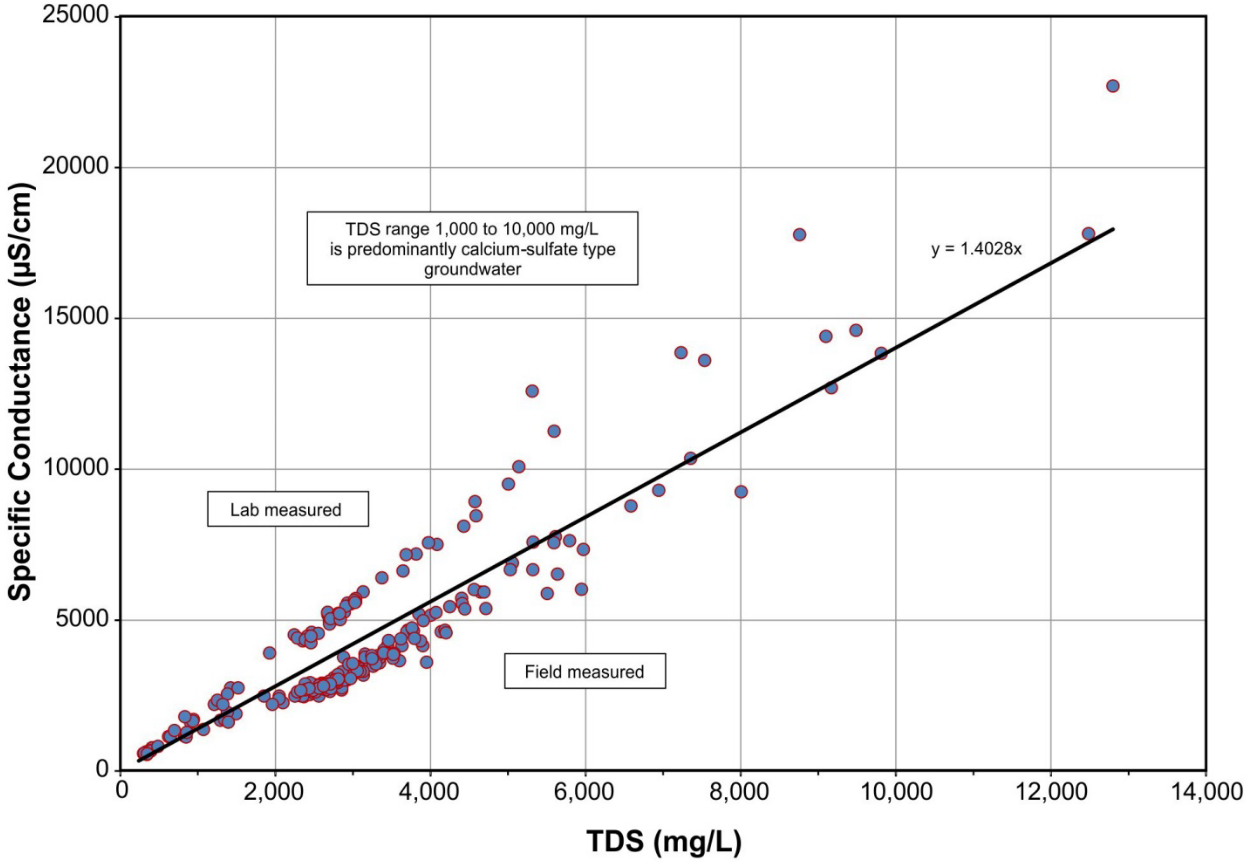

Figure 10-1. Graph of specific conductance versus TDS for wells completed in the Blaine Aquifer system.

Most of the fresh to moderately saline groundwater in the Blaine Aquifer system is a calcium-sulfate water, and the brine groundwater samples in the study area are predominantly sodium chloride. However, groundwater with TDS values less than 4,000 mg/L is predominantly calcium-sulfate type water (Figure 10-2), and groundwater with TDS values greater than 4,000 mg/L TDS contains calcium-sulfate with an increasing sodium chloride component with increasing TDS (Figure 10-3). This change in type of dissolved minerals with respect to salinity is controlled by the presence and solubility of halite and gypsum salts.

Local variations in the TDS of fresh to moderately saline groundwater likely reflect local or sub-regional groundwater flow paths. Fresh to slightly saline groundwater represents areas of groundwater recharge and parts of the aquifer with a high degree of karst permeability. Moderately saline groundwater and brine are more commonly found in areas of groundwater discharge, which occur at or near the terminus of local groundwater flow paths. The concept of the local flow paths is evident in the configuration of the water level elevation contours, which mimic the land surface and illustrates that groundwater recharge occurs on the ridges and regions of higher elevation, and groundwater discharge occurs in the valleys at springs and streams.

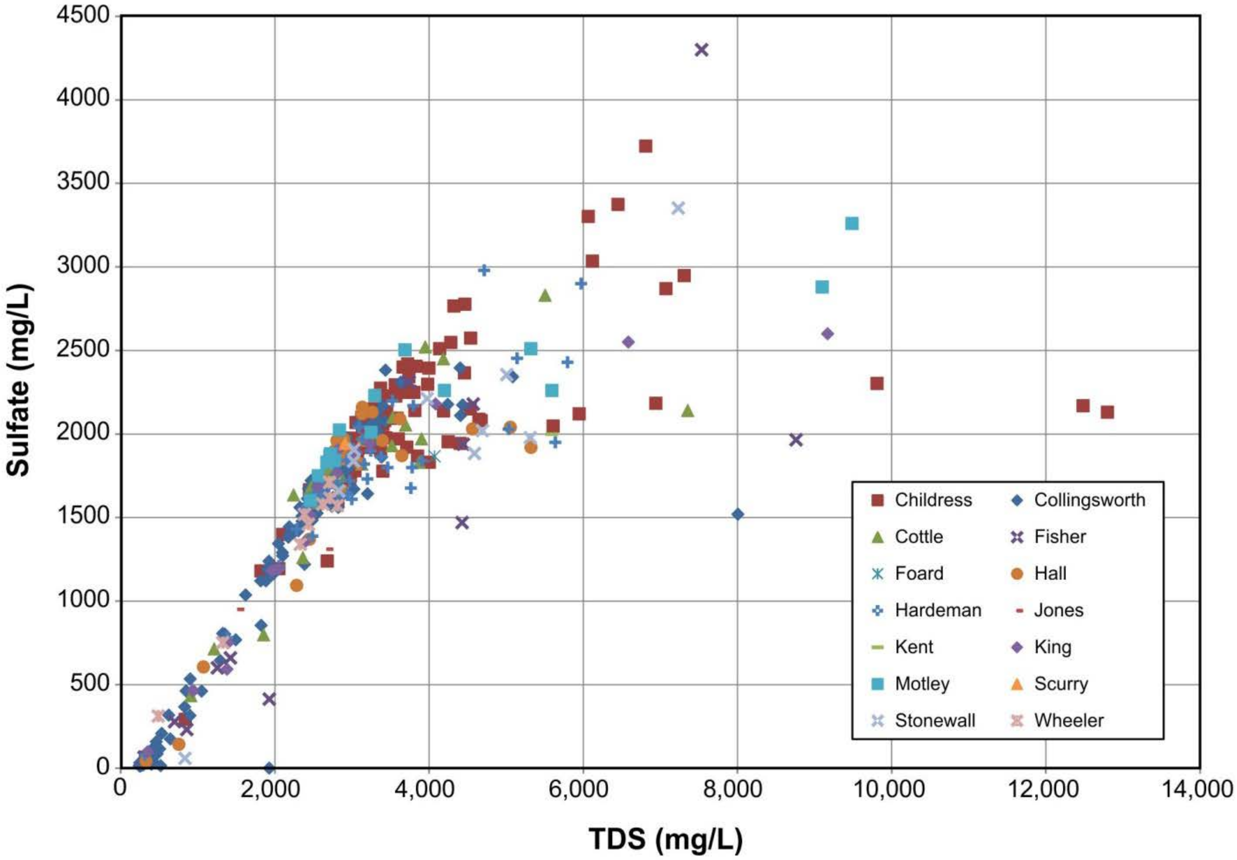

Figure 10-2. Graph of sulfate versus TDS for water wells completed in the Blaine Aquifer system.

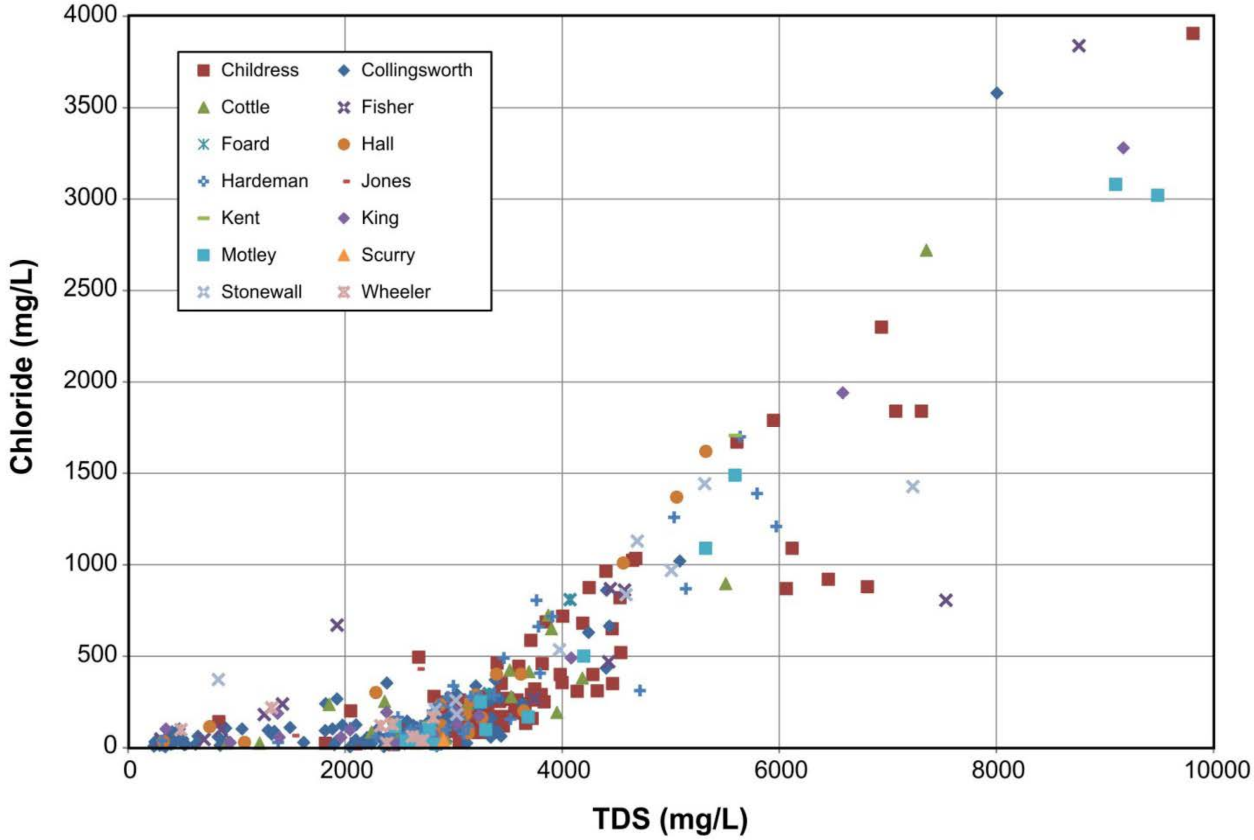

Figure 10-3. Graph of chloride versus TDS for wells completed in the Blaine Aquifer system.

10.2. Radionuclides

Results for radionuclide analyses were available for 14 wells in the study area. In all but one well, state well number 12-51-202, results were below the Texas Commission on Environmental Quality (TCEQ) drinking water maximum concentration level (MCL) of 15 picocuries for alpha and 5 picocuries for radium 226 and 228 (Ra-226 and Ra-228). The groundwater from well 1251202 in Motley County is used for stock watering and had a chemical analysis dated April 20, 1991 with an alpha particle analysis of 27 picocuries; this well had no analyses results for Ra-226 and Ra-228.

10.3. Spring water quality

Spring locations and observed water quality are summarized in Figure 10-4. A number of brine emission springs are evident from their very high TDS values, such as those on the Stonewall-King County line. Most other springs have water quality in the slightly to moderately saline range, and some fresh water springs do exist.

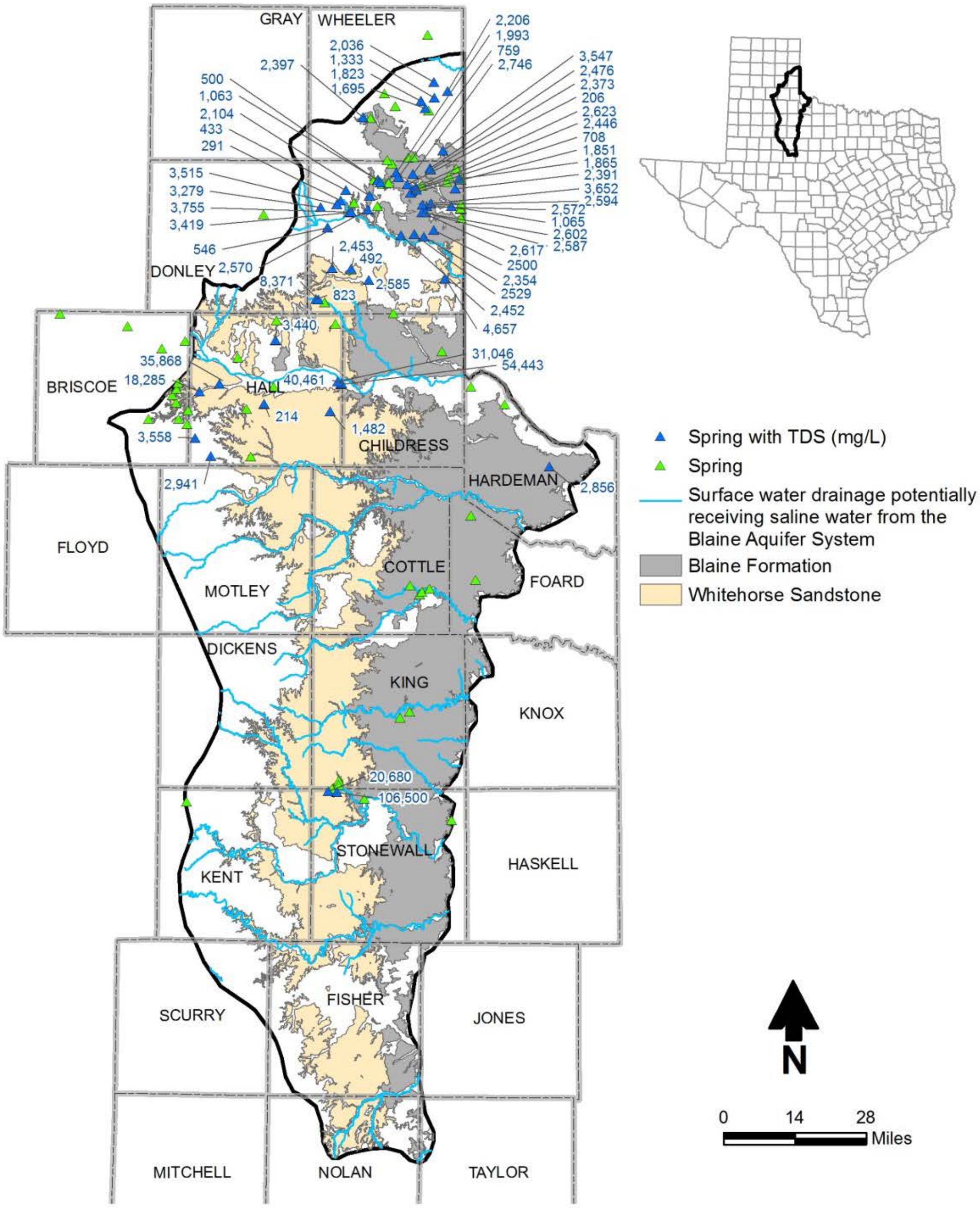

Figure 10-4. Spring water quality and streams potentially receiving saline water from the Blaine Aquifer system.

11. Production interval analysis

Known production intervals and regions of karst development that may be indicative of regions of favorable groundwater production were identified as described in Sections 11.1 and 11.2.

11.1. Cavity analysis

A total of 2,402 TDLR lithologic descriptions were reviewed for indications of subsurface cavities or karst development. Descriptions assumed to indicate the occurrence of a cavity or karst feature included cavity or cavedy, lost circulation or drilling blind zone, drilling break, cavity stream, broken rock or gypsum, and/or honeycomb rock or gypsum. The reports for 126 wells included such descriptions, and for each of these wells the identified cavity top and bottom depths were recorded and included in the project database.

Wells with multiple (up to five) cavity intervals occur in Collingsworth, Childress, and Hardeman Counties. TWDB and TDLR wells with reported higher well yields (i.e., greater than 100 gpm) appeared to correspond with wells containing multiple cavity intervals (Figure 11-1). The cavity data were used as an indicator of possible higher production zones for determining potential production areas (PPAs).

11.2. Sinkholes

Karst features that can be identified at land surface are also indicative of potential areas where the Blaine Aquifer system may have secondary permeability and the potential for high well yield. A good example of sinkholes formed at the land surface from dissolution and collapse of salt beds in the underlying Blaine Aquifer system is provided on the Google Earth aerial photograph presented in Figure 11-2. The area shown in the figure is near the center of Hall County along the north side of the Prairie Dog Town Fork of the Red River. The image shows several sinkholes; some are well developed and contain water, and others are in the initial stages of collapse with fracture rings.

Karst features related to sinkholes and breccia pipes were identified using land surface elevation contours (depressions) and were confirmed using aerial photography available through Google Earth (e.g., Figure 11-2). Digital land surface elevation contours, scaled to 1:24,000, obtained from National Geographic TOPO!, were used to complete this task. Manmade features such as stock tanks and diversion dams that resembled depressions in some of the topographic contours were excluded from the analysis. The remaining depressions were catalogued and digitized as a potential karst feature. Many of the karst features are obvious and readily identifiable as sinkhole or collapse features with fracture rings, while other depressions would need to be field-checked to verify that they are indeed a karst feature. In addition, karst features identified by Gustavson and others (1981), presented in Figures 74 and 75 of their report, were georeferenced, digitized, and added to the dataset.

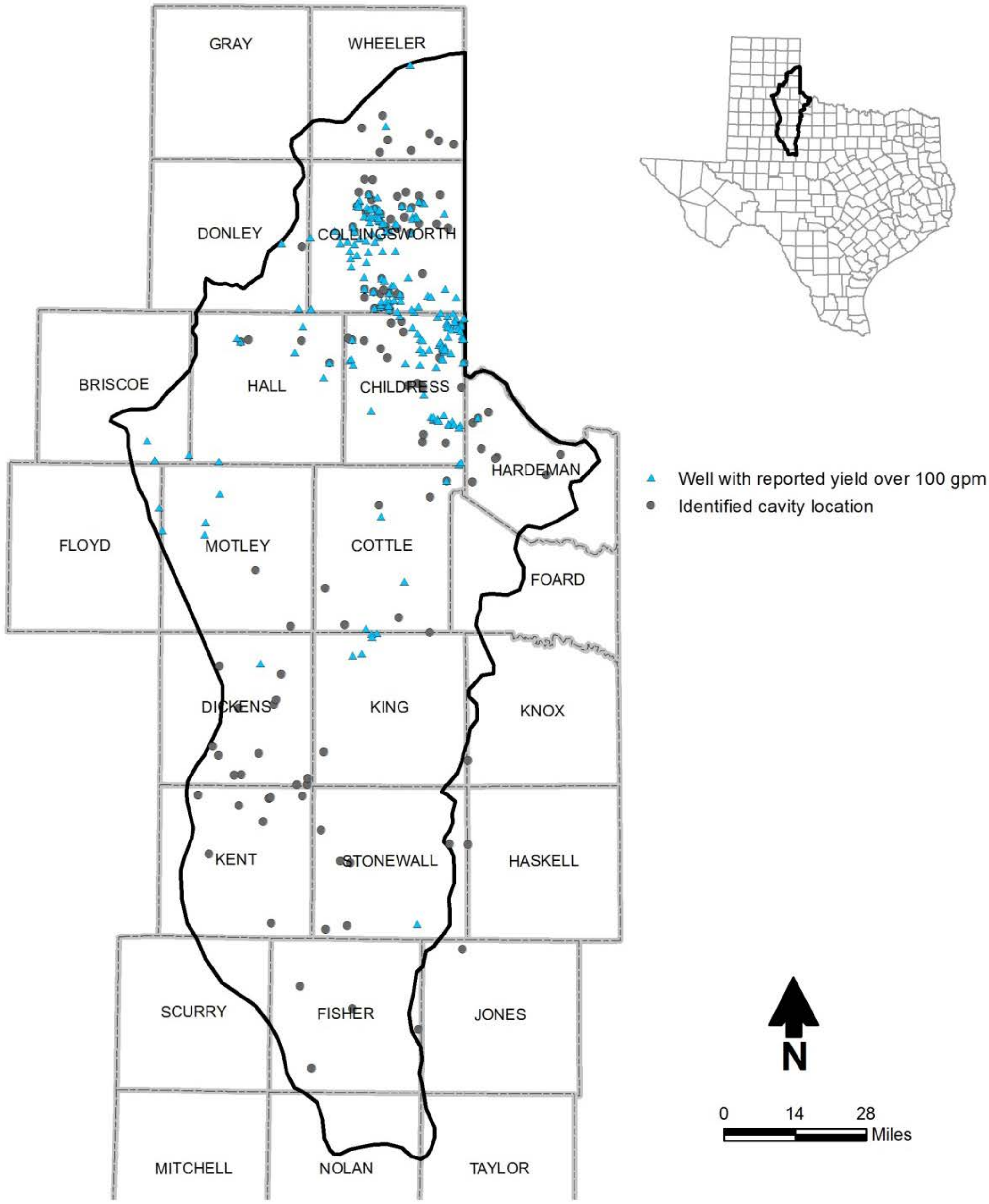

Figure 11-1. Wells with identified cavities.

