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# FLOW AND SALINITY PATTERNS IN THE LOW-TRANSMISSIVITY UPPER PALEOZOIC AQUIFERS OF NORTH-CENTRAL TEXAS

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## ABSTRACT

**Paleozoic aquifers of north-central Texas may become an important source of groundwater, particularly for use in the production of natural gas from the Barnett Shale in areas where the more prolific Cretaceous Trinity aquifer does not exist. Relatively little is known about those aquifers. In order to further their characterization, there is a need to understand the regional flow system and to develop a conceptual groundwater-flow model. We collected flow-parameter information from data available in the public domain. Sandstone bodies likely to host groundwater in extractable quantities were identified by integrating outcrop sandstone maps and subsurface well-log data. Aquifer hydraulic properties were derived from mostly domestic-well specific-capacity data. Regional flow pattern was derived using multi-year wintertime groundwater-level observations. Surface-water and groundwater Cl concentrations and Cl/Br ratios were examined to assess their interaction. County estimates of distributed recharge were determined using a Cl mass-balance approach.**

**Hydraulic conductivity averages 0.5 to 1.5 ft/day. Higher-than-usual surface-water salinity (>1000 mg/L) originates further upstream; salinity decreases in the downstream direction to <100 mg/L and does not impact aquifers. Groundwater salinity in the Paleozoic aquifers increases northwest to southeast, from younger to older formations, with a reversal and fresher water in those formations in contact with the Trinity aquifer, suggesting that the Trinity aquifer recharges the Paleozoic system through cross-formational flow. Average distributed recharge into the Paleozoic aquifers amounts to 0.1 in/yr. Overall, Paleozoic aquifers represent a shallow-flow system, mostly unconfined and discontinuous, with general flow toward the northeast, mostly discharging into streams and rivers, and receiving water input through limited distributed recharge and likely from the overlying Trinity aquifer, where present.**

## INTRODUCTION

In recent years, rapid development of natural gas production from the Barnett Shale has brought to the forefront the requirement for water for the extraction of hydrocarbons using hydraulic fracturing (HF) (Nicot, 2012; Nicot and Scanlon, 2012; Nicot et al., 2012a). The entire Barnett Shale's footprint in north-central Texas includes Cretaceous formations to the east and Paleozoic formations to the west (Fig. 1), but historically gas production has been concentrated in the core area where formations of Cretaceous age crop out (Fig. 2). Drilling has recently progressed to condensate-rich areas north of the play (Montague County) and could eventually extend into areas west of the play core. The study area comprises (1) Clay, Montague, Jack, Wise, Palo Pinto, Parker, Erath, and Hood counties (a total of ~7000 mi$^2$) in which hydrocarbon production and water use could become significant and (2) nearby Wichita, Archer, Young, Stephens, Eastland, and Comanche counties, which are unlikely to be areas of Barnett Shale production but were nevertheless studied to fully characterize the Paleozoic aquifer system (Fig. 1).

HF currently uses about 3 to 5 million gallons of water per Barnett well, and water use for gas production in the region is projected to rise in the next 20 or more years. In the study area, surface-water supplies are constrained by available water rights. More plentiful groundwater supplies are only available to the east of the study area—in the Cretaceous Trinity/Woodbine aquifers that have been heavily used for many decades (Harden et al., 2004) and west of the study area in the Seymour/Blaine aquifers (Ewing et al., 2004). Paleozoic aquifers of north-central Texas have not been subjected to systematic studies and many basic characteristics of their flow system remain unknown. In particular, groundwater flow and salinity trends and their genesis within the Paleozoic aquifers are poorly understood despite the fact that thousands of water wells have tapped these aquifers. Of these wells, most are domestic, but some within Montague County are