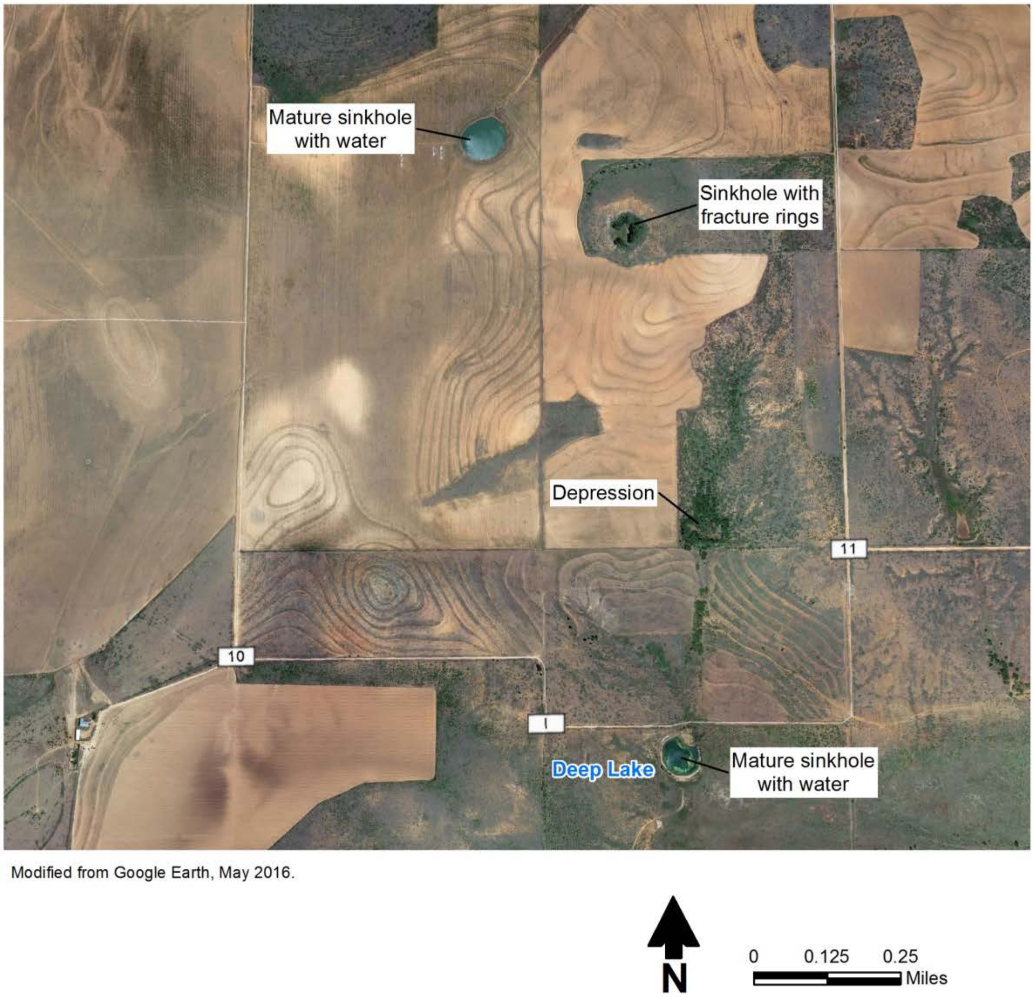

Figure 11-2. Aerial photograph with typical sinkholes identified.

All identified potential karst features in the study area are shown on Figure 11-3. The largest concentration of karst features occurs in the northern part of the study area within Wheeler, Collingsworth, Childress, and Hall Counties, where wells completed in the Blaine Aquifer system are known to have high yield. Localized areas with identified karst features occur in Motley, Cottle, Dickens, Kent, and Stonewall Counties. These localized areas may also have high well yield, but well log and well yield data are limited in these areas.

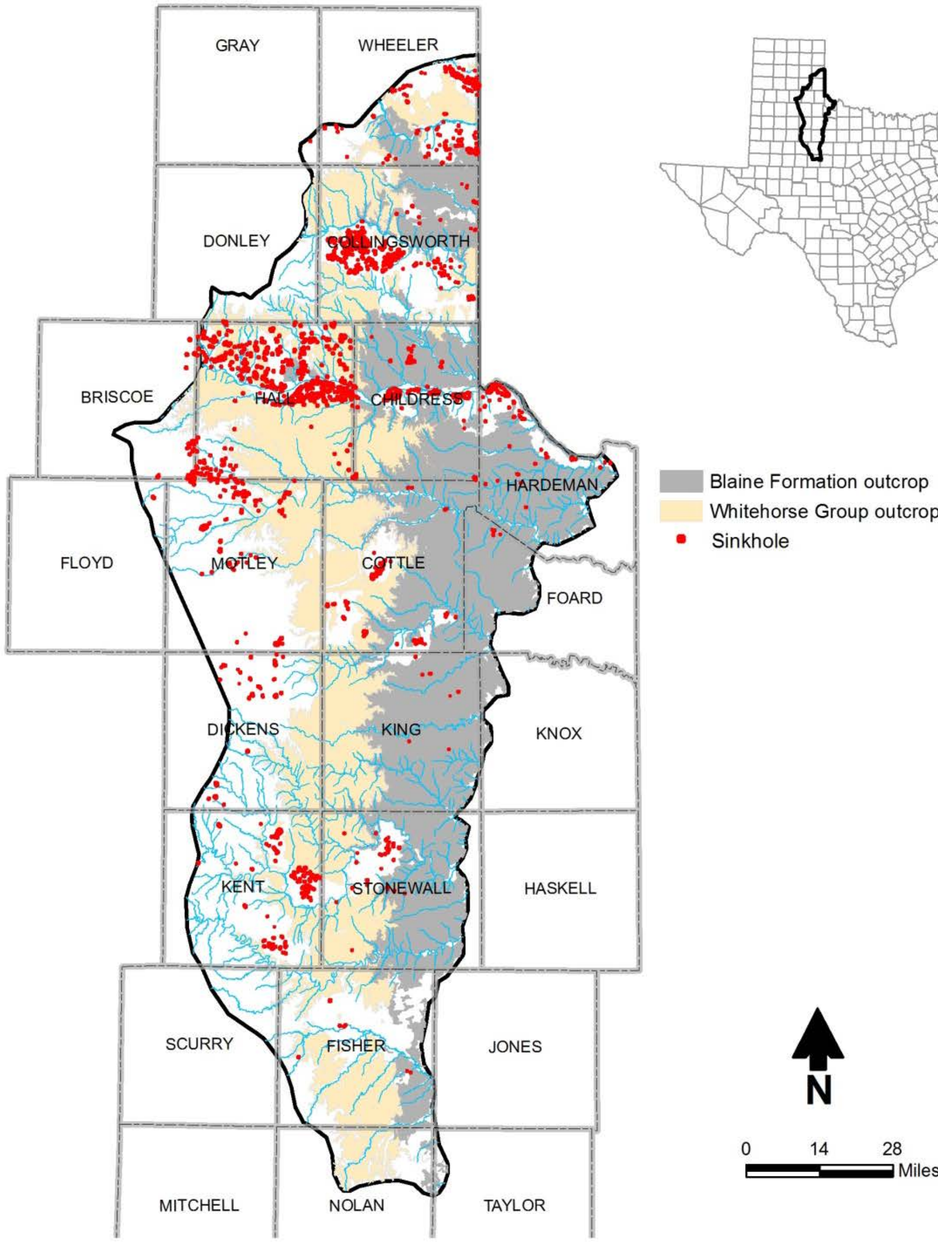

Figure 11-3. Identified sinkholes (karst features) within the study area.

12. Groundwater volume methodology

Three surfaces were used to estimate groundwater volumes. Two intersecting surfaces define the base of the Blaine Aquifer system: (1) the base of the Blaine Formation and (2) the brine interface, where it occurs, above the base of the Blaine Formation. The water level surface (Figure 8-3) defines the top of the aquifer system. The Blaine Aquifer system thickness is presented in Figure 12-1. As indicated in the figure, at most locations the aquifer is only several hundred feet thick, and at many places 200 feet or less in thickness. Because the brine interface may exist above the base of the Blaine Formation in Fisher and Nolan Counties but could not be delineated using existing data (Section 13.3), the aquifer thickness presented in Figure 12-1 and the corresponding groundwater volume calculation may be overestimated for the far southern portion of the study area.

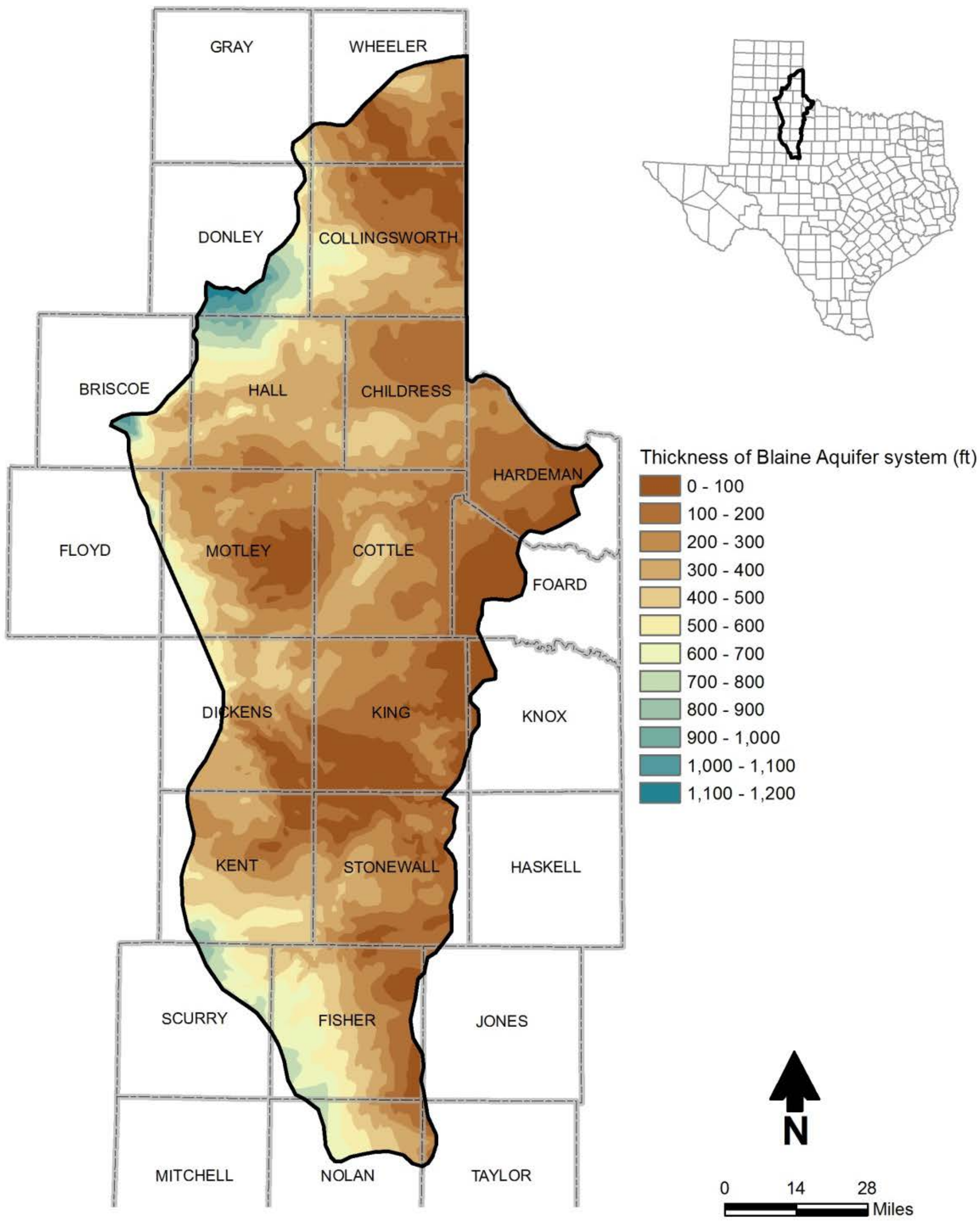

Figure 12-1. Blaine Aquifer system thickness.

Water quality data zones were delineated in Leapfrog Geo software using the reported water quality from wells. Based on the hydrogeologic conceptual model of water quality, the assumption was made that the observed water quality at a given well location is applicable to the full aquifer thickness. Aquifer volumes (Table 12-1) were calculated in GIS using interpolated surfaces exported from the Leapfrog Geo software. As noted in the table, the slightly saline and moderately saline water quality categories (Table 6-1) are combined in the groundwater volume calculation because the water quality throughout most of the Blaine Aquifer system is too variable to reasonably delineate distinct water quality zones within this range (Figure 6-1). Figure 12-2 illustrates the spatial distribution of water quality.

Table 12-1. Groundwater volume by salinity classification for the Blaine Aquifer system

Salinity zone (TDS in mg/L)	Salinity classification	Gross volume (ac-ft)	Water volume [1] (ac-ft)
< 1000	Fresh	121,176,168	1,211,762
1000 – 10,000	Slightly and moderately saline	1,789,687,866	17,896,879
> 10,000 – 35,000	Very saline to brine	17,000,103	170,000

[1] Assumes specific yield of 0.01 (1 percent)
ac-ft = acre-feet
TDS = total dissolved solids

The estimated volume of groundwater by salinity zone is broken out by county, regional water planning area, and GCD in Tables 12-2 through 12-4, respectively.

Table 12-2. Groundwater volume by salinity classification and county

	Groundwater volume (acre-feet)			
		Salinity zone (TDS in mg/L)		
County	**Total**	**0 – 1,000**	**1,000 – 10,000**	**> 10,000**
Briscoe	543,568	191,797	351,771	0
Childress	1,192,323	0	1,192,160	163
Collingsworth	1,638,837	451,430	1,187,407	0
Cottle	1,440,603	0	1,440,603	0
Dickens	1,148,223	91,990	1,056,233	0
Donley	1,150,444	64,154	1,086,290	0
Fisher	2,072,861	24,613	2,048,248	0
Floyd	164,953	109,225	55,728	0
Foard	102,753	0	102,753	0
Gray	59,932	0	59,932	0
Hall	2,470,582	14,466	2,456,116	0
Hardeman	462,638	0	462,638	0
Jones	5,240	0	5,240	0
Kent	1,695,978	0	1,695,978	0
King	782,008	0	776,730	5,278

Table 12-2. Groundwater volume by salinity classification and county (continued)

	Groundwater volume (acre-feet)			
		Salinity zone (TDS in mg/L)		
County		**0 – 1,000**	**1,000 – 10,000**	**> 10,000**
Knox	2,937	0	2,937	0
Motley	1,535,980	99,984	1,420,204	15,793
Nolan	618,964	0	618,964	0
Scurry	588,604	308	588,296	0
Stonewall	1,009,163	0	860,829	148,334
Taylor	27,435	0	27,435	0
Wheeler	564,616	164,860	399,756	0

TDS = Total dissolved solids
mg/L = Milligrams per liter

Table 12-3. Groundwater volume by salinity classification and regional water planning area

	Groundwater volume (acre-feet)			
		Salinity zone (TDS in mg/L)		
Regional water planning area	**Total**	**0 – 1,000**	**1,000 – 10,000**	**> 10,000**
A - Panhandle	7,079,403	694,910	6,384,331	163
B - Region B	2,789,559	0	2,784,281	5,278
F - Region F	592,813	308	592,505	0
G - Brazos G	5,428,836	24,613	5,255,889	148,334
O - Llano Estacado	3,388,030	492,996	2,879,241	15,793

TDS = Total dissolved solids
mg/L = Milligrams per liter

Table 12-4. Groundwater volume by salinity classification and GCD

	Groundwater volume (acre-feet)			
		Salinity zone (TDS in mg/L)		
GCD	**Total**	**0 – 1,000**	**1,000 – 10,000**	**> 10,000**
Area not covered by GCD	5,985,892	0	0	0
Clear Fork GCD	2,066,717	23,084	2,043,633	0
Gateway GCD	4,671,954	97,650	4,558,037	16,267
High Plains UWCD No.1	14,987	14,824	163	0
Mesquite GCD	4,156,589	468,995	3,687,595	0
Panhandle GCD	1,765,376	231,360	1,534,016	0
Rolling Plains GCD	2,616	0	2,616	0
Wes-Tex GCD	614,509	0	614,509	0

TDS = Total dissolved solids
mg/L = Milligrams per liter

The groundwater volumes listed in Tables 12-1 through 12-4 should be considered with caution. Only a small portion of the listed volume could be extracted from the Blaine Aquifer system without detrimental effects to groundwater in terms of depleted aquifer saturated thickness or significant degradation of groundwater quality.

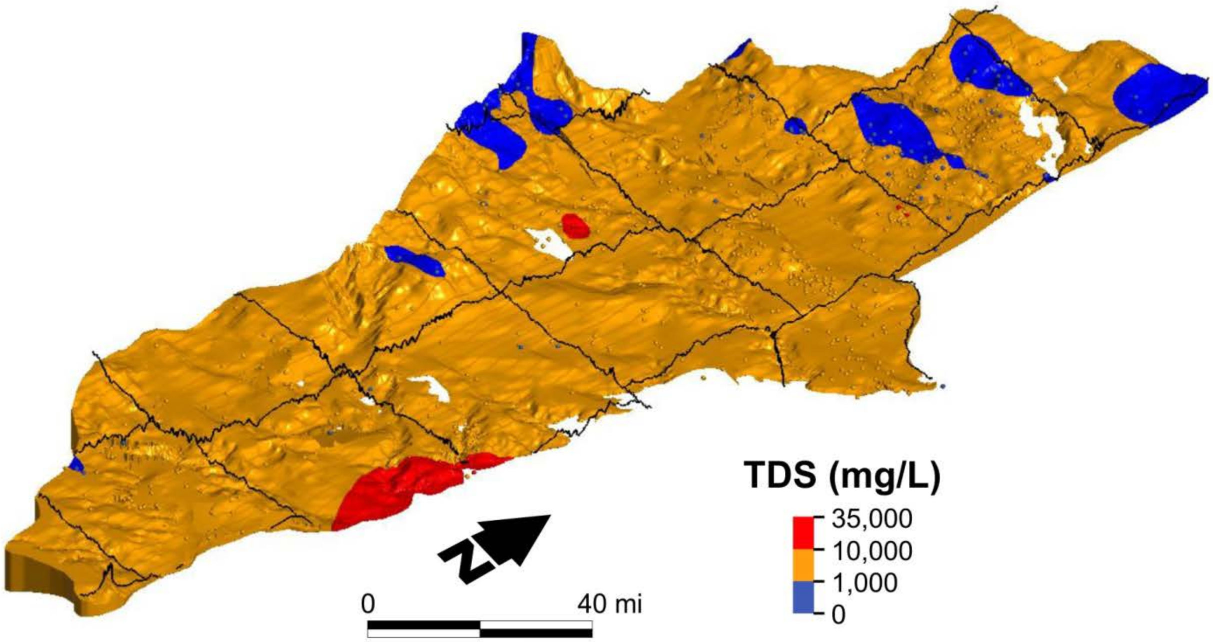

Figure 12-2. Blaine Aquifer system salinity zones illustrated on a three-dimensional visualization of the water table at 50x vertical exaggeration.

13. Geophysical well log analysis and methodology

Geophysical logs were obtained and evaluated to address two data gap issues:

- Identification and mapping of the brine surface for the study area.
- Identification and mapping of groundwater quality above the brine surface and within the aquifer system.

As explained in Section 13.3, geophysical logs were used successfully to identify the brine surface, but due to the nature of the Blaine Aquifer system, identification and mapping of water quality distribution (i.e., fresh, slightly saline, moderately saline, and very saline) using geophysical logs was not feasible. Geophysical logs were also used to assist with delineation of the base of Blaine Formation.

13.1. Identification of geophysical logs

The first step in developing the geophysical log database for the Blaine Aquifer system was to identify geophysical logs that include the target aquifer interval. Geophysical logs were obtained from the TWDB BRACS database and the RRC database. The starting geophysical log coverage for the study area is shown in Figure 8-5. Because the rocks that comprise Blaine Aquifer system crop out in the study area but gradually dip to the west, the bottom of the Blaine Formation (Figure 5-4) was used to identify geophysical logs that do not include the depth interval of interest.

The second step was to determine the depth of the top of the resistivity log interval. Typically the resistivity log interval for oil and gas wells is below the surface casing and sometimes only includes the target oil and gas production interval. A summary of the number of resistivity logs by depth to the top of the log interval is presented in Table 13-1. Most logs listed in Table 13-1 that include the shallow portion (less than 200-foot depth) are from the 1940s and 1950s, and many have limited information and data for analysis. Although limited, historical logs that include the shallow portion of the study area were considered in the analysis.

Table 13-1. Summary of the depth to top of resistivity log interval

Depth to top of resistivity log (feet)	Number of logs
< 200	225
201-400	132
401-600	8
601-800	2
801-1000	6
> 1000	8

None of the geophysical logs obtained from the RRC were used for stratigraphic picks or water quality analysis (Section 13.2). Most all of the RRC geophysical logs not in the BRACS database are newer logs completed over the last 10 years. These newer logs are from wells that have surface casing depths greater than the older logs incorporated in the BRACS database, with most of the surface casing depths greater than the bottom of the Blaine Formation and the brine surface. Electric logs must be run below the surface casing in the open hole to obtain meaningful interpretations of the brine surface or stratigraphy.

13.2. Geophysical logs for water quality analysis

An attempt was made to use spontaneous potential (SP) and resistivity logs to calculate formation water quality. The selection of applicable geophysical logs to conduct the required analysis required consideration of the drilling methods, drilling fluid quality and additives, quality of the log (e.g., scale), and other factors. The quality control and quality assurance of log selection included checking for the following:

- Adequate detail in the log header
- Omission of logs performed in holes with drilling fluid additives (e.g., caustic soda) that inhibit the calculation or analysis
- Identification of stray electrical currents or interferences with the SP log
- High fluid loss or indication of excessive invasion of drilling fluid in the formation
- Availability of a representative lithologic log to guide analysis of geophysical log

The intent was to perform water-quality calculations from electric logs for the log interval above the identified brine surface. However, several significant difficulties were encountered during the analysis, including:

- The analysis method requires a sandstone layer at least 10 feet in thickness with electric log response (Keys and MacCary, 1973; Schlumberger, 1987; Welenco, 1996). Finding a clean sandstone interval with an electric log response above the brine interface was nearly impossible due to the complex stratification of the Blaine Aquifer system and lack of lithologic descriptions near the geophysical logs evaluated. Based on this constraint alone, use of electric logs for water quality calculations may not be applicable to most of the Blaine Formation due to the lack of interbedded sandstone and shale beds.
- The SP method and resistivity water apparent (RWA) minimum method for determining formation salinity requires that the aquifer be composed of clastic sediments (Keys and MacCary, 1983). Adjustments to the method can be made to the formation factor to account for other lithologies and rock characteristics, but water quality data and other information required to calibrate the results were non-existent. Furthermore, it was found that the potential effects of gypsum, fractures, and voids on the log responses also complicated the analysis.
- The depth of surface casing also significantly limited the use of geophysical logs to estimate water quality. Out of the 1,634 geophysical logs reviewed, only 225 had surface casing depths less than 200 feet, whereas the primary depth interval above the brine surface averages about 200 feet.
- Drilling fluids need to have a higher resistivity than the formation. A large number of the electric logs were run in holes filled with salt gel, brine, oils, or other additives that prohibited the use of the log for water quality analysis or identification of the brine interface.
- Many of the logs reviewed did not have adequate header information to conduct the required analysis.
- Out of the 1,634 geophysical logs in the study area, only 2 were identified as suitable for water quality analysis and only 23 were identified as potentially suitable for water quality analysis. For these 25 logs, there were no nearby lithologic and water quality data for the corresponding interval that could be used to calibrate the results of the analysis method.

Use of geophysical logs for water quality analysis, therefore, was not feasible due to the complexity of the Blaine Aquifer system and the lack of required supporting data.

13.3. Geophysical log analysis for determination of the brine interface

The transition from brackish groundwater to brine was identifiable where the log interval included the brine surface and where the upper portion of the formation adjacent to the borehole has not been affected by upward flow of high-salinity fluids. Keys and MacCary (1973) evaluated characteristic log responses in approximately 150 oil company electric logs and used the results to identify the brine surface in places where the more porous rocks were saturated with brine. Geophysical log signatures and responses described by Keys and MacCary (1973) were used to identify the brine interface. Typical log responses included:

- Baseline shifts, such as shift to the left in the point-resistance log
- Decreases in average resistivity
- Sudden loss of lithologic detail with depth in the SP log when compared to gamma-ray and neutron logs, indicating brine influences on SP log response

Based on these criteria, identification of the brine surface was based on multiple interpretations from a suite of logs.

The salinity differences between the borehole fluids and the formation fluids also played a role in the analysis. SP logs in general had little character (limited variations in readings) below the brine interface where the borehole and interstitial fluids have similar conductivities, and above the interface the SP curve is the reverse of the gamma log response. Boreholes with circulated fresh mud provided a better SP response to the saline surface.

Water table responses in logs were determined from the water level surface elevation contours developed during this project (Figure 8-3). The depth to water and lithologic logs helped guide the analysis to identify responses in logs to the brine surface. An example is presented as Figure 13-1 for a well approximately 5 miles southeast of Paducah in Cottle County. At this well location, the brine surface is indicated at about 350 feet below land surface on the SP log in the bottom portion of the Blaine Formation.

More than 300 geophysical logs were analyzed in detail, leading to the identification of the brine interface in 64 logs. The brine interface analysis involved the following steps:

1. Determine if the geophysical log contains the information required for analysis (electric log with SP, fresh water based drilling fluids, required header information, and appropriate log scale).
2. Identify the top of the Flowerpot Shale (bottom of Blaine Aquifer system).
3. Determine if SP or resistivity response is due to lithology or a drastic change in salinity for the interval between the surface casing and the top of the Flowerpot Shale.
4. List identified SP or resistivity response as “yes” or “maybe” under database column titled “Suitable for determining Brine Interface.” Entries for “yes” indicate a high level of certainty for the identification of the brine interface, and entries for “maybe” indicate a low to moderate level of certainty.

5. Record the depth to the brine interface selected from the log and add additional comments, which typically included an explanation of the level of certainty and whether the brine interface is above, at, or below the top of the Flowerpot Shale.
6. Use elevation and depth inputs in the geophysical log database to calculate the brine surface elevation.

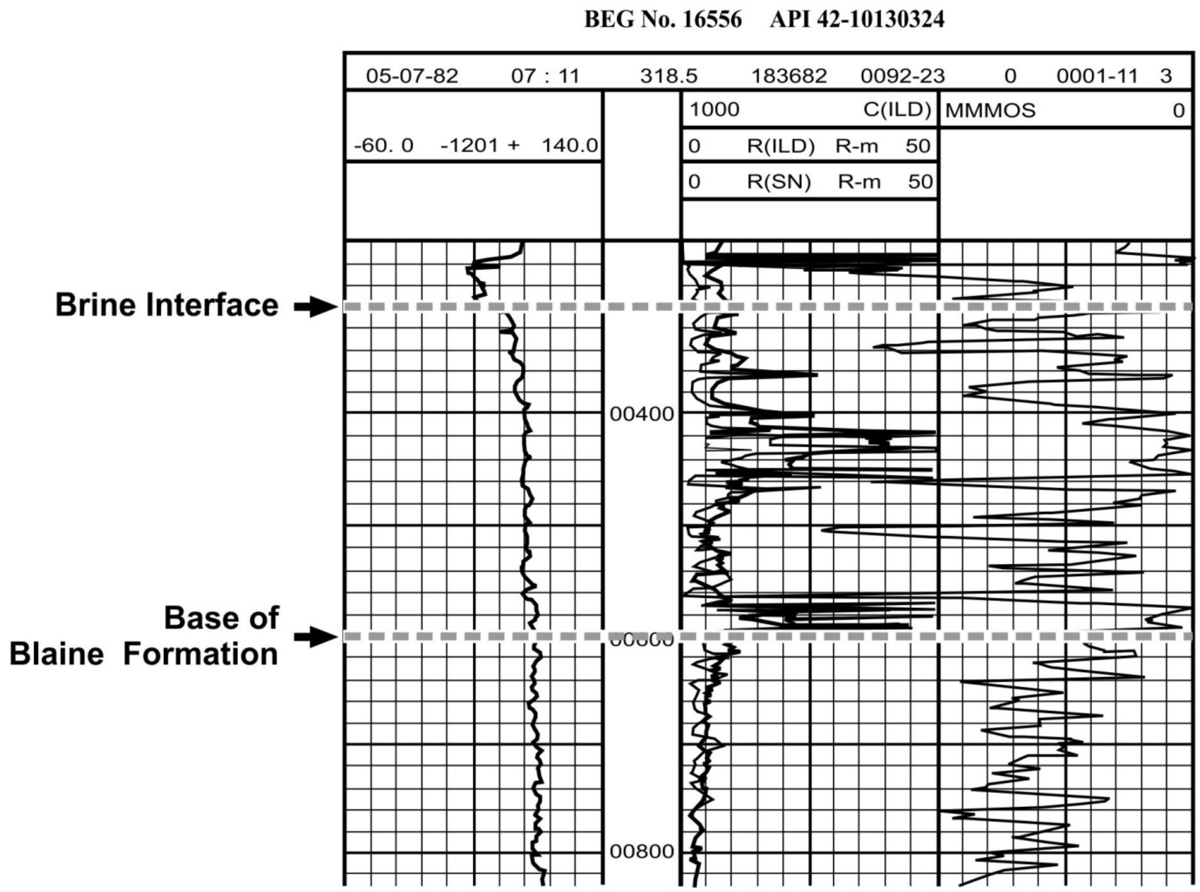

Figure 13-1. Portion of electric log from BEG No. 16556 located approximately 5 miles southeast of Paducah, Cottle County, Texas. Neighboring water wells have depth to water of 100 feet and TDS of 3,900 mg/L, and the lithology consists of alluvium from 0 to 60 feet, Blaine Formation from 60 to 500 feet (karstified from 120 to 240 feet), and Flowerpot Shale > 500 feet (base of aquifer noted on log by brown line at 500 feet). Shift in SP at 350 feet is indicative of the brackish-brine interface.

The brine surface elevation points were plotted on a base map of the Blaine Aquifer system along with the georeferenced brine surface elevation contours from Stevens and Hardt (1965) for the Dickens, King, Kent, and Stonewall County area. It was determined that the brine surface is at or below the top of the Flowerpot Shale (base of the Blaine Aquifer system) for most of the northern and eastern portions of the project area. The brine surface is prominently above the top of the Flowerpot Shale in the western part of the southern half of the aquifer system (Figures 13-2 and 13-3). The brine surface data points matched well with the Stevens and Hardt

(1965) surface, although the Stevens and Hardt surface was based on a more detailed data set and therefore had higher resolution.

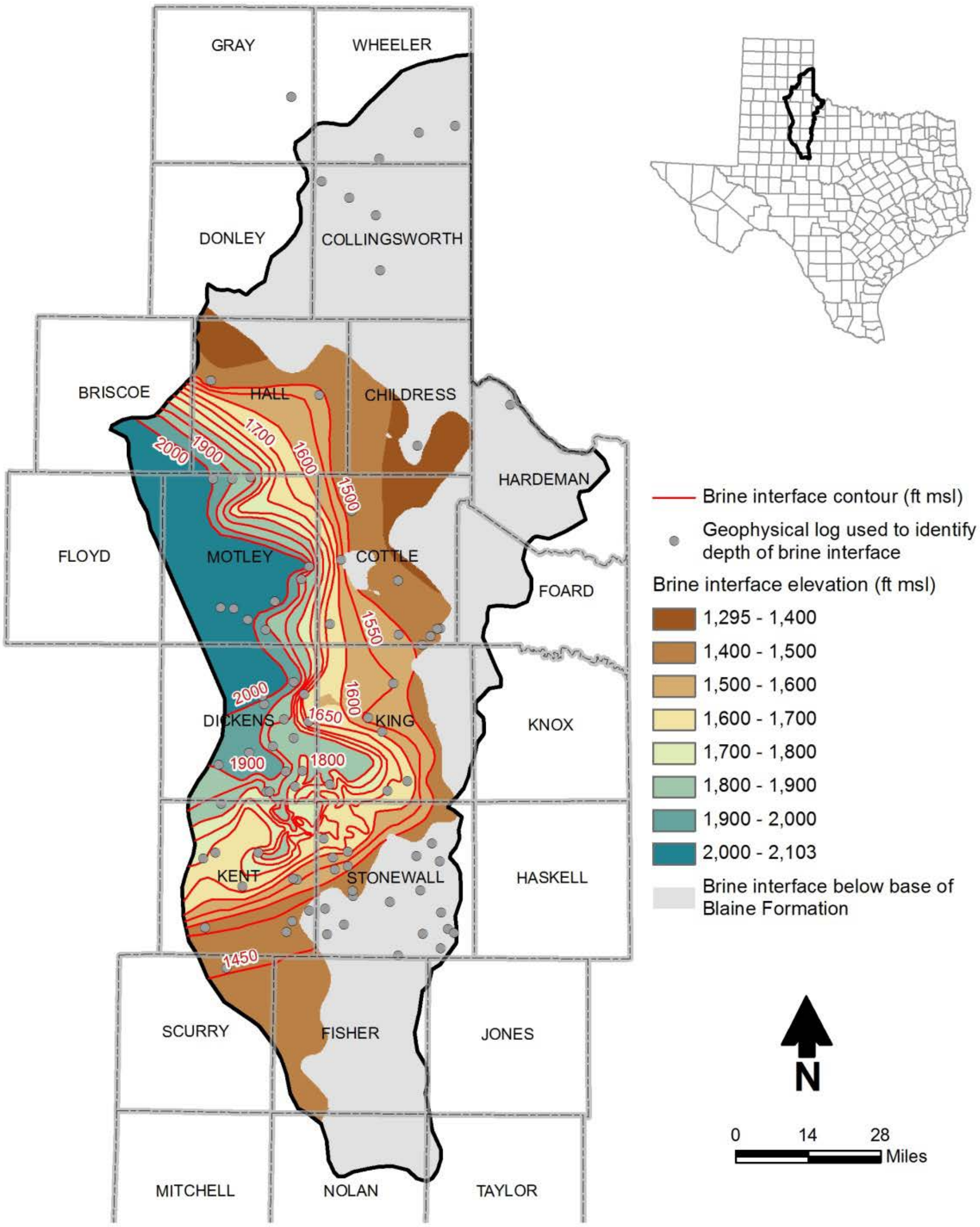

Figure 13-2. Estimated elevation of brine interface where it occurs above the base of the Blaine Formation.

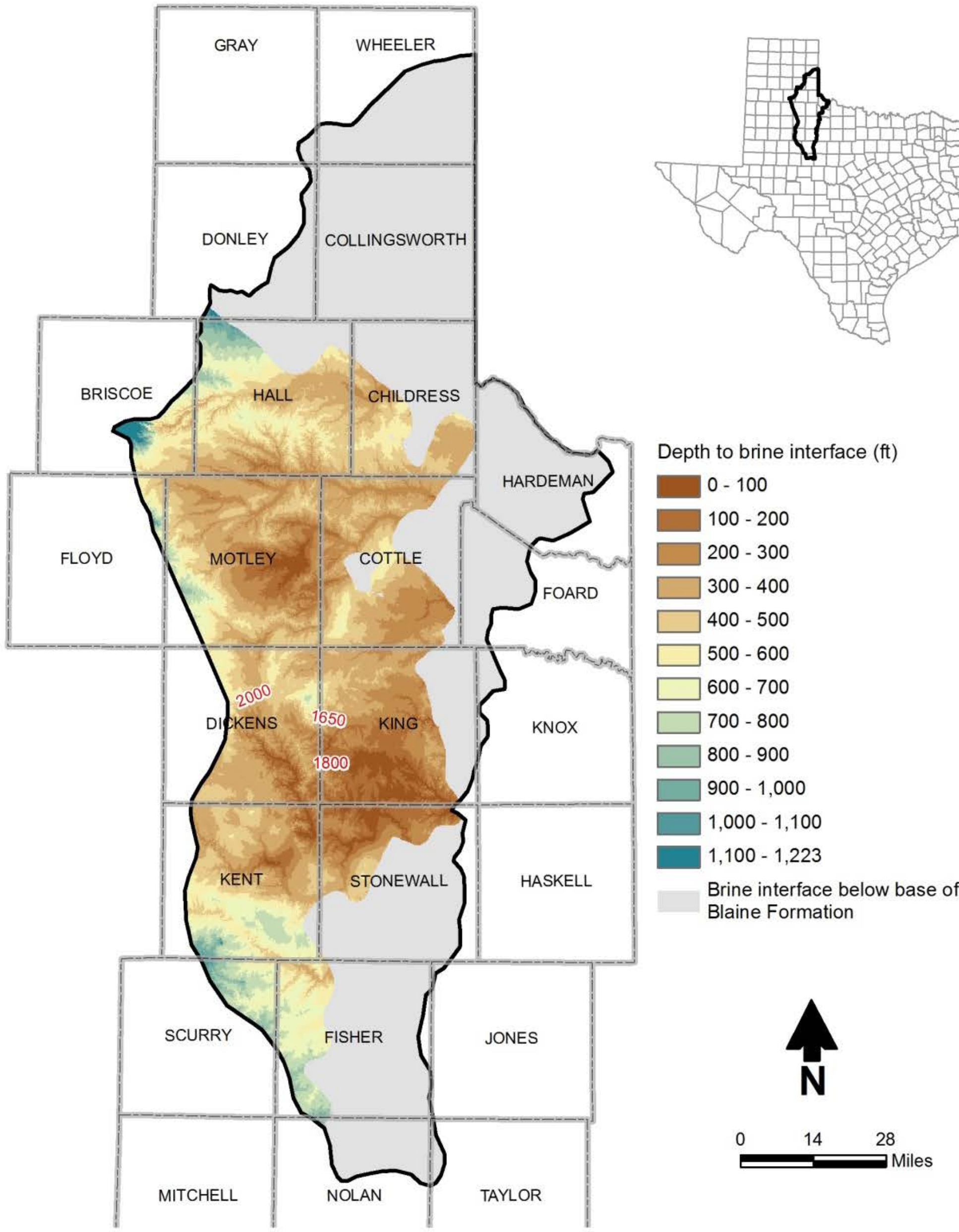

Figure 13-3. Depth below land surface to the brine interface where the brine interface occurs above the base of the Blaine Formation.

The brine surface could not be identified for Fisher and Nolan Counties due to surface casing depths greater than the depth to the brine surface, drilling methods and borehole fluids, and the large-scale effects of historical brine contamination described by Burnitt (1963). Limited data from Fisher and Nolan Counties indicate that the brine surface is relatively shallow and the Blaine Aquifer is not highly productive.

14. Potential brackish groundwater production area analysis and modeling methodology

HB-30 requires that brackish groundwater production zones be identified and the amount of brackish groundwater within each zone that can be produced over a 30- and 50-year period be determined. The brackish groundwater production is not supposed to have a significant impact on water availability or quality relative to significant sources of water supply already being used for municipal, domestic, or agricultural purposes. In this report potential production areas (PPAs), not "production zones" as referred to in HB-30, are identified. Computations of expected hydrologic effects of pumping from the PPAs are presented. Whether or not one or more of the PPAs will be considered a production zone will be determined at a later date, based in part on stakeholder input. Identification of the PPAs and the computation of potential hydrologic effects are presented in Sections 14.1 and 14.2.

14.1. Identification of exclusion areas

The first step in determining the PPAs was to define exclusion areas based on known regions of significant municipal, domestic, and agricultural groundwater use. Exclusion areas were also determined for regions where injection wells are relatively shallow and for protected wildlife areas. The process of identifying exclusion areas is outlined in Sections 14.1.1 through 14.1.6. Detailed figures of the exclusion areas are provided in Appendix B.

14.1.1. Public water supply wells (municipal)

A shapefile of the TCEQ public water supply wells was created for the study area, which includes a total of 91 public water supply wells. The Red River Water Authority of Texas (RRWA) supplies public water to a number of very small cities and towns in the northern third of the study area. The RRWA was contacted by phone to obtain the locations of their public water supply wells, and it was determined that 9 of the RRWA wells are located in the study area. A 2-mile exclusion area was created around each public water supply well location (Figure 14-1). The 2-mile distance is an assumption, but it corresponds to approximately two times the well spacing commonly used in municipal well fields.

14.1.2. Cities (domestic)

The Texas Department of Transportation (TxDOT) city limit data set was used to locate cities in the study area. This effort yielded a shapefile that included 23 city limit boundaries. A 3-mile exclusion area surrounding each city limit boundary extent was created (Figure 14-1). The purpose of this exclusion area was to include potential domestic well development outside (but near) the city limits. The selected distance of 3 miles is an assumed distance.

14.1.3. Populated places (domestic)

In addition to the city limit data set, a point shapefile was created to account for populated areas not covered in the city shapefile. The source used to locate these areas was the USGS

Geographic Names Information System (GNIS) "populated places" data set. This shapefile included 85 populated places within the study area. A 2-mile exclusion area was created around each populated place point location to account for domestic supply wells likely to occur in these areas (Figure 14-1). The 2-mile distance is an assumption. The exclusion area around populated places is smaller than that around city limits (where 3 miles was used) because the populated places are smaller entities and likely have less adjacent development than the cities.

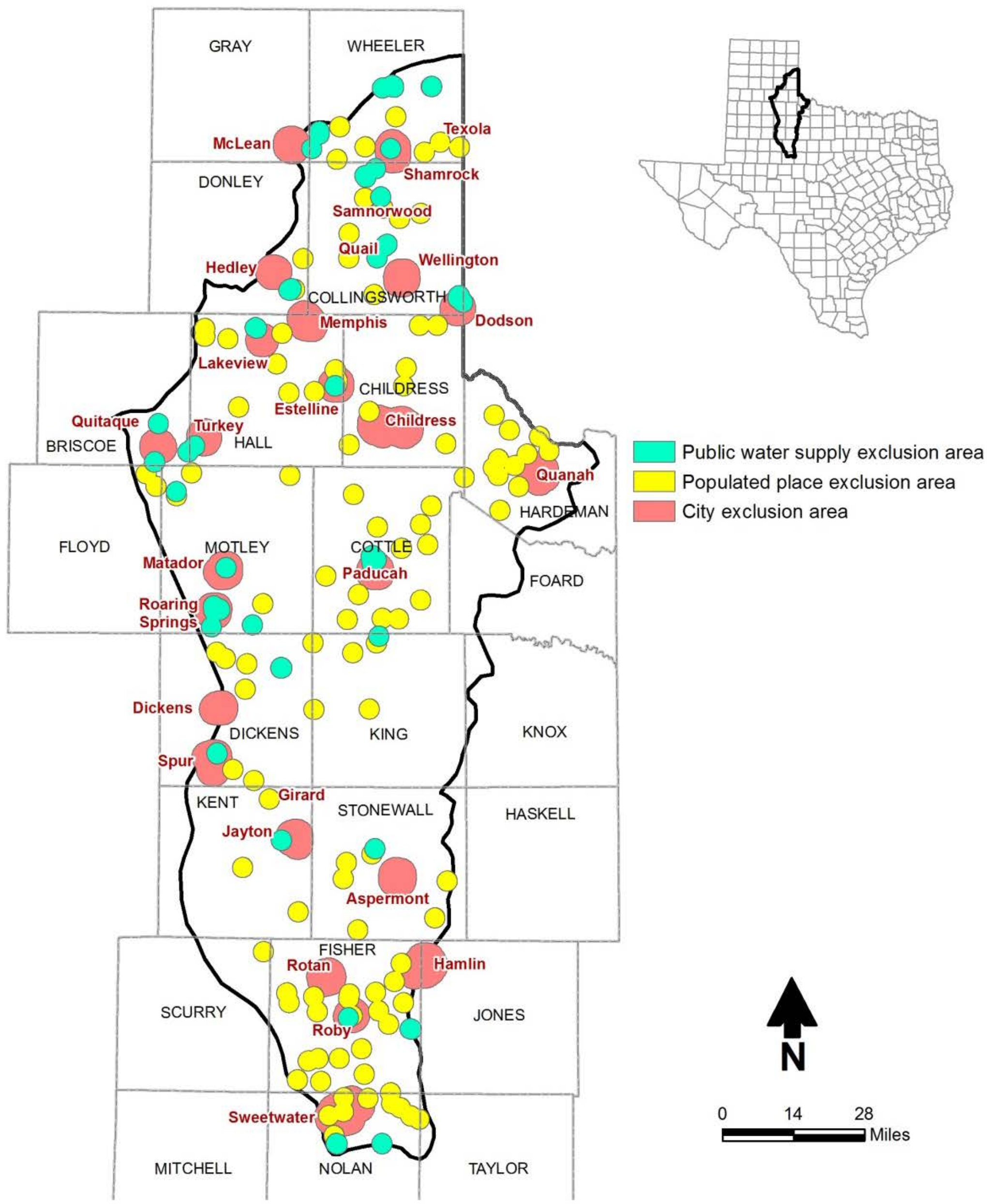

Figure 14-1. Exclusion areas identified for public water supply wells, cities, and populated places.