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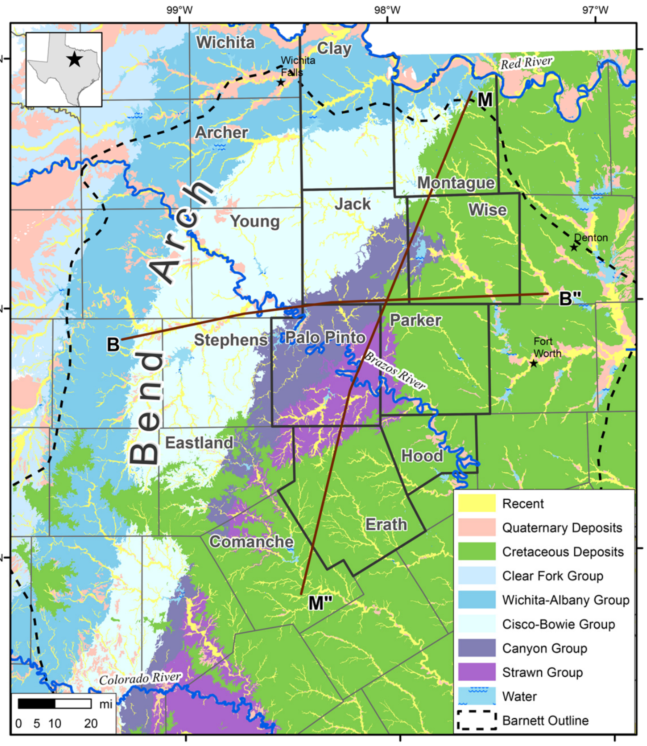



**Figure 1. Simplified geologic map from 1:250,000 Geologic Atlas of Texas (GAT) sheets. Names of counties in the study area and boundaries of those counties most likely to see expansion of Barnett shale production are bolded. Boundaries of the Barnett Shale Formation footprint also depicted with a dotted line (Pollastro et al., 2007). Bend Arch and cross-sections of Figure 5 shown. Quaternary deposits consist of alluvium along rivers and of the Seymour Formation elsewhere.**

larger municipal wells. Investigating the feasibility of using the Paleozoic aquifers for additional water supply is of practical interest, in particular for use during drought when surface-water supply declines quickly and more users rely on groundwater.

Useful insights can be gained through numerical modeling of a groundwater flow system to assess, for example, sustainable yield. However, before a numerical model can be constructed, a general understanding of the regional groundwater flow pattern is needed to develop the conceptual flow model that guides its construction. Topography, land use, climate, and geology influence groundwater flow with complex interrelations that translate into heads, fluxes, and salinity distribution in both groundwater and surface water. Several observable parameters act as constraints on the conceptual model. For example, a common characteristic of Paleozoic formations is a relatively abrupt transition from fresh to brackish and saline waters. It follows that evaluation of salinity distribution may help define groundwater flow patterns. Salinity of aquifers is influenced by a combination of factors, such as recharge, rock-water interaction, evaporite dissolution, or mixing with deeper saline formation water. River salinity has been studied intensively and many researchers have demonstrated the connection between groundwater salinity and river salinity (e.g., Moore et al., 2008). Understanding salinity sources and variations is also important in recharge estimation using the Cl mass-balance method (Scanlon et al., 2002).

The objective of our study is to gain greater insight into the Paleozoic aquifers of the study area by answering three fundamental questions: (1) What is the general groundwater flow direction? (2) What are the evolving patterns of salinity in surface water and groundwater? Salinity in the Paleozoic formations increases greatly in the downdip direction of each formation and is much higher than that in the neighboring Trinity aquifer. (3) How large and discontinuous is the regional flow system, and how does it interact with neighboring flow systems? In order to achieve this general objective, we focused on the following, more narrowly defined goals: (1) determine the general extent of the aquifer system components, (2) quantify aquifer hydraulic properties, (3) establish the regional pattern of groundwater flow, (4) examine salinity profiles in surface water and groundwater and describe surface-water–groundwater interactions, and (5) provide recharge estimates. The observations and tools used to achieve these goals were (1) sandstone-distribution and structural maps in the public domain, (2) readily available and abundant specific-capacity data, (3) aquifer groundwater-level data observed both aerially and in vertical section and hydrochemical analyses, (3) Cl concentration and Cl/Br ratio, and (4) a Cl mass-balance approach.

## STUDY AREA

The area of study has been defined in terms of counties (Fig. 1); here we refined it by introducing topographic and geological features. Paleozoic aquifers in the study area are associated with Pennsylvanian (mostly) and Permian formations to the east of the Bend Arch, which separates the Fort Worth Basin from the Midland Basin (Fig. 1). The north limit of the study area is defined by the Red River, a major hydrologic feature. Outcrops of the Trinity Formation loosely mark the eastern limit of the study area as we extended the aquifer limits beneath the Trinity aquifer (Fig. 2). To the south, Trinity Formation remnants form a topographic high and a hydrologic divide and mark the southern boundary of the study area (Fig. 2).