14.1.4. Irrigation (agricultural)

Irrigation areas were delineated by identifying irrigation wells available from the TWDB and TDLR databases and coupling the identified irrigation well locations with the U.S. Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) 2014 color infrared imagery. The irrigation area extents are hand-drawn polygons that include all of the identified irrigation wells and bright to dull red irrigated tracts of land. A total of 14 irrigation areas were delineated (Figure 14-2). Wheeler, Collingsworth, Hall, Childress, Hardeman, Motley, Cottle, and (to a lesser degree) Fisher Counties have large regions of active irrigation.

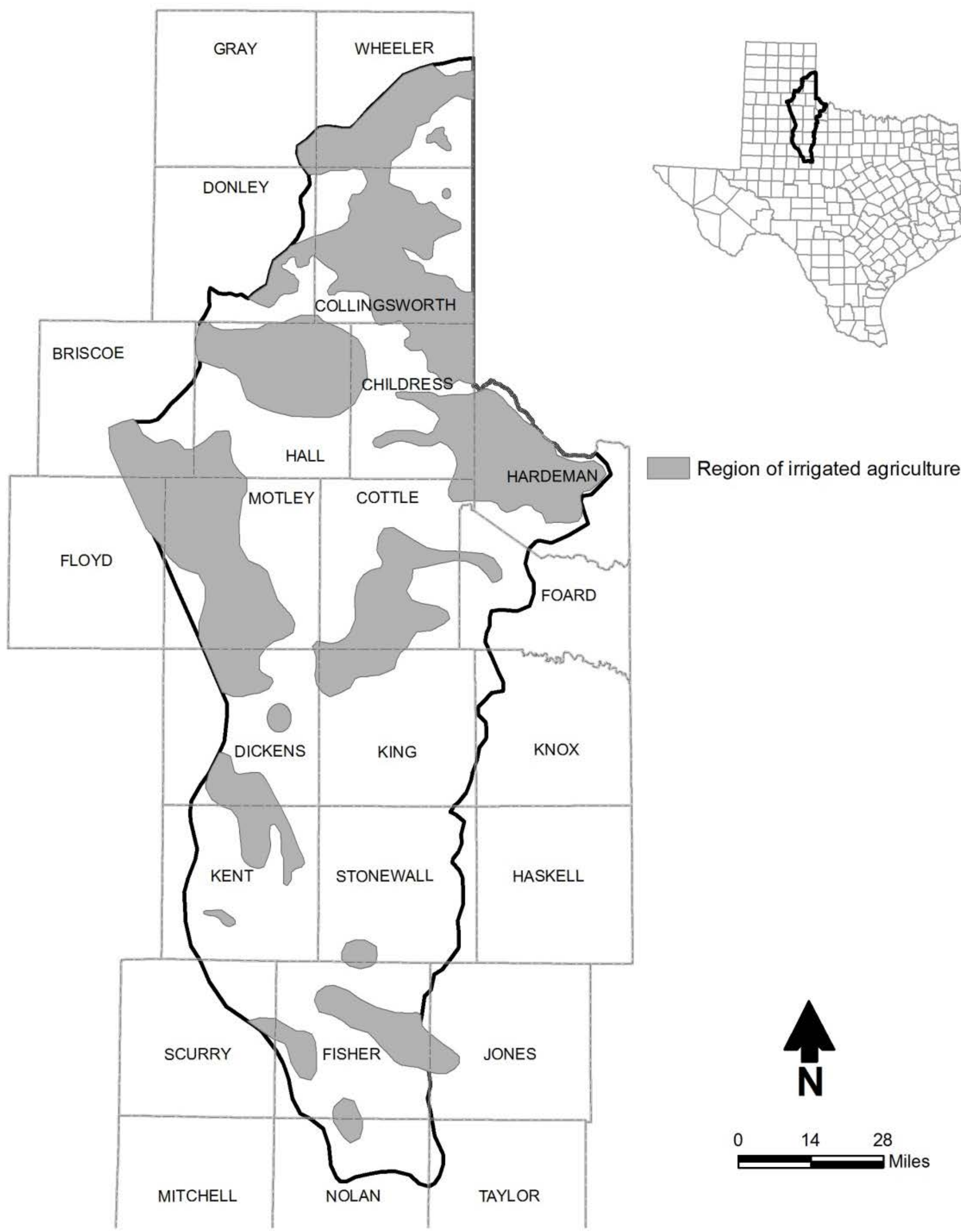

Figure 14-2. Exclusion areas identified for irrigated regions.

14.1.5. Injection wells

In May 2016 a request was submitted to the RRC for all active injection wells (W-14, disposal into nonproductive zone) and water-flood (H-1, disposal into productive zone / secondary recovery) within the study area. After quality assurance/quality control, 950 wells remained: 141 active injection wells, 122 water-flood wells, and 687 secondary recovery wells.

Active injection wells were identified as having one of the following H-10 statuses (1) active, authorized by RRC to inject but not yet drilled, (2) authorized for storage but not yet drilled, (3) drilled but not yet completed, (4) drilled but not yet in storage service, and (5) other (temporarily abandoned, temporarily abandoned/shut-in, or active storage service). Wells with the status of no H-10 report were also included in this feature class. Active wells without an injection interval or coordinates in the Underground Injection Control (UIC) database were excluded from the data set. Well location coordinates are recorded in NAD 83 coordinates. Saltwater was the dominant fluid used in injection and water-flood wells. Secondary recovery well fluids included saltwater, gas, and/or carbon dioxide.

All but 8 of the 950 wells are injecting at depths greater than 1,500 feet. Of those 8 wells, 7 in Wheeler County are injecting fluids at less than 500 feet below land surface. This area of shallow injection wells in Wheeler County was hand contoured and defined as an exclusion area (Figure 14-3). The remaining injection well (well W-14) is injecting below the Blaine Aquifer in Fisher County; that well location is illustrated in Figure 14-3.

14.1.6. Texas wildlife management areas and protection of endangered species

The DBS&A team added an exclusion criterion for the preservation of protected wildlife areas and springs that contain endangered species. The Texas Parks and Wildlife Department (TPWD) maintains a data set with active wildlife management areas (WMAs), which was used to determine that the only WMA within the study area is the Matador WMA in Cottle County (Figure 14-3). The Matador WMA includes 28,183 acres purchased by the TPWD in 1959.

Springs in areas that include endangered species were also considered for exclusion areas. The TPWD website (http://tpwd.texas.gov/gis/rtest/) allows users to query for the endangered species present in each county. The primary 16 counties within the study area were queried, and no endangered species were identified in areas with spring habitats.

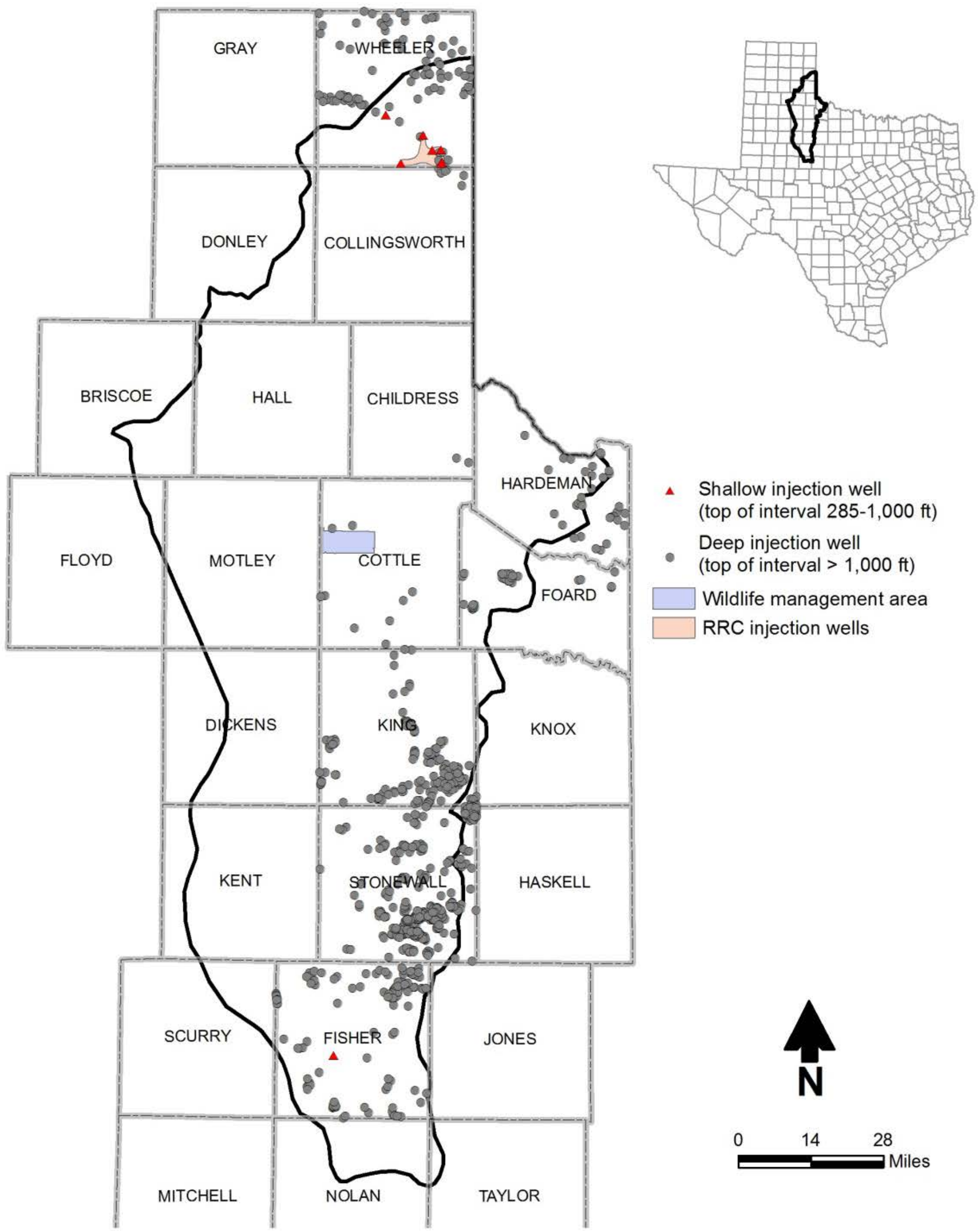

Figure 14-3. Exclusion areas identified for shallow injection wells and protected wildlife area.

14.2. Identification of potential production areas

Figure 14-4 illustrates the combined extent of all identified exclusion areas. Any PPA has to be located outside of these areas. The primary consideration in the selection of PPAs was the expected aquifer yield to supply a hypothetical brackish aquifer well field. The following five selection criteria were used to select PPAs outside of the delineated exclusion areas:

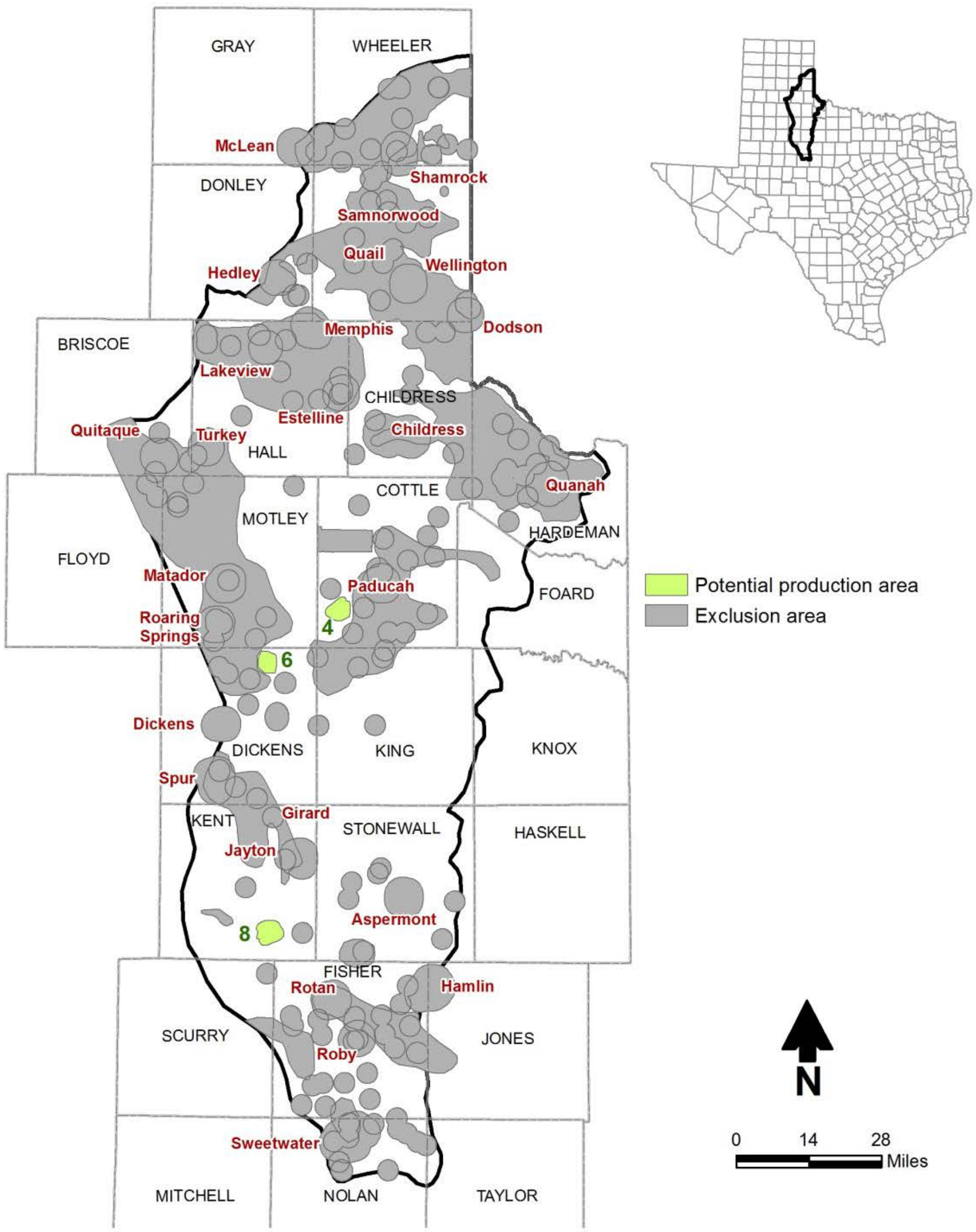

Figure 14-4. Combined extent of all identified exclusion areas and final potential production areas.

- *Identified cavities in area.* Cavities appear to be associated with higher well yields in Wheeler, Collingsworth, Hall, Childress, and Hardeman Counties.
- *Well yields greater than 100 gpm.* Areas of higher well yields are more likely to be economically developed.
- *Identified sinkholes.* Sinkholes result from evaporite dissolution and are indicators of karst development. Sinkholes appear to be associated with higher well yields in Wheeler, Collingsworth, Hall, Childress, and Hardeman Counties

- *Structural features.* Areas with structural features have more faulting and may have a higher likelihood of karst development and therefore higher well yields.
- *Aquifer thickness greater than 100 feet.* An aquifer thickness of less than 100 feet was assumed to be too small for significant, long-term groundwater development.

Eight PPAs were originally identified based on these selection criteria. At a stakeholder meeting held in Quanah, Texas on June 29, 2016, hosted by the Gateway GCD, the eight identified PPAs were presented to the stakeholders in attendance. Based on stakeholder input during and subsequent to the meeting, and based on guidance from the TWDB, five areas were removed (Areas 1, 2, 3, 5, and 7) because of irrigation activities or existing wells identified within the PPA. The areal extents of the remaining three PPAs (Areas 4, 6, and 8) were reduced in size if needed to exclude known wells. Areas 4, 6, and 8 are illustrated in Figure 14-5 and are summarized in Table 14-1. More detailed figures of the three PPAs and the exclusion areas are provided in Appendix B, and a description of all GIS files is provided as Appendix C.

Table 14-1. Summary of selection criteria for final potential production areas

Potential Production Area	Identified Cavities	Wells Yields > 100 gpm	Identified Sinkholes	Structural Features	Estimated Aquifer Thickness (feet)
4	Yes	No	Yes	Yes	332
6	No	Yes	Yes	Yes	426
8	Yes	No	Yes	No	507

gpm = gallons per minute

An additional stakeholder meeting hosted by the Mesquite GCD was held in Wellington, Texas on August 18, 2016. At this meeting the final three proposed PPAs were presented, along with an overview of the technical analysis completed during this study. An overview of HB-30 was also provided. Stakeholders at the meeting unanimously opposed the designation of any PPAs within the Blaine Aquifer system because of, among other things, the limited thickness of the aquifer system and limited yields experienced by some water users, particularly during periods of drought and near the end of irrigation seasons. In addition, one stakeholder provided a comment that PPA 6 may be too close to water supply wells for the community of Afton in Dickens County. This is a potential concern to be considered further by the TWDB during evaluation of the PPAs.

14.3. Drawdown computations

For each of the remaining PPAs, it was assumed that a well field would be developed consisting of nine wells spaced 0.75 mile apart. Each well field was assumed to pump at 1,000, 2,000, and 3,000 acre-feet per year (ac-ft/yr), with pumping divided equally among the nine wells. This amount of pumping corresponds to an operational pumping rate per well of about 100 to 300 gpm, assuming a 70 percent average run time for each well. Each hypothetical well field is assumed to operate independently of the others (i.e., only one well field is operational in each predictive simulation).

The range of total pumping of 1,000 to 3,000 ac-ft/yr was selected because it is sufficient to provide all or a significant portion of the water demand for the towns and municipalities within or immediately adjacent to the study area (Figure 1, Table 14-2). These production volumes correspond to 800, 1,600, and 2,400 ac-ft/yr of deliverable water, assuming 80 percent treatment efficiency; these amounts are approximately consistent with the 2014 water demand for several of the entities listed in Table 14-2.

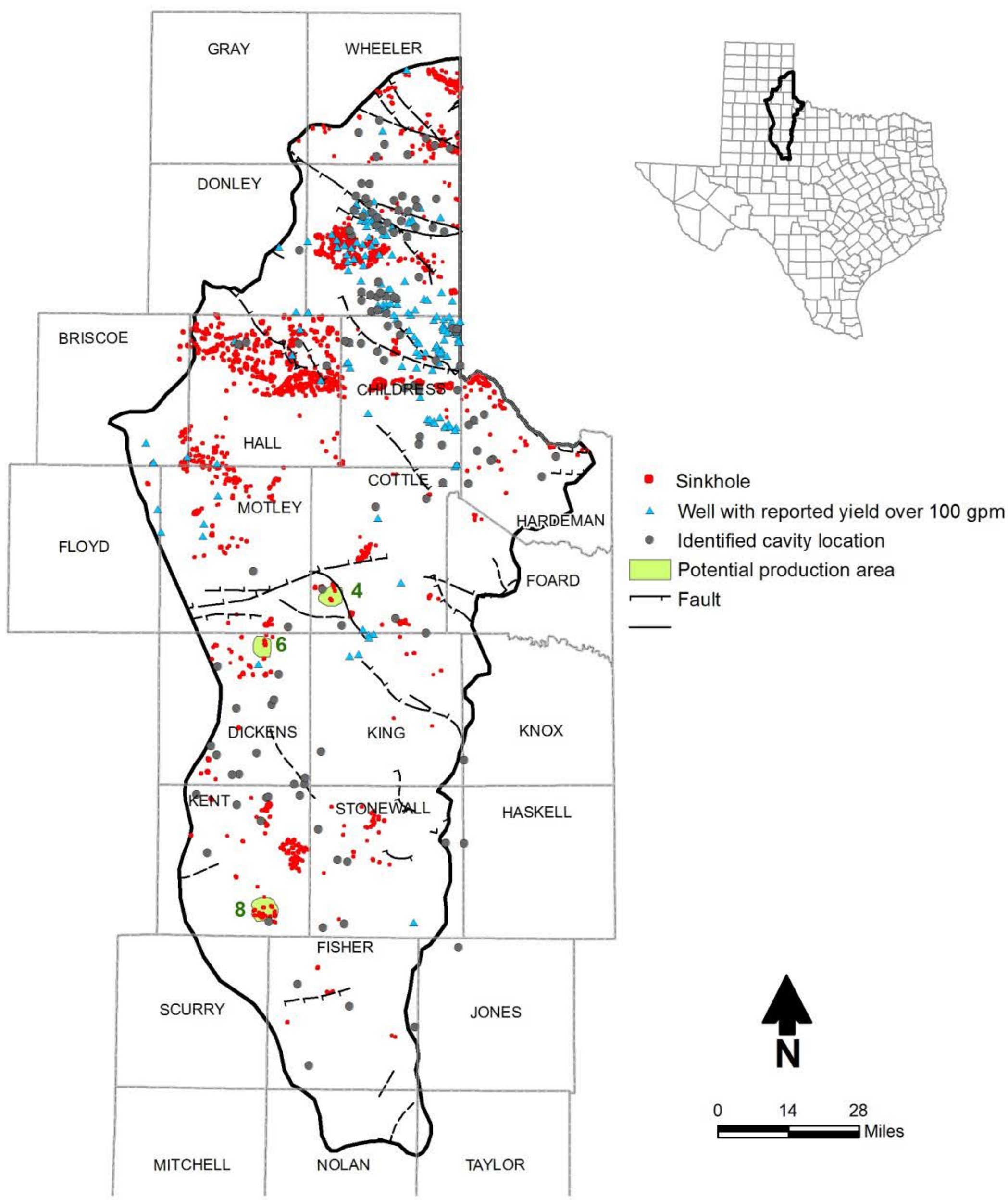

Figure 14-5. Final potential production areas and physical indicators of potential well yield.

Table 14-2. Municipal water demand within and near the study area from 2014 water use surveys.

Entity Name	Population	Intake Total (ac-ft/yr)
Anson	2,341	461
Aspermont	885	134
Childress	6,105	1,378
Crowell	895	232
Hamlin	2,037	372
Haskell	3,297	471
Jayton	521	99
Matador	544	120
Mclean	792	186
Memphis	2,235	341
Paducah	1,137	231
Quanah	2,501	335
Roby	631	130
Rotan	1,480	235
Shamrock	2,041	914
Snyder	11,711	2,235
Spur	1,229	209
Sweetwater	10,722	2,253
Wellington	2,090	481

Sources: TWDB web site, accessed on August 26, 2016

ac-ft/yr = acre-feet per year

Predictive drawdown computations were conducted using the Theis (1935) equation as follows:

$$s = \frac{Q}{4\pi T} \int_u^{\infty} \frac{e^{-u}\, du}{u} \qquad \text{Eq. 14-1}$$

where s = drawdown in water level
Q = pumping rate of the well
T = aquifer transmissivity
u = $\frac{r^2 S}{4Tt}$
r = distance from the pumping well to a given point
S = aquifer storage coefficient
t = time since pumping began

Equation 1 is generally written in the form of the well function, W(u), as follows:

$$s = \frac{Q}{4\pi T} W(u) \qquad \text{Eq. 14-2}$$

Assumptions intrinsic to utilization of the Theis equation are that the aquifer hydraulic conductivity is homogeneous and isotropic throughout the region of analysis, the aquifer thickness is uniform, the production wells penetrate the full thickness of the aquifer, and the aquifer thickness does not change significantly with pumping if the aquifer is unconfined (i.e., computed drawdown is relatively small compared to the aquifer thickness). Although these assumptions are unlikely to be fulfilled at any location, the Theis equation often provides a reasonable initial estimate of potential pumping effects. More accurate estimates can be obtained if site-specific data (e.g., aquifer tests) are available.

Equations 14-1 and 14-2 are linear, so that the effects of pumping multiple wells can be superimposed (added) to one another in order to estimate the total drawdown at a given location (r) and time (t). Aquifer boundary conditions, such as barrier boundaries (e.g., aquifer pinch-out) or streams can be considered using the Theis method, but these conditions were not identified near the PPAs based on the existing data.

The pumping assumptions are noted above. The times of analysis were 30 and 50 years. A hydraulic conductivity of 40 ft/d was assumed for all PPAs. This is in agreement with the analysis we performed of the specific capacity data reported by Popkin (1973b). This value also represents approximately 9 percent of the value reported by Steele and Barclay (1965) for areas where solution channels are best developed (i.e. region of highest reported well yields).

For each PPA, the average thickness was calculated, using GIS, as the difference between the water level surface and the brine interface (Table 14-1). If production wells were completed in the PPAs, they would not be completed to full aquifer thickness to avoid pumping groundwater immediately adjacent to the brine interface. It was assumed, therefore, that production wells would be completed to a depth of 70 percent of the estimated aquifer thickness. This reduced thickness was multiplied by the assumed hydraulic conductivity of 40 ft/d to obtain aquifer transmissivity. Using a smaller value of aquifer thickness will lead to a smaller transmissivity value, which will lead to greater simulated drawdown at the well field than if the full aquifer thickness were considered.

A storage coefficient of 0.01 was applied, consistent with the estimates reported by Steele and Barclay (1965) and Johnson (1990). This is a reasonable storage coefficient to use for unconfined conditions where secondary porosity is limited relative to the full volume of aquifer material, as is the case for much of the Blaine Aquifer system. Higher storage coefficients might be identified if site-specific aquifer tests are conducted within the PPAs, particularly for the sandstones in the Whitehorse Group.

The simulated drawdowns at 30 and 50 years for PPAs 4, 6, and 8 are presented in Figures 14-6 through 14-8, respectively. As indicated in the figures, the extent and magnitude of simulated drawdown for the low pumping scenario (1,000 ac-ft/yr) is small, with about 10 feet or less of drawdown at the well field area after 50 years of pumping. In this scenario the 5-foot drawdown contour extends several miles from the well field center at 50 years. For the highest pumping scenario (3,000 ac-ft/yr), simulated 50-year drawdown at the center of each well field is about 20 feet, and the extent of the 5-foot drawdown extends about 12 to 18 miles from the well field center, depending on the PPA.

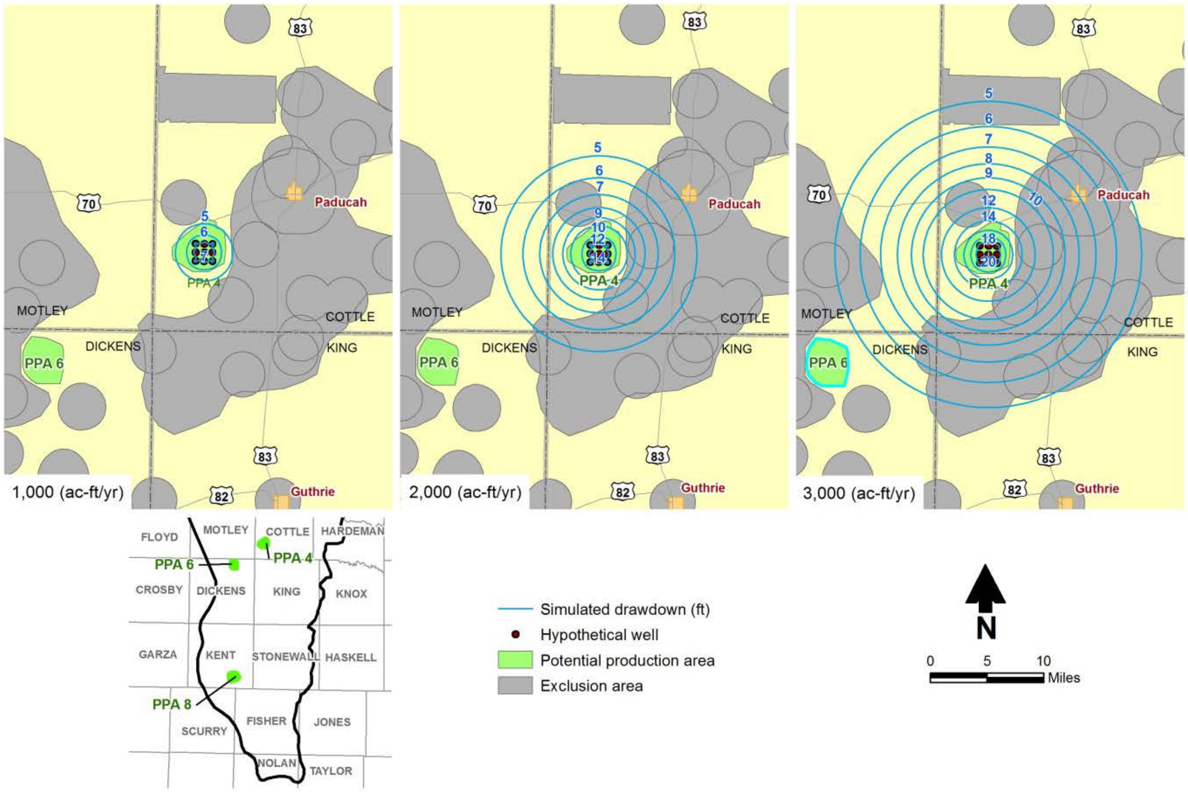

Figure 14-6a. Potential production area 4 simulated 30-year drawdown.

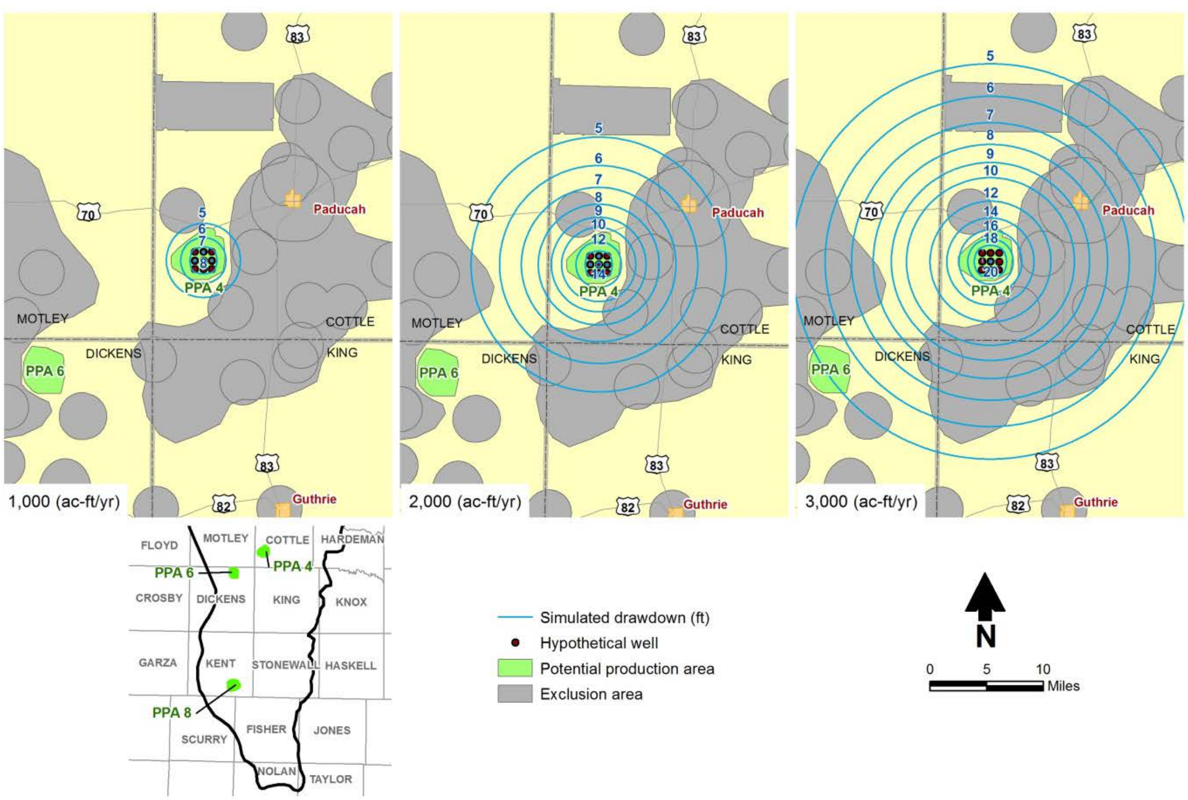

Figure 14-6b. Potential production area 4 simulated 50-year drawdown.

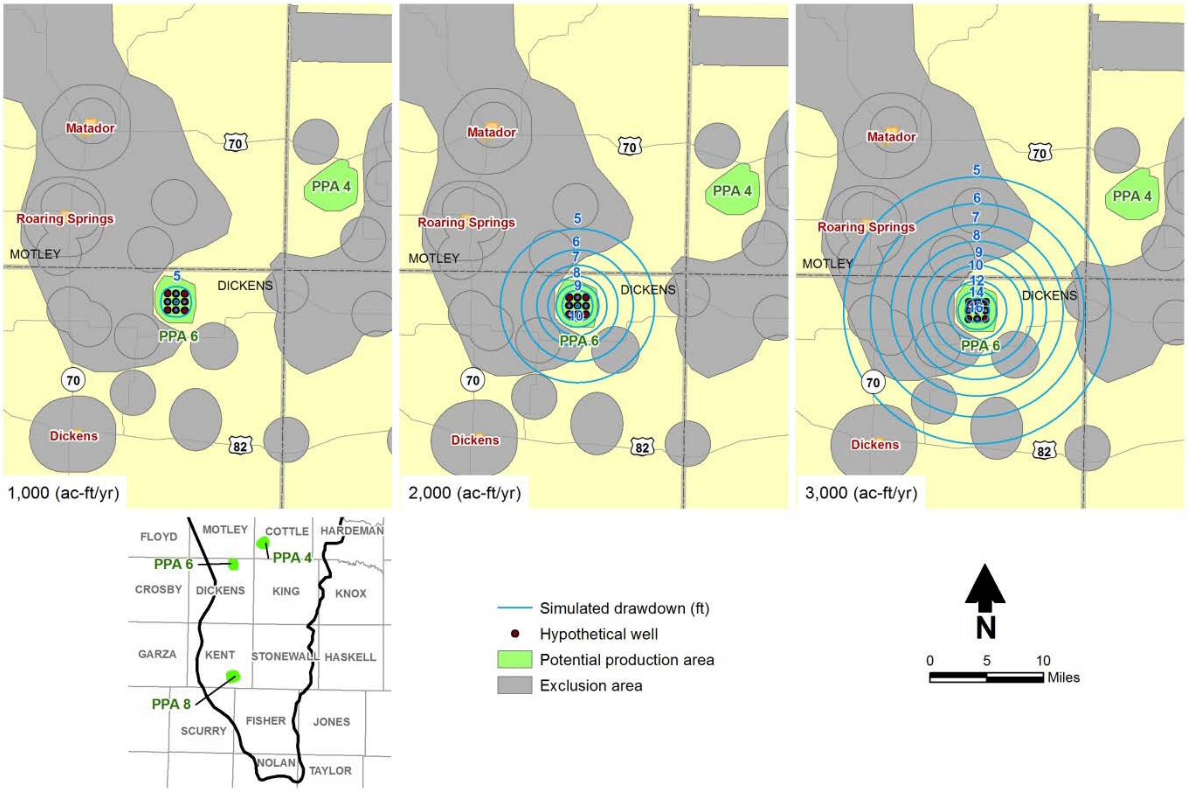

Figure 14-7a. Potential production area 6 simulated 30-year drawdown.

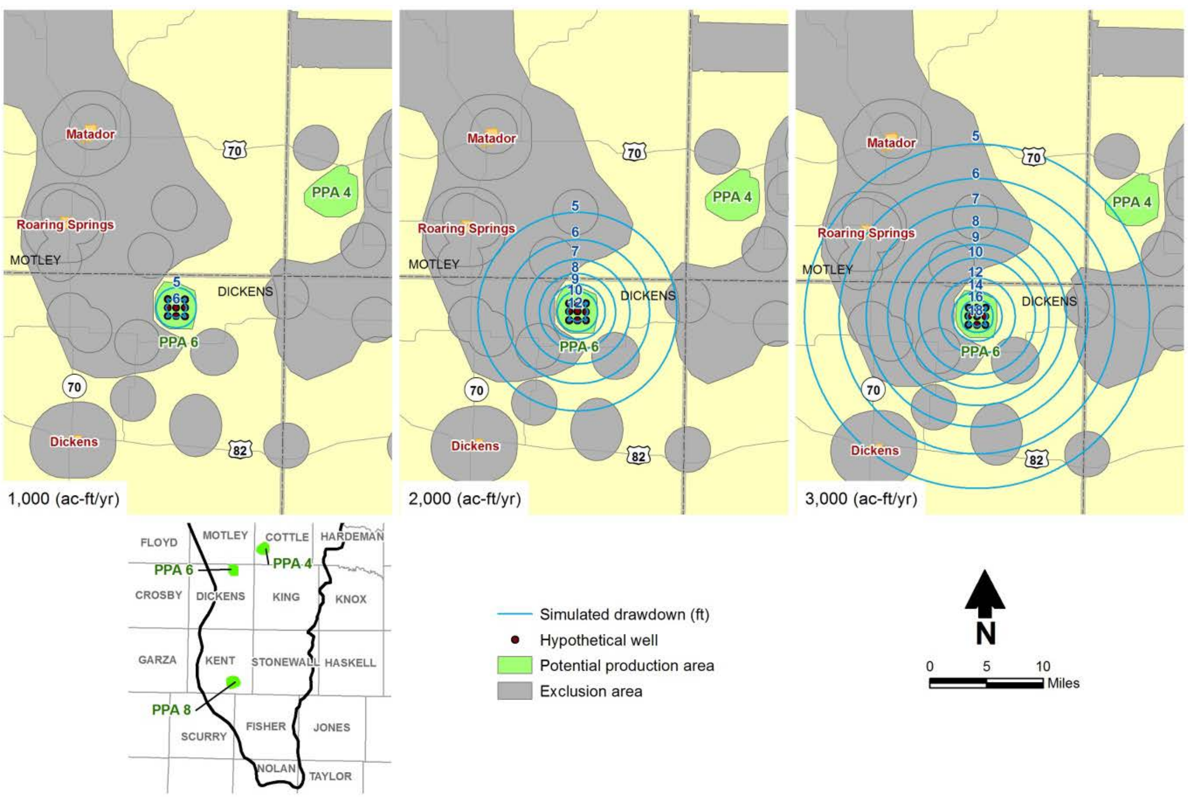

Figure 14-7b. Potential production area 6 simulated 50-year drawdown.

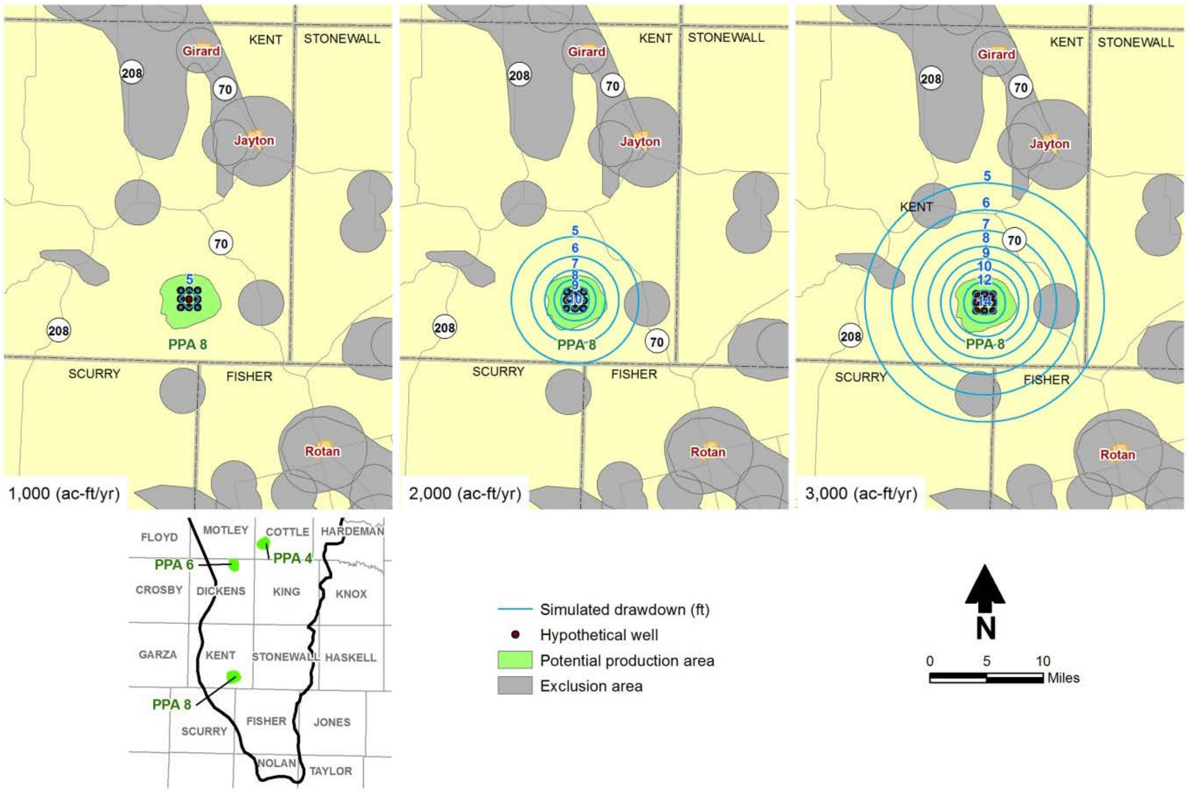

Figure 14-8a. Potential production area 8 simulated 30-year drawdown.