### Surface Characteristics

The study area's climate is classified as subtropical subhumid (Larkin and Bomar, 1983). Long-term annual precipitation

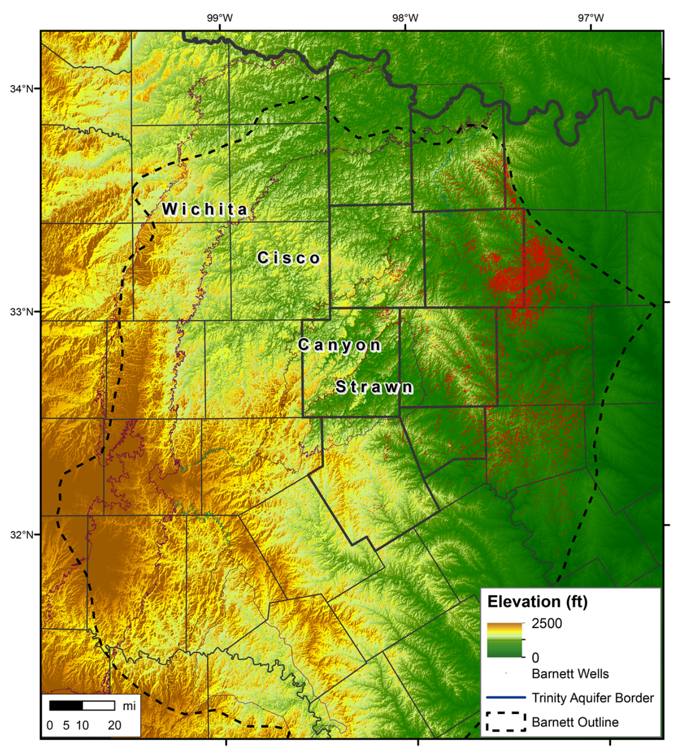



**Figure 2. Topography (feet above sea level) (U.S. Geological Survey, http://ned.usgs.gov/). Total of 18,146 wells shown (red dots), 516 of which are outside of Trinity footprint. The Barnett Shale core area is delineated by the high well density in Wise and neighboring (Denton and Tarrant) counties.**

averages ~700 mm/yr, and much of the precipitation is derived from thunderstorms in May and October. The Red River and Brazos River are major perennial streams in the study area. The main channels of those rivers are aligned perpendicular to the Paleozoic outcrop belts (Fig. 1). Land use and land cover types in the study area include grassland (50%), woodland (27%), cultivated land (12%), and urban (7%) (Fig. 3). Overall, the area is dominated by rangeland and forest, the latter particularly in Jack, Palo Pinto, and Erath counties. Elevation generally decreases toward the north and east, interrupted by rivers valleys (Fig. 2). About 70 documented springs, mostly seeps, exist in the Paleozoic outcrop area (Heitmuller and Reece, 2003) and are located either along the contacts between Paleozoic formations or along river valleys.

## Geology and Stratigraphy

North-central Texas is a large, mature petroleum province, and its geology is thus well studied (e.g., Wermund and Jenkings, 1969; Hentz, 1988; Brown et al., 1990). Thickness of the formations of interest in the study area decreases toward the west (Fig. 4). The complex stratigraphy has resulted in an imprecise and inconsistent nomenclature. We followed that used in 1:250,000 Geologic Atlas of Texas (GAT) sheets and in Bureau of Economic Geology publications from the 1970s and 1980s (Proctor et al., 1970; Brown et al., 1972; McGowen et al., 1972, 1991; Kier et al., 1976; Hentz et al., 1987). Pennsylvanian strata comprise fluvial, deltaic, interdeltaic, and shelf deposits derived from nearby mountainous areas uplifted during the Ouachita Orogeny (Brown et al., 1990). Self-edge reefs and slope and basinal terrigenous clastics exist to the west of the study area. Pennsylvanian sediments mark a change from earlier platform-related depositional environments and comprise, from older to younger, the Bend, Strawn, Canyon, and Cisco groups, overlain by the Cisco (Pennsylvanian/Permian) and Permian Wichita-Albany groups.

The Strawn Group overlies rocks from the Lower Pennsylvanian (clastics from the Bend/Atoka Group) that do not crop out in the study area. It generally consists of alternating sandstone and shale layers that were deposited in mostly deltaic and some marine environments. Deposition occurred during a period of relatively high sedimentary input from multiple delta complexes sourced from the Ouachita and Arbuckle mountains to the east and north of the study area, as documented on net-sandstone maps (Cleaves and Erxleben, 1982).