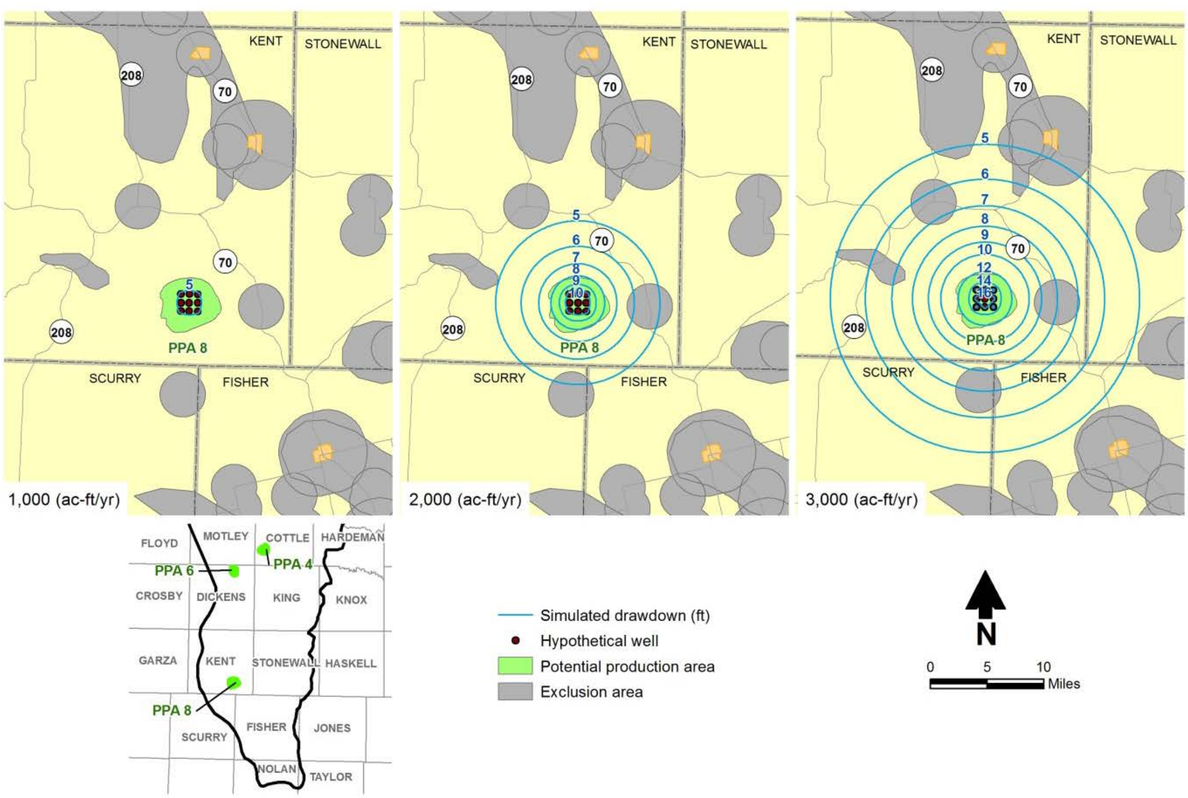

Figure 14-8b. Potential production area 8 simulated 50-year drawdown.

In accordance with TWDB requirements, the equivalent volume for each of these scenarios for 30- and 50-year time periods is provided in Table 14-3, and the estimated volume of groundwater within each PPA is provided in Table 14-4.

Table 14-3. Volume of groundwater produced from each PPA at 30 and 50 years.

Assumed Pumping (ac-ft/yr)	Time (years)	PPA Cumulative Volume Pumped (acre-feet)		
		4	6	8
1,000	30	30,000	30,000	30,000
	50	50,000	50,000	50,000
2,000	30	60,000	60,000	60,000
	50	100,000	100,000	100,000
3,000	30	90,000	90,000	90,000
	50	150,000	150,000	150,000

ac-ft/yr = acre-feet per year

Table 14-4. Estimated groundwater volume for final potential production areas

Potential Production Area	County	GCD	RWPA	Total (ac-ft)	TDS 1,000-10,000 mg/L
4	Cottle	Gateway	B - Region B	33,594	33,594
6	Dickens	None	O - Llano Estacado	36,087	36,087
8	Kent	None	G - Brazos G	64,351	64,351

ac-ft = acre-feet
TDS = Total dissolved solids
mg/L = Milligrams per liter

The simulated 50-year drawdown was subtracted from the current water level surface (Figure 8-3) to estimate the groundwater flow field after 50 years of assumed pumping. This analysis did not prove useful, however, due to the fairly coarse (regional) nature of the water level surface, which was developed at a 50-foot contour interval.

The available aquifer property and water quality information in the vicinity of the PPAs is insufficient to definitively determine the effects of groundwater pumping on water quality. Because wells would be completed above the brine interface, and since long-term aquifer drawdown would be modest, at about 6 percent or less of the estimated aquifer thickness at the center of each well field, the expected effects of the PPAs on water quality or the productivity of adjacent wells is expected to be small.

There are no known fresh groundwater sources near PPAs 4 and 8. Fresh groundwater does exist immediately south of PPA 6 in Dickens County (Figure 6-1); however, there is insufficient data to determine in detail where the fresh groundwater zone begins As noted previously, PPA 6 may also be too close to water supply wells for the community of Afton, an issue that should be considered further by the TWDB.

14.4. Limitations

The analysis of pumping effects on water levels and water quality presented and discussed in this section is based on prior publications as referenced and the geologic and hydrogeologic interpretations presented in this report. The PPAs were selected to avoid adverse future impacts on adjacent groundwater uses as required by HB-30. There is very limited information on aquifer characteristics and water quality at and near the PPAs. If development of groundwater from the PPAs were to be pursued, water rights from the landowners would need to be obtained, and detailed, site-specific studies would need to be conducted.

15. Future improvements

The Blaine Aquifer as currently defined by the TWDB incorporates approximately 5,700 square miles of Blaine Formation outcrop and subcrop in north-central Texas. This study considered a region nearly double that size through consideration of the Whitehorse Group in addition to the Blaine Formation, with the combined groundwater system referred to as the Blaine Aquifer system. This study defined the aquifer framework, including stratigraphy, aquifer top and bottom elevations, water quality distribution, and areas with secondary permeability and potentially higher well yield.

Improvements to Blaine Aquifer system framework and understanding could be made through the collection and compilation of additional data and subsequent analysis as follows:

1. Compile available pumping test data from consultant reports, water providers, and potentially other sources.
2. Collect water quality data from recently drilled water wells in Cottle County.
3. Install nested piezometers, particularly in Motley, Dickens, Cottle, and King Counties, to better define the brine interface and the variation of water quality with depth.
4. Estimate recharge to the Blaine Aquifer system using methods applicable for karst conditions. A better understanding of recharge will help determine the sustainability of developing the brackish groundwater resource in this shallow aquifer system.
5. Consider the full aquifer system in additional studies and efforts conducted by the TWDB, such as GAM updates.

16. Conclusions

The Blaine Aquifer system covers a region of more than 10,000 square miles in north-central Texas. The aquifer is a recharge-driven system, where the thickness of fresh to moderately saline water ranges from less than 100 to several hundred feet. The region has long been known to be a discharge zone of high-salinity water derived from both local, relatively shallow groundwater flow through the aquifer system and discharge of brines derived through deeper, regional groundwater flow paths. Brine exists beneath the entire aquifer system, but in much of the southern two-thirds of the aquifer system the brine interface occurs above the base of the Blaine Formation. Where this occurs, the brine surface functions as the base of the aquifer system.

As is typical of karst aquifer systems, well yields and production zones can be highly variable, with low-yield wells located close to high-yield wells. Water quality is also variable, with numerous slightly saline wells adjacent to moderately saline wells. Fresh water does occur over limited portions of the aquifer system in topographically high regions, which are the recharge zones. Based on the limited existing information, water quality appears to be relatively consistent with depth in the portion of aquifer above the brine interface.

Based on existing information, three PPAs were evaluated that meet HB-30 and TWDB guidance. The effects of future groundwater pumping in these PPAs were analyzed at assumed well field production rates of 1,000, 2,000, and 3,000 ac-ft/yr. Based on the assumed aquifer properties, each PPA should be able to sustain the maximum amount of pumping for both 30- and 50-year periods. These PPAs or others considered for groundwater development would need to be investigated in detail through field studies prior to actual development. There are likely many other areas that might be developed to produce these general quantities of water. Local stakeholders at a meeting held on August 18, 2016 unanimously opposed the designation of any PPAs within the Blaine Aquifer system because of, among other things, the limited thickness of the aquifer system and limited yields experienced by some water users, particularly during periods of drought and near the end of irrigation seasons.

Because the Blaine Aquifer system is shallow, relatively thin, and dependent on groundwater recharge within the outcrop area, and because target groundwater zones with slightly to moderately saline water occur adjacent to brine at depth, any brackish groundwater development project would need to be carefully planned and executed in order to be sustainable and avoid adverse impacts to adjacent water users.

17. Acknowledgments

We would like to acknowledge the input of the GCDs within the study area, and in particular the Gateway and Mesquite GCDs, which hosted the local stakeholder meetings. Consultant Mr. Ray Brady also provided useful input. The Red River Municipal Water District provided details on public water supply well locations and their assistance is gratefully acknowledged. Michelle Sutherland of Michelle A. Sutherland LLC constructed the three-dimensional Leapfrog model provided with this report. Technical staff that played significant roles in completing this project include Sherry Galemore (John Shomaker & Associates Inc.), Vince Clause (Allan R. Standen, LLC), and Kenny Calhoun, Lloyd DeWald, Farag Botros, and Ellen Torgrimson (Daniel B. Stephens & Associates, Inc.).

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Appendix A

Summary of Blaine Aquifer system specific capacity data and hydraulic conductivity estimates

Appendix A. Summary of Blaine Aquifer system specific capacity data and hydraulic conductivity estimates

County	State well #	Well depth (ft)	Casing size (in)	Screen interval	Aquifer	Water level	Reported pumping rate (gpm)	Corresponding drawdown (ft)	Specific capacity (gpm/ft)	TWDB database remarks	Estimated transmissivity (gpd/ft)	Aquifer thickness tapped by well(ft)	Estimated hydraulic conductivity (ft/d)
Childress	1223501	210	12	183-210	313BLIN	-44.25	700	35.75	19.6	water level 80 ft while pumping 700 gpm	26,250	166	21.2
	1224303	320	16	20-320	313BLIN		600	20	30.0	water level 20 ft while pumping 600 gpm	46,700	300	20.8
	1224305	317	14	92-317	313BLIN	-30	900	145	6.2	water level 175 ft while pumping 900 gpm	8,400	287	3.9
	1224607	120	16	70-120	313BLIN	-59.57	1,100	30	36.7	30 ft ddn while pumping 1100 gpm	60,000	90	89.1
	1224810	226	16	119-226	313BLIN	-36.79	700	10	70.0	10 ft ddn while pumping 700 gpm for 4-5 hrs	128,000	189	90.4
	1240404	270	16	30-270	313BLIN	*-80*	1,100	72	15.3	72 ft ddn while pumping 1100 gpm	28,500	190	20.1
	1240506	312	16	15-312	313BLIN	*-95*	700	90	7.8	90 ft ddn while pumping 700 gpm for 2 days	14,400	217	8.9
	1240509	297	14	128-297	313BLIN	-89.75	1,000	140	7.1	140 ft ddn after pumping 1000 gpm for several	9,400	207	6.1
	1240605	120	18	50-120	313BLIN	-34.44	1,300	17	76.5	17 ft ddn after pumping 1300 gpm for one wee	165,000	86	257.8
Collingsworth	562419	130	16	0-90	313BLIN	-80	120	25	4.8	25 ft ddn after pumping 120 gpm for 4 hrs	6,600	50	17.6
	562504	180	12	40-180	313BLIN	-44.3	500	30.7	16.3	30.7 ft ddn while pumping 500 gpm	23,500	136	23.2
	562608	108	12		313BLIN	-71	390	2	195.0	2 ft ddn while pumping 390 gpm	357,000	37	1,289.8
	562616	113	7	53-113	313BLIN	-74	15	25	0.6	25 ft ddn after pumping 15 gpm for 2 hrs	750	39	2.6
	562618	120	5	100-120	313BLIN	-73	8	7	1.1	7 ft ddn after pumping 8 gpm for 24 hrs	1,900	47	5.4
	562705	183	4	155-183	313BLIN	-86.8	2	0.4	5.0	0.4 ft ddn while pumping 2 gpm	7,350	96	10.2
	562803	143	12	93-143	313BLIN	-114.2	320	35	9.1	35 ft ddn while pumping 320 gpm	12,300	29	57.1
	562804	157	12	107-157	313BLIN	-69.4	360	15	24.0	15 ft ddn while pumping 360 gpm	16,700	88	25.5
	562810	220	14	100-220	313BLIN	-70.1	1,210	24	50.4	24 ft ddn while pumping 1,210 gpm	79,500	150	70.9
	562905	150	16	70-150	313BLIN	-99.8	750	3	250.0	3 ft ddn while pumping 750 gpm	445,000	50	1,185.0
	562907	220	12	160-220	313BLIN	-108	1,000	2	500.0	2 ft ddn while pumping 1000 gpm	980,000	112	1,169.7
	562910	225	14		313BLIN	-119.4	600	45	13.3	45 ft ddn while pumping 600 gpm	18,200	106	23.0
	563907	93	12	72-93	313BLIN	-30	500	30	16.7	30 ft ddn while pumping 500 gpm	24,000	63	50.9
	1205702	160			313WTRS	-116.7	3	3	1.0	3 ft ddn while pumping 3 gpm	1,200	43	3.7
	1205703	152			313WTRS	-111.7	4	16.7	0.2	16.7 ft ddn while pumping 4 gpm	200	40	0.7
	1206201	43			313BLIN	-15.7	1,180	14	84.3	14 ft ddn while pumping 1,180 gpm	140,000	27	685.5
	1206811	212	16	162-202	313WTRS	-41.2	400	158	2.5	158 ft ddn after pumping 400 gpm for 24 hrs	4,100	171	3.2
	1212303	160			313WTRS	-100.4	2	4	0.5	4 ft ddn while pumping 2 gpm	800	60	1.8
	1213102	56			313WTRS	-24.8	2	4.7	0.4	4.7 ft ddn while pumping 2 gpm	420	31	1.8
	1213202	71			313WTRS	-44.1	2	6.5	0.3	6.5 ft ddn while pumping 2 gpm	300	27	1.5
	1213204	93			313WTRS	-70.4	2	14.4	0.1	14.4 ft ddn while pumping 2 gpm	90	23	0.5
	1213502	100	6	70-100	313WTRS	-58.8	3	8.3	0.4	8.3 ft ddn while pumping 3 gpm	430	41	1.4
	1213802	104			313WTRS	-96.8	2	3	0.7	3 ft ddn while pumping 2 gpm	820	7	15.2
	1214302	150	6	135-150	313BLIN	-98.8	4	0.4	10.0	0.4 ft ddn while pumping 4 gpm	16,000	51	41.8
	1214307	124			313BLIN	-95.7	3	1.4	2.1	1.4 ft ddn while pumping 3 gpm	2,800	28	13.2
	1214413	100	5	80-100	313WTRS	-40	8	20	0.4	20 ft ddn after pumping 8 gpm for 8 hrs	550	60	1.2
	1214706	210	5	190-210	313BLIN	-90	30	25	1.2	25 ft ddn after pumping 30 gpm for 6 hrs	1,800	120	2.0
	1214801	90	6	50-90	313WTRS	-52.9	6	1	6.0	1 ft ddn while pumping 6 gpm	9,000	37	32.4
	1214916	125	12	95-125	313BLIN	-87.5	600	10	60.0	10 ft ddn while pumping 600 gpm	99,000	38	352.9
	1214923	177	12	97-177	313BLIN	-60.5	760	20	38.0	20 ft ddn while pumping 760 gpm	60,000	117	68.8
	1214924	210	16	18-210	313WDCB	-72.5	1,000	14	71.4	14 ft ddn while pumping 1,000 gpm	113,000	138	109.9
	1215108	90	6	70-90	313WTRS	-66.2	4	1.8	2.2	1.8 ft ddn while pumping 4 gpm	2,500	24	14.0
	1215201	128	12	98-128	313WTRS	-31.63	600	49	12.2	49 ft ddn while pumping 600 gpm	17,000	96	23.6
	1215225	104	8	20-104	313WTRS	-17.1	45	38	1.2	38 ft ddn while pumping 45 gpm	1,400	87	2.2
	1215402	50			313WTRS	-26.3	2	0.7	2.9	0.7 ft ddn while pumping 2 gpm	3,800	24	21.4
	1215509	205	16	0-205	313BLIN	-70.4	500	105	4.8	105 ft ddn while pumping 500 gpm	5,600	135	5.6
	1215801	170	12	153-170	313BLIN	-40	700	80	8.8	80 ft ddn while pumping 700 gpm	11,800	130	12.1
	1215803	311	12	190-311	313BLIN	-49.9	550	8	68.8	8 ft ddn while pumping 550 gpm	115,000	261	58.9
	1215904	85			313WTRS	-66.5	3	11.7	0.3	11.7 ft ddn while pumping 3 gpm	240	19	1.7
	1216503	125			313WTRS	-38.1	100	80	1.3	80 ft ddn while pumping 100 gpm	1,350	87	2.1

Appendix A. Summary of Blaine Aquifer system specific capacity data and hydraulic conductivity estimates

County	State well #	Well depth (ft)	Casing size (in)	Screen interval	Aquifer	Water level	Reported pumping rate (gpm)	Corresponding drawdown (ft)	Specific capacity (gpm/ft)	TWDB database remarks	Estimated transmissivity (gpd/ft)	Aquifer thickness tapped by well(ft)	Estimated hydraulic conductivity (ft/d)
Donely	559903	147	5	127-147	313WTRS	-119.16	3	40	0.07	40 ft ddn after pumping 2.75 gpm for 1 hr	5	27.84	0.02
	560802	206	5	186-206	313WTRS	-128.68	8	20	0.40	20 ft ddn while pumping 8 gpm	25	77.32	0.04
Fisher	2931604	40	5	15-35	313BLIN	-7.23	5	35	0.14	35 ft/5 gpm (spec. capacity: 0.14 gpm/ft)	125	32.77	0.51
Hall	1218707	200			313ARTS	-75	1,000	50	20.00	50 ft ddn while pumping 1,000 gpm	29,500	125	31.55
	1236102	185			313ARTS	-173.4	20	20	1.00	20 ft ddn after pumping 20 gpm for 5 hrs	1,250	11.6	14.41
	1244602	212			313ARTS	-115	15	80	0.19	80 ft ddn after bailing 15 gpm for 4 hrs	180	97	0.25
Hardeman	1333202	210			313BLIN	-93	6	112	0.05	112 ft ddn after pumping 6 gpm for 2 hrs	30	117	0.03
	1344907	46			313BLIN	-22	100	17	5.88	17 ft ddn after pumping 100 gpm for 36 hrs	10,700	24	59.60
King	2214704	80	13	37-77	313BLIN	-37	20	40	0.50	40 ft ddn after pumping 20 gpm for 72 hrs	750	43	2.33
Wheeler	546704	200	7	140-200	313BLIN	-118	20	22	0.91	22 ft ddn after pumping 20 gpm for 1 hr	1,100	82	1.79
	547502	50	10	0-30	313WTRS	-8.7	250	36	6.94	36 ft ddn while pumping 250 gpm	9,000	41.3	29.13

ft = feet
in = inches
gpm = gallons per minute
gpd = gallons per day
ft/d = feet per day
ddn = drawdown

Appendix B

Exclusion area details

Table B-1. Public water supply well exclusion areas

PWS label	Name
G0230002A	CITY OF QUITAQUE
G0230002B	CITY OF QUITAQUE
G0230002C	CITY OF QUITAQUE
G0230003A	TPWD CAPROCK CANYON STATE PARK
G0440001A	WELLINGTON MUNICIPAL WATER SYSTEM
G0440001B	WELLINGTON MUNICIPAL WATER SYSTEM
G0440001C	WELLINGTON MUNICIPAL WATER SYSTEM
G0440001D	WELLINGTON MUNICIPAL WATER SYSTEM
G0440002A	DODSON WATER WORKS
G0440002B	DODSON WATER WORKS
G0440016A	RRA SAMNORWOOD WATER SYSTEM
G0440016B	RRA SAMNORWOOD WATER SYSTEM
G0440016C	RRA SAMNORWOOD WATER SYSTEM
G0440016D	RRA SAMNORWOOD WATER SYSTEM
G0440016E	RRA SAMNORWOOD WATER SYSTEM
G0440018A	RRA DODSON WATER SYSTEM
G0440018B	RRA DODSON WATER SYSTEM
G0510001A	CITY OF PADUCAH
G0510001B	CITY OF PADUCAH
G0510001C	CITY OF PADUCAH
G0510001D	CITY OF PADUCAH
G0510001E	CITY OF PADUCAH
G0510001F	CITY OF PADUCAH
G0510001G	CITY OF PADUCAH
G0510001H	CITY OF PADUCAH
G0510001I	CITY OF PADUCAH
G0510001J	CITY OF PADUCAH
G0510001K	CITY OF PADUCAH
G0510001L	CITY OF PADUCAH
G0510004A	KING COTTLE WSC
G0510004B	KING COTTLE WSC
G0510004C	KING COTTLE WSC
G0630012A	CITY OF SPUR
G0630012B	CITY OF SPUR
G0630012C	CITY OF SPUR
G0630012D	CITY OF SPUR
G0630012E	CITY OF SPUR
G0760001A	CITY OF ROBY
G0760012A	SYLVESTER MCCAULLEY WSC
G0760012B	SYLVESTER MCCAULLEY WSC
G0760012C	SYLVESTER MCCAULLEY WSC
G0960001A	RRA ESTELLINE TURKEY WATER SYSTEM
G0960001B	RRA ESTELLINE TURKEY WATER SYSTEM
G0960002A	CITY OF MEMPHIS
G0960002B	CITY OF MEMPHIS
G0960002C	CITY OF MEMPHIS