As source-area uplift decreased and erosion progressed, sediment input declined and a generally carbonate- and mud-rich environment persisted throughout deposition of the Canyon Group (Erxleben, 1975), which contrasts with the higher percentage of coarse siliciclastics in the overlying Cisco Group and the underlying Strawn Group. The sandstone facies that do occur in the Canyon succession include valley-fill, distributary-channel-fill, and delta-front deposits mostly related to the Perrin delta system in Jack and Wise counties (Erxleben, 1975, their Figure 6; Cleaves and Erxleben, 1982).

Uplift of the Ouachita Mountains increased again in the Upper Pennsylvanian, leading to active deposition of the sandstone-rich Cisco Group, which is dominated by fluvial-deltaic sediments with beds of limestone, shale, mudstone, and conglomerate (Hentz, 1988; Brown et al., 1990). Cisco-equivalent continental rocks in Montague and Clay counties (Bowie Group) are primarily fluvial in origin (Hentz, 1988).

Strata from the Lower Permian Wichita-Albany Group (Wolfcamp and Leonard series) are composed of highly heterogeneous open marine, marginal marine, and continental facies of interstratified mudstones, carbonates, and sandstones (Hentz, 1988) with regionally discontinuous mappable sandstone bodies.

The Clear Fork Group (not included in the study but mapped in Figure 1) displays signs of decreased clastic sediment input, with shale deposition and thin beds of limestone, marl, dolomite, anhydrite, gypsum, and sandstone. Clear Fork Group and younger formations contribute to saline seeps and springs. Paleozoic strata dip to the west in the southern half of the study area and change dip direction to the northwest to the north of the study area (Wermund and Jenkins, 1969; Hentz, 1988) (Figs. 1 and 5). Eastward-dipping Cretaceous strata of the Trinity aquifer unconformably overly the Paleozoic section.