Table B-1. Public water supply well exclusion areas

PWS label	Name
G0960002D	CITY OF MEMPHIS
G0960002E	CITY OF MEMPHIS
G0960003A	TURKEY MUNICIPAL WATER SYSTEM
G0960003B	TURKEY MUNICIPAL WATER SYSTEM
G0960003C	TURKEY MUNICIPAL WATER SYSTEM
G0960014A	LAKEVIEW WSC
G0960014B	LAKEVIEW WSC
G1320001A	CITY OF JAYTON
G1320001B	CITY OF JAYTON
G1350001A	RRA GUTHRIE DUMONT WATER SYSTEM
G1350001B	RRA GUTHRIE DUMONT WATER SYSTEM
G1350001C	RRA GUTHRIE DUMONT WATER SYSTEM
G1730001A	CITY OF MATADOR
G1730001B	CITY OF MATADOR
G1730001C	CITY OF MATADOR
G1730001D	CITY OF MATADOR
G1730002A	CITY OF ROARING SPRINGS
G1730002B	CITY OF ROARING SPRINGS
G1730002C	CITY OF ROARING SPRINGS
G1730002D	CITY OF ROARING SPRINGS
G1730002E	CITY OF ROARING SPRINGS
G1730003A	FLOMOT WATER ASSOCIATION
G1730005A	ROARING SPRINGS RANCH CLUB INC
G1730006A	ROARING SPRINGS YOUTH CAMP
G1770002AM	CITY OF SWEETWATER
G1770002AN	CITY OF SWEETWATER
G1770002AO	CITY OF SWEETWATER
G1770007A	BITTER CREEK WSC SOUTH
G1770007B	BITTER CREEK WSC SOUTH
G2170002A	SWENSON WSC
G2170002B	SWENSON WSC
G2170002C	SWENSON WSC
G2170002D	SWENSON WSC
G2420001A	SHAMROCK MUNICIPAL WATER SYSTEM
G2420001B	SHAMROCK MUNICIPAL WATER SYSTEM
G2420001F	SHAMROCK MUNICIPAL WATER SYSTEM
G2420001G	SHAMROCK MUNICIPAL WATER SYSTEM
G2420001H	SHAMROCK MUNICIPAL WATER SYSTEM
G2420001I	SHAMROCK MUNICIPAL WATER SYSTEM
G2420001J	SHAMROCK MUNICIPAL WATER SYSTEM
G2420001K	SHAMROCK MUNICIPAL WATER SYSTEM
G2420007A	KELTON ISD
G2420007B	KELTON ISD
G2420012A	SHADY ACRES TRAILER PARK
G2420015A	NINE MILE STATION CAFE

Table B-2. City exclusion areas

City	County
Childress	Childress
Dodson	Collingsworth
Wellington	Collingsworth
Paducah	Cottle
Dickens	Dickens
Spur	Dickens
Hedley	Donley
Roby	Fisher
Rotan	Fisher
McLean	Gray
Lakeview	Hall
Memphis	Hall
Quanah	Hardeman
Hamlin	Jones
Jayton	Kent
Matador	Motley
Roaring Springs	Motley
Sweetwater	Nolan
Aspermont	Stonewall
Shamrock	Wheeler

Table B-3. Populated places exclusion areas

Populated place name	County
Quitaque	Briscoe
Abington	Childress
Arlie	Childress
Carey	Childress
Kirkland	Childress
Loco	Childress
Smithdale	Childress
Tell	Childress
Aberdeen	Collingsworth
Dozier	Collingsworth
Lutie	Collingsworth
Marilla	Collingsworth
Quail	Collingsworth
Rolla	Collingsworth
Samnorwood	Collingsworth
Baker	Cottle
Chalk	Cottle
Coleyville	Cottle
Delwin	Cottle
Dunlap	Cottle
Ginsite	Cottle
Hackberry	Cottle
Narcisso	Cottle
Ogden	Cottle
Sneedville	Cottle
Swearingen	Cottle
Afton	Dickens
Croton	Dickens
East Afton	Dickens
Gilpin	Dickens
Glenn	Dickens
Steele Hill	Dickens
Giles	Donley
McKnight	Donley
Bernecker	Fisher
Busby	Fisher
Capitola	Fisher
Claytonville	Fisher
Cross Roads	Fisher
Eskota	Fisher
Fisher	Fisher
Gannon	Fisher
Hitson	Fisher
Hobbs	Fisher
Longworth	Fisher
McCaulley	Fisher

Table B-3. Populated places exclusion areas

Populated place name	County
North Roby	Fisher
Palava	Fisher
Pledger	Fisher
Reynolds	Fisher
Roby	Fisher
Royston	Fisher
Sardis	Fisher
Scotts Corner	Fisher
Sylvester	Fisher
Fairmont	Floyd
Gray Mule	Floyd
Brice	Hall
Eli	Hall
Estelline	Hall
Hulver	Hall
Lesley	Hall
Newlin	Hall
Parnell	Hall
Plains Junction	Hall
Plaska	Hall
South Brice	Hall
Tampico	Hall
Turkey	Hall
Acme	Hardeman
Carnes	Hardeman
Goodlett	Hardeman
Lazare	Hardeman
Middleburg	Hardeman
North Groesbeck	Hardeman
Punkin Center	Hardeman
Seven L Crossing	Hardeman
Talbert Crossing	Hardeman
Wheatland	Hardeman
Williams	Hardeman
Willowview	Hardeman
Clairemont	Kent
Girard	Kent
Harmony	Kent
Corner Windmill	King
Dumont	King
Finney	King
Grow	King
Guthrie	King
Flomot	Motley
Folley	Motley
Northfield	Motley

Table B-3. Populated places exclusion areas

Populated place name	County
Russellville	Motley
Avenger Village	Nolan
Grimes	Nolan
Herndon	Nolan
Orient	Nolan
Shaufler	Nolan
Tecifie	Nolan
Tesco	Nolan
Toland	Nolan
Jacobs	Rusk
Hudd	Scurry
Double Mountain	Stonewall
Flat Top	Stonewall
Old Glory	Stonewall
Peacock	Stonewall
Red Bluff Crossing	Stonewall
Swenson	Stonewall
Benonine	Wheeler
Fuller	Wheeler
Kelton	Wheeler
Lela	Wheeler
Norrick	Wheeler
Pakan	Wheeler
Ramsdell	Wheeler
Twitty	Wheeler

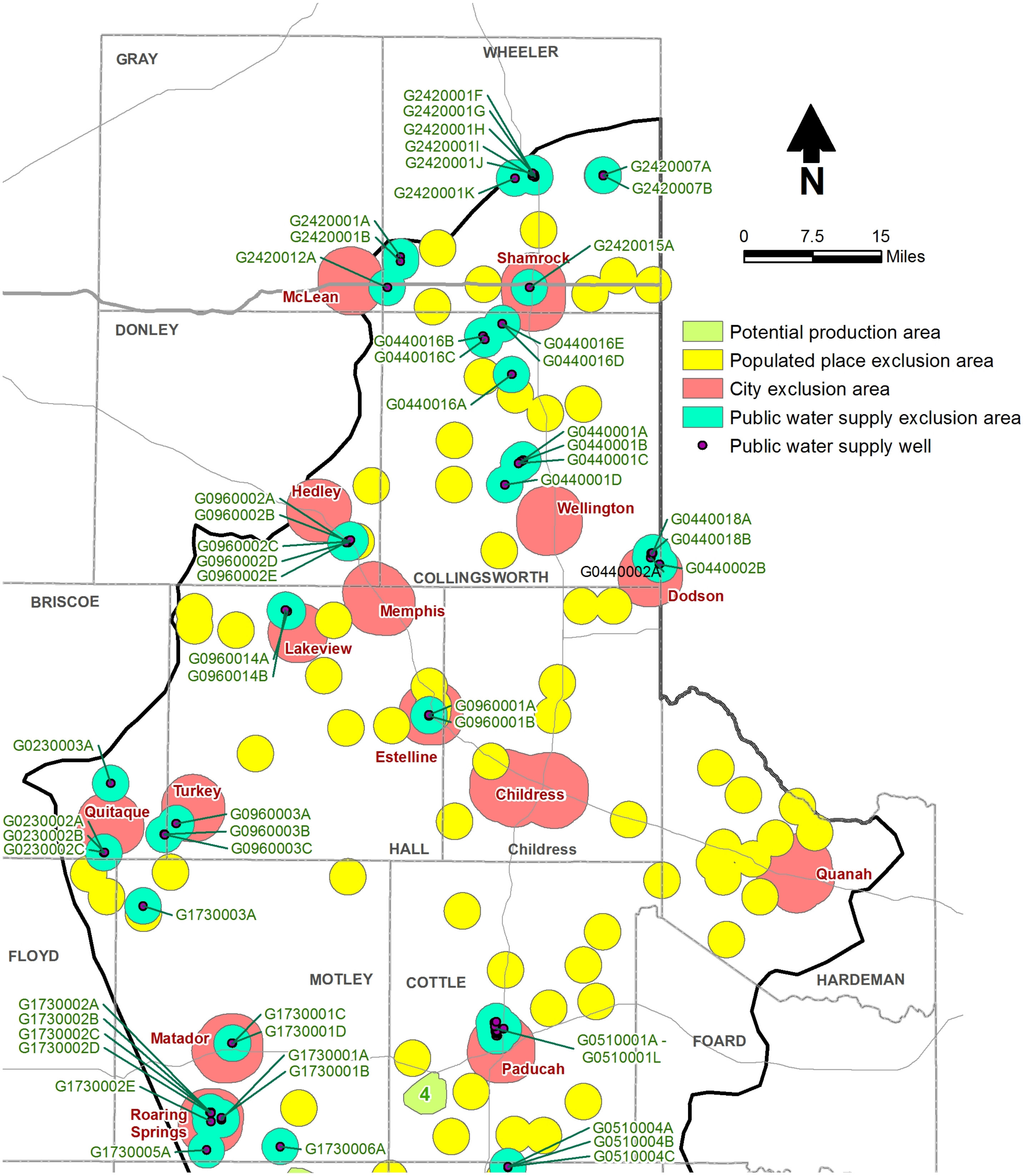

Figure B-1. Exclusion areas for public supply wells, cities and populated places

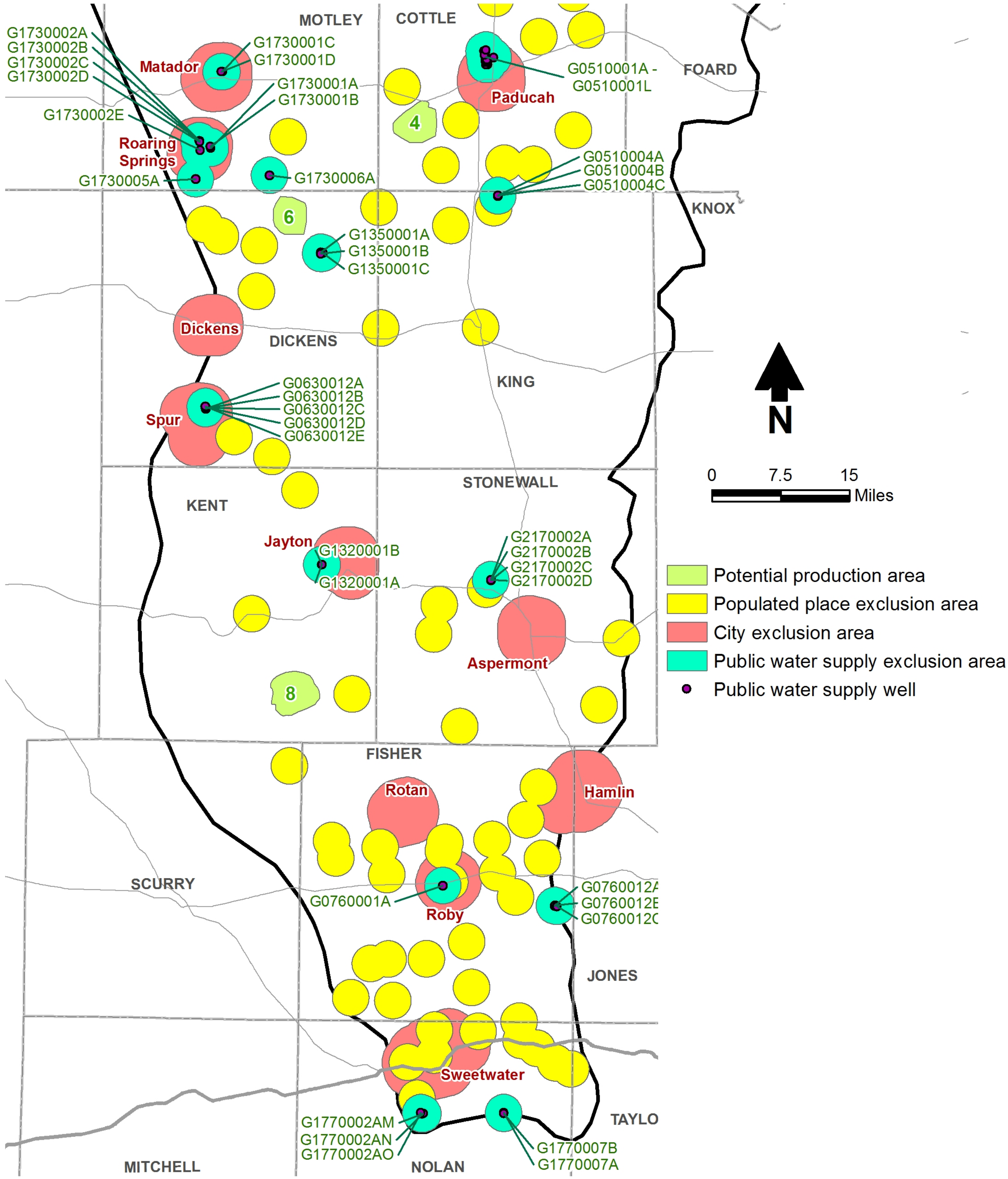

Figure B-2. Exclusion areas for public supply wells, cities and populated places

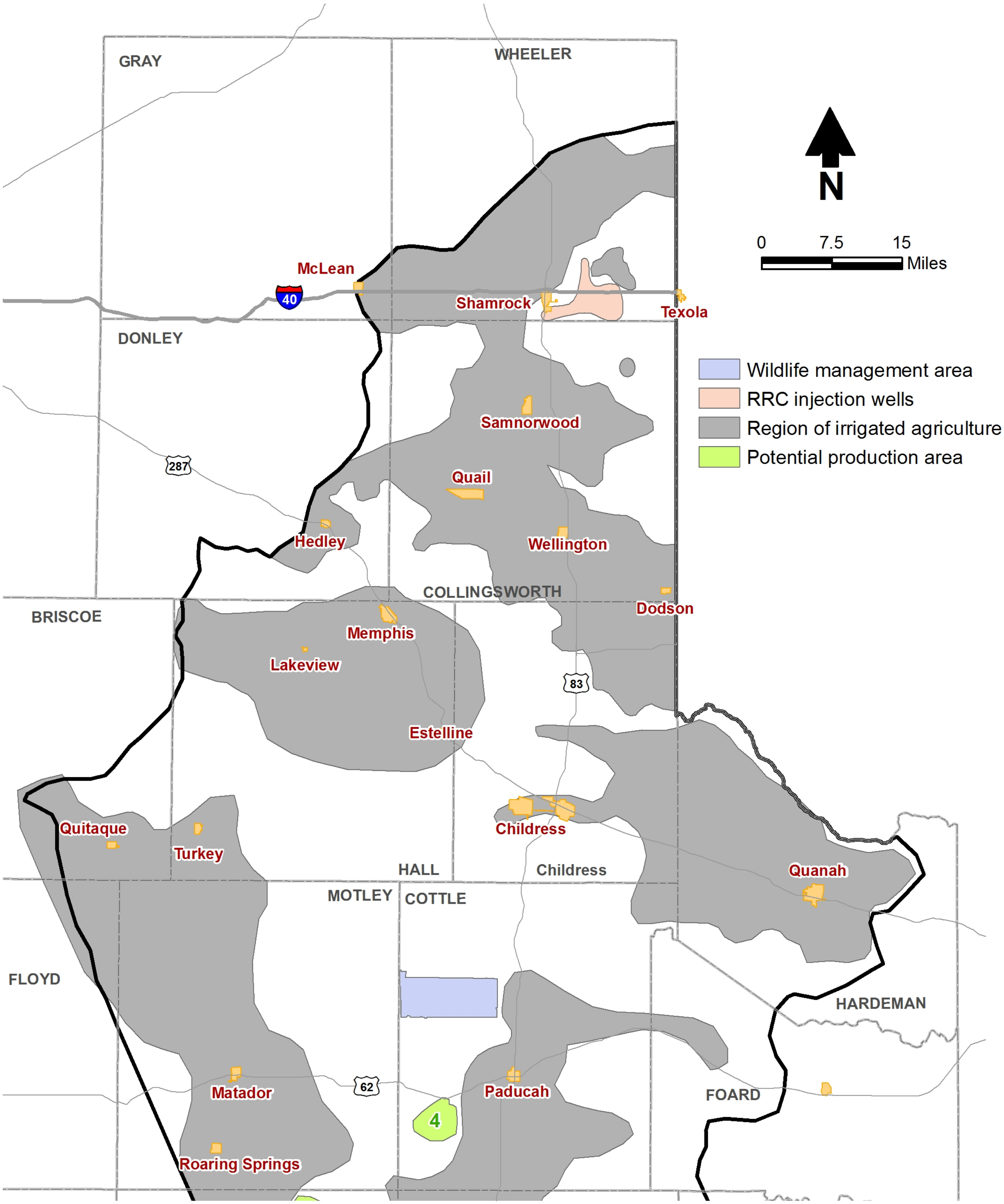

Figure B-3. Exclusion areas for irrigated igriculture, RRC injection wells, and wildlife wanagement area

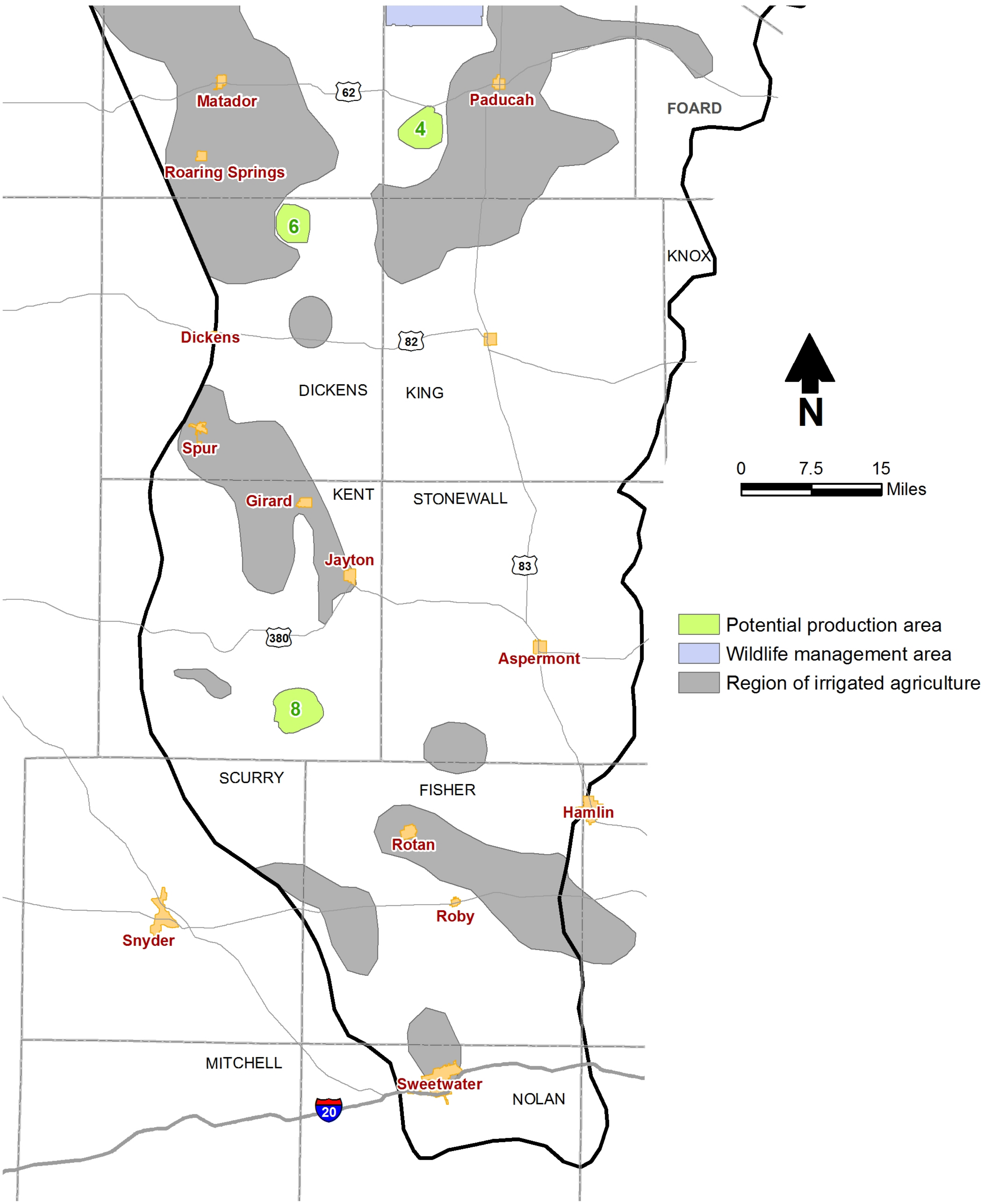

Figure B-4. Exclusion areas for irrigated igriculture, RRC injection wells, and wildlife wanagement area