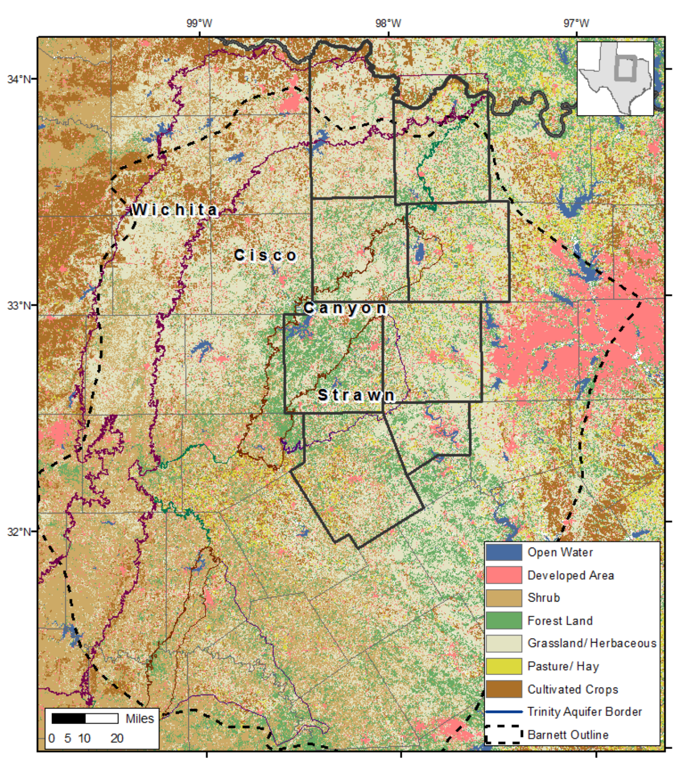


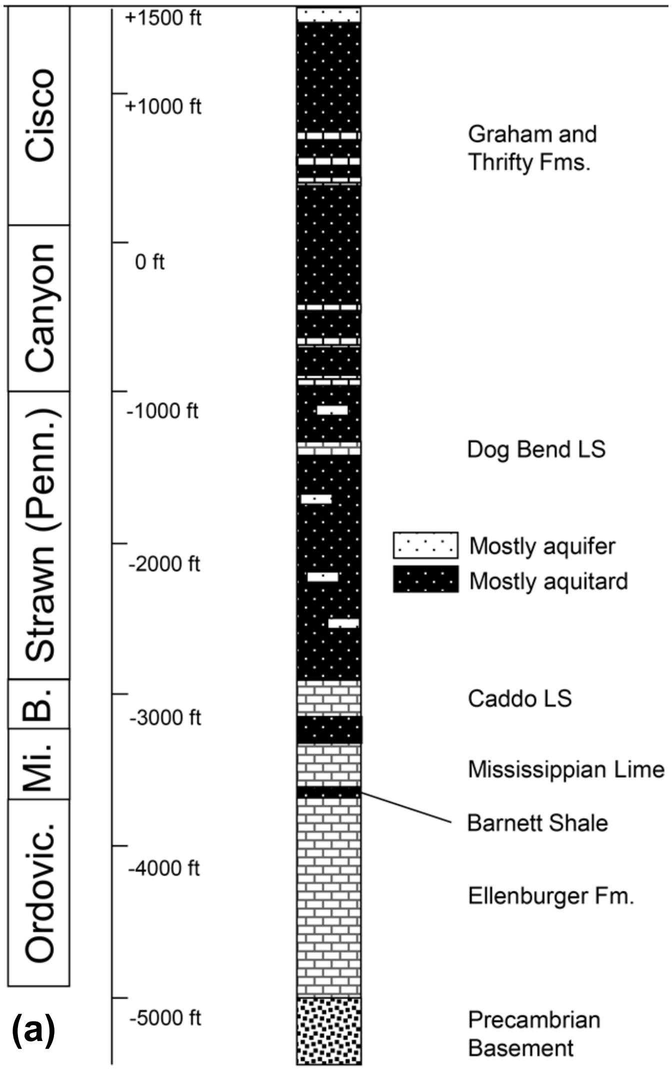

**Figure 3. Land use (U.S. Geological Survey, http://www.usgs.gov/pubprod/data.html#data).**

## Hydrostratigraphy

From a hydrostratigraphic standpoint, sandstone units in the Paleozoic succession are spatially highly discontinuous. At the regional scale, they occur as sandstone lenses—some are areally extensive enough to have been mapped on 1:250,000-scale geological maps (GAT sheets). Many are unnamed, although dozens can be followed in outcrop for a least a significant fraction of a county length. For example, sandstones of the Mineral Wells Formation (Strawn Group) and Graham and Thrifty formations (Cisco Group) yield small quantities of water. Most water-bearing sandstone bodies are limited in dip extent, with water quickly becoming brackish; hence, the most likely flow direction is down the topographic gradient, which is along strike. Limestones of the Palo Pinto Formation (Canyon Group) are also water bearing, with accessible water present mostly in fractures. These beds are likely in hydrogeologic connection with the nearby Possum Kingdom reservoir. The limestones originated as carbonate mudstones and strike-oriented banks (Erxleben, 1975) and have not been exposed to extended surficial conditions and regional karstification. Discontinuity is a characteristic of the hydrogeology of Paleozoic formations, and the extent of regional connectivity remains an open question. In outcrop, Paleozoic strata are generally undeformed and unfaulted. In this study, each geological group was treated as a single hydrogeological unit.

## PREVIOUS WORK

The Paleozoic aquifers were noted in several earlier works assessing saline groundwater resources in the state (Winslow and Kister, 1956; CLI, 1972). The fact that these reports are still cited in recent work (e.g., Alley, 2003) is witness to the lack of recent studies. From 1960 through the 1990s, the Texas Water Development Board (TWDB) studied groundwater occurrence in



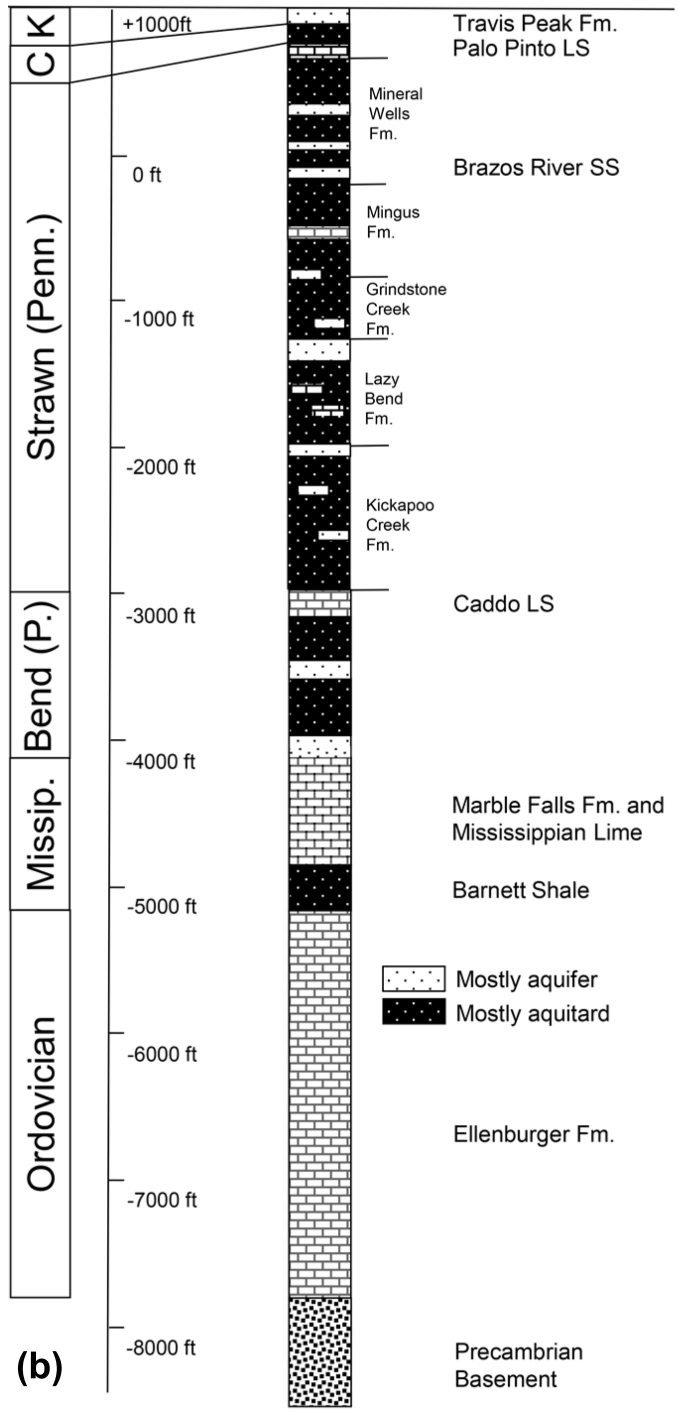




**Figure 4. Generalized stratigraphic columns in (a) Stephens County where it meets Throckmorton and Young counties and (b) Parker County where it meets Jack and Wise counties. Ordovic. = Ordovician; Mi. = Missip. = Mississippian; Penn. = P. = Pennsylvanian; Fm. = formation; LS = limestone; C = Canyon; K = Cretaceous; and SS = sandstone.**

the Paleozoic aquifers on a county-by-county basis or in a few blocks of counties (Bayha, 1964, 1967; Morris, 1967; Thompson, 1967; Walker, 1967; Preston, 1969, 1970, 1978; Price et al., 1983; Nordstrom, 1988, Duffin and Beynon, 1992; Preston et al., 1996). Study scope in most cases was limited to an inventory of groundwater wells, estimation of extraction rates, and groundwater-quality sampling. Most studies noted discontinuous zones of low permeability and "erratic" occurrence of groundwater, regarding these as characteristic of the Paleozoic formations. Although some of the Paleozoic formations were recognized as potentially good sources of fresh water and saline water, flow patterns were not described. Some studies noted oil field brine contamination prior to 1961 as a result of brine disposal in unlined pits (McMillion, 1965) or leaky wells. The major modeling efforts undertaken by TWDB to model the state's aquifers included analysis of the Trinity aquifer (Harden et al., 2004) and aquifers to the west of the Bend Arch (Permian-age Blaine Formation; Ewing et al., 2004). Ewing et al. (2004) included some formations of the Wichita-Albany Group in their study of the Quaternary Seymour Formation.

## METHODS

In addition to inspection of land use and topographic maps, the study focused on four elements to develop a conceptual flow model: estimating aquifer hydraulic properties from specific-capacity data and sand fraction maps, mapping regional groundwater flow through groundwater-level observations, identifying salinity pattern in surface water and groundwater, and estimating recharge using the Cl mass-balance method.