Appendix C

Description of GIS files

Appendix C. Description of GIS files

File name	Description	File Type
Study_area.shp	Blaine aquifer study area boundary.	Polygon shapefile
Counties.shp	County boundaries	Polygon shapefile
Highways.shp	Highway lines from ESRI data	Polyline shapefile
Cities_detail.shp	City layer extracted from ESRI data urban_dtl file.	Polygon shapefile
Cities.shp	City layer extracted from ESRI data cities_local file.	Polygon shapefile
TWDB_RWPAs_2014.shp	TWDB Regional Water Planning Areas	Polygon shapefile
Groundwater_Management_Areas_08_26_15.shp	TWDB Groundwater Management Areas	Polygon shapefile
TWDB_GCDs_Nov_2015.shp	TWDB Groundwater Conservation Districts	Polygon shapefile
Major_aquifers.shp	TWDB minor aquifer	Polygon shapefile
Minor_aquifers.shp	TWDB major aquifers	Polygon shapefile
Blaine_StudyAreaGAT.shp	GAT Geology File	Polygon shapefile
Well_with_Blaine_Formation_pick.shp	Point file of wells with Blaine formation picks	Point shapefile
TDLR_TWDB_Wells.shp	Point file of wells designating TDLR wells from TWDB wells	Point shapefile
b_Blaine	Base of Blaine elevation formation (ft msl)	ESRI GRID raster
d_b_Blaine	Depth to the Base of Blaine elevation formation (ft)	ESRI GRID raster
Well_with_TDS.shp	Well with TDS value > 0	Point shapefile
Water_Quality_TDS_from_Duffin_and_Beynon_1992.shp	TDS contoured from Duffin and Benyon report (1992)	Polygon shapefile
Brine_emission_wells.shp	Brine emission wells digitized from Duffin and Benyon	Polyline shapefile
Wells_used_for_hydrographs.shp	Wells used for hydrographs on map	Point shapefile
wle_Blaine_a	Water level elevation (ft msl) for the Blaine Aquifer	ESRI GRID raster
d_wl_Blaine_a	Depth to water level of the Blaine Aquifer	ESRI GRID raster
Tx_Rivers_Detail_NHD.shp	USGS NHD dataset of Rivers	Polyline shapefile
Springs.shp	Shapefile of Springs	Point shapefile
Tx_Rivers_Detail_NHD_saline.shp	Surface water drainage potentially receiving saline water from the Blaine Aquifer System	Polyline shapefile
Well_with_identified_cavity_location.shp	Wells where a cavity thickness was identified	Point shapefile
Well_with_yield_greater_than_100gpm.shp	Well with well yield exceeding 100 gallons per minute.	Point shapefile
tk_Blaine_a	Thickness of Blaine Aquifer system (ft)	ESRI GRID raster
d_br	Depth to brine interface (ft)1	ESRI GRID raster

ft msl = Feet above mean sea level
ac-ft/yr = Acre-feet per year

Appendix C. Description of GIS files

File name	Description	File Type
Lateral_extent_of_Brine_Interface.shp	Lateral extent of Brine Interface. Used to show on map where Brine interface is below base of Blaine Formation	Polygon shapefile
Brine_Interface_Contours_clip.shp	Brine interface contour (ft msl)	Polyline shapefile
Geophysical_logs_used_to_identify_depth_of_brine_interface.shp	Geophysical log used to identify depth of brine interface	Point shapefile
br_int_elev	Brine interface elevation (ft msl)	ESRI GRID raster
Exclusion_Area_Public_Water_Supply.shp	Exclusion Areas for public water supply wells	Polygon shapefile
Exclusion_Area_Populated_Place.shp	Exclusion Areas for populated places	Polygon shapefile
Exclusion_Area_City.shp	Exclusion Areas for Cities	Polygon shapefile
Exclusion_Area_Wildlife_Management_Areas.shp	Exclusion Areas for Wildlife Management Area	Polygon shapefile
Exclusion_Area_RRC_Injection_Wells.shp	Exclusion Areas for Railroad Commission injection wells	Polygon shapefile
Exclusion_Area_Irrigated_Areas.shp	Exclusion Areas for Irrigated areas	Polygon shapefile
Exclusion_Area_Combined.shp.shp	File merging all exclusion areas into one file	Polygon shapefile
Model_grid	Snap-to-raster of the model grid.	ESRI GRID raster
Potential_Production_Areas.shp	Potential production areas 4, 6, and 8.	Polygon shapefile
Injection_wells.shp	Injection wells	Point shapefile
30y_Drawdown_1000afy_Area4.shp	Simulated drawdown contour for 30 year 1,000 ac-ft/yr drawdown for Area 4	Polyline shapefile
30y_Drawdown_2000afy_Area4.shp	Simulated drawdown contour for 30 year 2,000 ac-ft/yr drawdown for Area 4	Polyline shapefile
30y_Drawdown_3000afy_Area4.shp	Simulated drawdown contour for 30 year 3,000 ac-ft/yr drawdown for Area 4	Polyline shapefile
50y_Drawdown_1000afy_Area4.shp	Simulated drawdown contour for 50 year 1,000 ac-ft/yr drawdown for Area 4	Polyline shapefile
50y_Drawdown_2000afy_Area4.shp	Simulated drawdown contour for 50 year 2,000 ac-ft/yr drawdown for Area 4	Polyline shapefile
50y_Drawdown_3000afy_Area4.shp	Simulated drawdown contour for 50 year 3,000 ac-ft/yr drawdown for Area 4	Polyline shapefile
30y_Drawdown_1000afy_Area6.shp	Simulated drawdown contour for 30 year 1,000 ac-ft/yr drawdown for Area 6	Polyline shapefile

ft msl = Feet above mean sea level
ac-ft/yr = Acre-feet per year

Appendix C. Description of GIS files

File name	Description	File Type
30y_Drawdown_2000afy_Area6.shp	Simulated drawdown contour for 30 year 2,000 ac-ft/yr drawdown for Area 6	Polyline shapefile
30y_Drawdown_3000afy_Area6.shp	Simulated drawdown contour for 30 year 3,000 ac-ft/yr drawdown for Area 6	Polyline shapefile
50y_Drawdown_1000afy_Area6.shp	Simulated drawdown contour for 50 year 1,000 ac-ft/yr drawdown for Area 6	Polyline shapefile
50y_Drawdown_2000afy_Area6.shp	Simulated drawdown contour for 50 year 2,000 ac-ft/yr drawdown for Area 6	Polyline shapefile
50y_Drawdown_3000afy_Area6.shp	Simulated drawdown contour for 50 year 3,000 ac-ft/yr drawdown for Area 6	Polyline shapefile
30y_Drawdown_1000afy_Area8.shp	Simulated drawdown contour for 30 year 1,000 ac-ft/yr drawdown for Area 8	Polyline shapefile
30y_Drawdown_2000afy_Area8.shp	Simulated drawdown contour for 30 year 2,000 ac-ft/yr drawdown for Area 8	Polyline shapefile
30y_Drawdown_3000afy_Area8.shp	Simulated drawdown contour for 30 year 3,000 ac-ft/yr drawdown for Area 8	Polyline shapefile
50y_Drawdown_1000afy_Area8.shp	Simulated drawdown contour for 50 year 1,000 ac-ft/yr drawdown for Area 8	Polyline shapefile
50y_Drawdown_2000afy_Area8.shp	Simulated drawdown contour for 50 year 2,000 ac-ft/yr drawdown for Area 8	Polyline shapefile
50y_Drawdown_3000afy_Area8.shp	Simulated drawdown contour for 50 year 3,000 ac-ft/yr drawdown for Area 8	Polyline shapefile
Area4_well.shp	Hypothetical well location for Area 4 drawdowns	Point shapefile
Area6_well.shp	Hypothetical well location for Area 6 drawdowns	Point shapefile
Area8_well.shp	Hypothetical well location for Area 48drawdowns	Point shapefile
b_blaine_wh	Bottom surface of the Blaine-Whitehorse Formation contacts	ESRI GRID raster
t_cf	Top surface of the Clearfork Formation	ESRI GRID raster
b_seymour	Bottom surface of the Seymour Aquifer	ESRI GRID raster

ft msl = Feet above mean sea level
ac-ft/yr = Acre-feet per year

Appendix D

Executive Administrator's comments on the draft report

Texas Water Development Board
P.O. Box 13231, 1700 N. Congress Ave.
Austin, TX 78711-3231, www.twdb.texas.gov
Phone (512) 463-7847, Fax (512) 475-2053

August 29, 2016

Mr. James Kelsey, President
Daniel B. Stephens & Associates, Inc.
6020 Academy NE, Suite 100
Albuquerque, NM 87109

RE: Research Contract between Daniel B. Stephens & Associates, Inc. and the Texas Water Development Board; TWDB Contract No. 1600011948, Draft Report Comments Entitled ***"Identification of Potential Brackish Groundwater Production Areas – Blaine Aquifer"***

Dear Mr. Kelsey:

Staff members of the Texas Water Development Board (TWDB) have completed a review of the draft report prepared under the above-referenced contract. ATTACHMENT 1 provides the comments resulting from this review. As stated in the TWDB contract, Daniel B. Stephens & Associates, Inc. (DBSA) will consider revising the final report in response to comments from the Executive Administrator and other reviewers. In addition, DBSA will include a copy of the Executive Administrator's draft report comments in the Final Report.

The TWDB looks forward to receiving one (1) electronic copy of the entire Final Report in Portable Document Format (PDF) and six (6) bound double-sided copies. **Please further note, that in compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites), the digital copy of the final report must comply with the requirements and standards specified in statute. For more information, visit http://www.sos.state.tx.us/tac/index.shtml.** If you have any questions on accessibility, please contact David Carter with the Contract Administration Division at (512) 936-6079 or David.Carter@twdb.texas.gov.

DBSA shall also submit one (1) electronic copy of any computer programs or models, and, if applicable, an operations manual developed under the terms of this contract.

If you have any questions concerning the contract, please contact Jean Perez, the TWDB's designated contract manager for this project at (512) 936-4017 or jean.perez@twdb.texas.gov.

Sincerely,

Robert E. Mace, Ph.D., P.G.
Deputy Executive Administrator
Water Science and Conservation

Attachment

c: Jean Perez, TWDB

Attachment 1
TWDB Comments on
Draft Final Report for the Identification of Potential Brackish Groundwater Production Areas – Blaine Aquifer
TWDB Contract No. 1600011948

Deliverables include:

- Blaine DRAFT Completion Report.pdf
- Blaine Aquifer report figures_7-31-2016.pdf
- Appendix A_Specific capacity.pdf
- Blaine 3D Geologic Model 08-02-2016.lfview
- MS Access file TwdbBracsDeliverable.accdb
- Digital files organized in folders DrillerWellLogs and TDLR_SDRs
- Geodatabase: Blaine_Aquifer.mdb

General Comments

1. Please provide all GIS datasets used for figures in the report and the ArcGIS mxd files used to prepare the figures.
2. Please provide an appendix to the report that includes the GIS files provided as a deliverable. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 3 (e).
3. Professional Geoscientist seals, signatures, and dates will be required in the final report.
4. Please ensure all figure captions are thorough and correct. Draft captions (for example: Fig07-2_NW-SE_Hydrogeo_Cross_Sec_Gray_Wheeler_Co_TX) need to be rewritten.

Specific Comments

1. Page 1. First Paragraph. Please list the four aquifers mandated by House Bill 30.
2. Page 2. Second paragraph, third sentence: Please consider replacing “identify” with “evaluate”.
3. Page 2. Fourth Paragraph, first sentence: Please consider replacing “identify” with “evaluate”.
4. Page 3. First Paragraph. Please list the four aquifers mandated by House Bill 30.
5. Page 6. Section 6: Please consider adding subsections such as Very Saline Zone. Table 12-1 lists three classifications (Fresh, Slightly to moderately saline, and Very Saline), but Section 6 discusses two classifications (Fresh to moderately saline and Brine). Please explain why there are differences.
6. Page 8. Table 6-3: Please change Well number # 2N-26W-3cba1 to # 2N-26W-3dbc1.

7. Page 20. Section 12: Please provide tables of groundwater volume subdivided by county, groundwater conservation district, and regional water planning area. Refer to Contract Exhibit B, Task 6.12.

8. Page 20. Section 12: Please explain why a specific yield value of 0.01 was chosen for the groundwater volume calculations.

9. Page 20. Section 12: Please provide a brief rationale for grouping the slightly and moderately saline zones into one category for the groundwater volume calculations.

10. Page 26. Section 14.1: Please include a discussion of how the following categories of water wells that fall within the exclusion definition were used:

    a. TWDB GWDB domestic and public water wells

    b. TWDB GWDB stock (agricultural) water wells

    c. TDLR SDR domestic and public water wells

    d. TDLR SDR stock (agricultural) water wells

    e. GCD domestic, public, and stock water wells

    f. TCEQ water well image files: domestic and public water wells

    g. TCEQ water well image files: stock (agricultural) water wells

11. Page 26. Section 14.1: Please include a discussion of how the diameter values for the exclusion area buffer were determined.

12. Page 26. Section 14.1: Many readers will not have access to GIS that is needed to review the detailed datasets developed for this study. There is tremendous stakeholder interest in the mapped PPAs and exclusion zones. Please provide an appendix to the report that includes:

    a. A table listing each exclusion zone and the reasons for exclusion.

    b. A sufficient number of detailed figures showing the spatial relationship of each numbered exclusion zone.

    c. Include the proposed PPAs on each applicable map.

13. Page 31. Third paragraph, first sentence: Please consider replacing "identified" with "evaluated".

14. Page 28. Section 14.3, first paragraph: Please provide a table showing selected city average annual pumping volumes for the study area to support the following statement: "the range of pumping was selected because it is sufficient to provide all or a significant portion of the water demand for the towns and municipalities within the study area". Please also indicate if calculations account for the potential loss of a certain percentage of pumped water due to desalination concentrate waste or does it assume all water pumped is fresh with no treatment required.

15. Page 28. Section 14.3: Per Contract Exhibit B Task 5, please provide data for the 30-year pumping analysis.

16. Page 28. Section 14.3: Per Contract Exhibit B Task 6.12, please provide groundwater volumes for each PPA by county, groundwater conservation district, and groundwater management area.
17. Page 28. Section 14.3: Please provide the volume of groundwater that each PPA is capable of producing over a 30 and 50 year timeframe per Contract Exhibit B Task 5
18. Page 28. Section 14.3: Please provide all modeling files as a deliverable. The modeling files should include all datasets used in determining input variables for each PPA. Refer to Contract Exhibit B, Task 6, Deliverables, Part 12.
19. Page 28. Section 14.3: Please provide a discussion of the potential impact to water quality based on the PPA pumping scenarios.
20. Page 28. Section 14.3: Please provide a discussion of potential impact to water quantity based on the PPA pumping scenarios. Please indicate if the amount of drawdown in these scenarios are reasonable based on this recharge-driven karstic system.
21. Page 28. Section 14.3: Please provide a discussion of potential impact to fresh groundwater sources based on the 30 and 50 year pumping scenarios.

Figures Comments:

1. Figure 5-2. Please add the source of this data in the figure caption. Please consider listing geologic formations in the legend in stratigraphic (age) order, from youngest at the top to oldest at the bottom.
2. Figure 5-3. Please consider adding the Ogallala, Seymour, and Clear Fork Group. These are mentioned in the report (Section 8.1.2) and some are layers in the Leapfrog dataset but the reader is not provided information about their stratigraphic position.
3. Figure 7-1. Please include definitions of acronyms used in the reference to reports in the figure caption.
4. Figure 8-3. Please add the modifier "static" to the caption "water level map" and state that this data is for the Blaine Aquifer system.
5. Figure 11-2. Please include an index map and north arrow to this figure. Please consider adding karst feature interpretations. Please consider adding a brief description of how air photo and topographic map interpretation led to identification of these karst features.
6. Figure 12-2. Please consider adding county line overlay, a north arrow, and a figure caption that described the salinity zones in terms of TDS ranges and colors.
7. Figure 13-2. Please modify this figure by:
    a. Correcting the legend so elevations are in integers.
    b. Providing a polygon showing the lateral extent of the brine interface where it occurs above the base of the Blaine Aquifer System.
    c. If there is an area where the brine interface surface is not known with certainty, use a polygon symbol to represent this. For example, the elevation data in Fisher and Nolan counties appear to be questionable.

d. Please modify the caption to more clearly state that the contours are in feet above the base of the Blaine Aquifer System.

8. Figures 5-4, 8-3, and 13-2. Please consider including additional figure for each map using a scale in depth below ground surface.

9. Figure 6-3. Please consider making the figure more legible.

10. Figures 7-2, 7-3, and 7-4. Please consider making the figures more legible.

11. Figure 8-2. Please consider including a line connecting the data points for the individual hydrographs

12. Figures 14-6, 14-7, and 14-8. Please consider adding exclusion zones so that the reader can understand the spatial relationship of the impact in these areas. Please number these exclusion areas so that the reader can link each areas to an exclusion zone listed in the appendix.

13. Table 6-1. Please use colors for each salinity zone in this table. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 5 (c).

14. Figure 6-1. Please use colors for each salinity zone in this table. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 5 (c). In addition, the well symbols can be improved by omitting the black circle borders.

15. Page 13. Section 8.2, second bullet. Please define the "313" aquifer code referenced.

16. Page 15. Section 9.1: Please provide a more detailed discussion of and insert equations to derive transmissivity from specific capacity using the re-written Cooper-Jacob solution. Please consider including an example using a set of data from this study.

17. Page 18. Table 12-1: Please indicate the upper end of salinity for the Very Saline Zone that was used in the volume calculation.

18. Page 25. Section 14. Please provide a discussion on the assumptions and limitations of the Theis solution used in this study. Please consider that the Theis solution assumes a confined, homogeneous, isotropic, and uniform thickness aquifer.

Data comments:

1. Table tblBracs_ForeignKey. Please append well owner name/number for all wells with this information. For example, the 943 records from the Railroad Commission collection of oil and gas geophysical well logs and a subset of the 646 TDLR SDR well reports may have an owner well number or name assigned.

2. Table tblGeophysicalLogs_Header. Please provide a table. Please append the 24 geophysical well logs collected from the Railroad Commission of Texas (Section 8.4 of the draft report). Please append these records in the location table and foreign key tables. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 7.

3. Table tblGeophysicalLogs_Suite. Please provide table. Please append the geophysical well log tools (including top and bottom depth of tool recordings) from the 24 geophysical well logs collected from the Railroad Commission of Texas. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 7.

4. Please provide the 24 digital geophysical well logs obtained from the Railroad Commission of Texas in a folder system named with state and county codes. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 1 (d) (iii).

5. Please submit well reports (if available; if not, scanned data from the report) associated with well records obtained from the USGS (13 wells: report USGS OF 82-90) and TWC (18 wells: report TWC_MR_63_02) and append records to the table called tblBracsWaterWellReports.

6. Table tblBracs_AqufierTestInformation. Please append aquifer properties to the table. Sources of this information include:

   a. Refer to Appendix A of the draft report

   b. TDLR SDR wells (646) collected for this study

7. Table tblWell_Geology. Please append the top depth, bottom depth, thickness, and stratigraphic name of each geologic formation evaluated in the study to this table. There are no well records with a geologic_pick value of stratigraphic in the table. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 9 (a).

8. Table tblWell_Geology. Please incorporate data mentioned in Section 8.1.2 (describes the stratigraphic analysis performed) and shown in Figures 5-4 and 8-1 (BEG and TDLR well control used for stratigraphic analysis).

9. Table tblWell_Geology. Please append the top depth, bottom depth, thickness, and lithologic name of each geologic strata evaluated to this table. There are no well records with a geologic_pick value of lithologic in the table.

10. The following GIS raster files may be corrupt. These do not load in ArcGIS v. 10.2 and the file cannot be previewed in ArcCatalog:

    a. B_blaine

    b. Br_interface

    c. Swl

    d. Tk_blaine

11. Please provide a snap grid file in an ArcGIS raster format. The GIS model grid file is in a polygon shape file format. Refer to Contract Exhibit G BRACS Program Contract Data Requirements Section 3 (c) and Contract Exhibit B, Task 6.12.

12. GIS files must have a map projection as specified in Contract Exhibit G BRACS Program Contract Data Requirements Section 3 (b). The following GIS files have a different map projection:

    a. Karst_formations

    b. Modelgrid

13. Class II injection well dataset used for the study (Figure 14-3). This information was used to determine exclusion areas for potential production areas.

a. Database table. The 943 wells were added to the BRACS Database location table with most of the data listed in the field [remarks]. Please provide the "remarks" data in a separate related table with fields for each data type to facilitate use.

b. Please provide GIS point file that includes well numbers, latitude and longitude, and the well attributes parsed into fields from the field [remarks] noted on point 13 (a)

14. Please submit the GIS raster formation surfaces (top and bottom) developed for the Blaine Aquifer System. These may include:

    a. Seymour Formation (applicable portions that overlie the Blaine)

    b. Whitehorse Group

    c. Flowerpot Shale

    d. Clear Fork Group

    e. Blaine Aquifer system

    f. Any other formation surfaces prepared for this study

15. GIS file naming conventions are specified in Contract Exhibit G BRACS Program Contract Data Requirements Section 3 (d) and Contract Exhibit B, Task 6.12. Please apply this naming convention to GIS datasets.

16. Please submit GIS polygon shape files for the potential production areas.

17. Please submit GIS point file used to create Figure 8-1 (BEG and TDLR wells used for stratigraphic analysis).

18. Section 8.2. Please provide the water level elevation georeferenced maps prepared for this study from:

    a. Stevens and Hardt (1965)

    b. Garza (1982)

    c. Smith (1970)

    d. Cronin (1972)

    e. Maderak (1972, 1973)

    f. Popkin (1973, 1973a)

19. Section 13.3. Please include log analysis and data parameters used to map the brine interface in a BRACS Database table with appropriate field descriptions and key fields.

20. Because this analysis is unique to this aquifer (and region of Texas) it may require a custom table linked to the BRACS Database table tblGeophysicalLog_Header (analysis is based on a geophysical log in the BRACS collection) so it will require the key fields [well_id] and [gl_number] at a minimum.

21. Section 11.2. The geodatabase provided as a deliverable contained a polyline shapefile named karst_features. Please confirm this shapefile is the sinkhole dataset described in the report.

22. Section 11.1. Please provide a GIS file of cavities shown on Figure 11-3.

23. Section 11.1. Please append cavities data to the table tblWell_Geology. If additional data fields are necessary to fully attribute these features, prepare a custom table.

24. Section 8.3. Please provide a GIS file of the springs as shown on Figure 10-4.

25. Section 8.2. Please make sure the static water level data was obtained from TDLR SDR wells for the table new_tblBracs_SWL. Please indicate in Section 8.2, if these data points were used to prepare Figure 8-3. If not, please provide a discussion of why this data was not used.

26. Figure 8-3 was prepared using static water level point data. Please provide a GIS point shapefile of this dataset that includes the well number (state_well_number; track_number), static water level, and date of measurement.

27. Section 12. Please provide GIS files used calculate the groundwater volumes after dividing the study area into 2-dimensional areas based on a salinity classification (fresh; slightly + moderately saline; very saline).

    a. Well point shapefile reflecting the water quality salinity zone

    b. Salinity zone polygon shapefile

    c. Individual salinity zone raster surfaces (top and bottom) for each classification:

        i. Fresh (0 to 1,000 mg/L TDS)

        ii. Slightly to moderately saline (1,000 to 10,000 mg/L TDS)

        iii. Very saline (> 10,000 mg/L TDS)