### Data Sources and Compilation

Publicly available datasets were used in the study. Surface geology is from the GAT sheets. Top and bottom elevation of the layers and sand-fraction maps were scanned, digitized, and

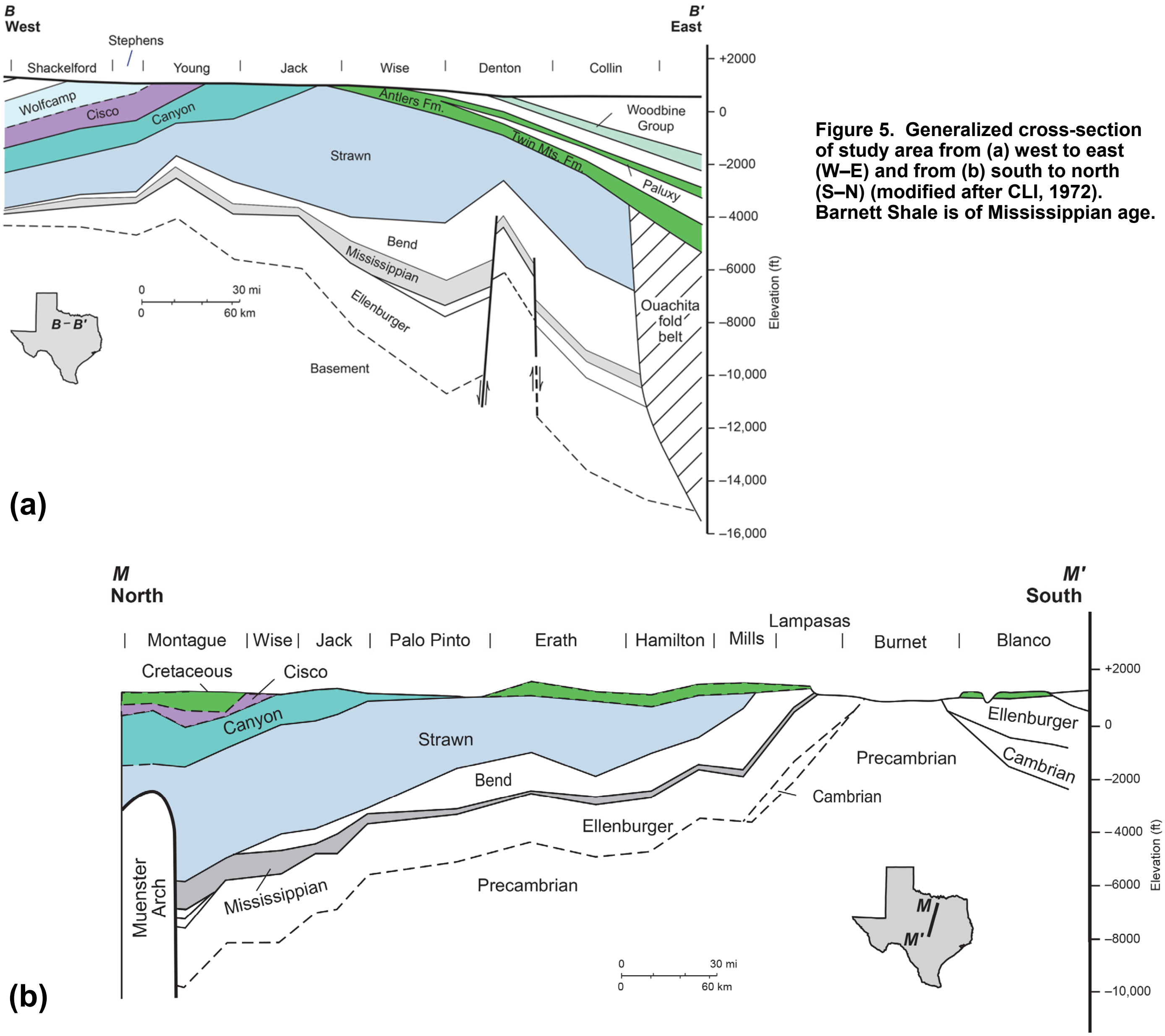



**Figure 5. Generalized cross-section of study area from (a) west to east (W–E) and from (b) south to north (S–N) (modified after CLI, 1972). Barnett Shale is of Mississippian age.**

georeferenced from previous studies (Wermund et al., 1962; Erxleben, 1975; Nordstrom, 1982; Brown et al., 1990). No well logs were directly examined; only derivative data were used. A CLI (1972) study allowed for an independent overall check of formation thickness and also provided inferred total dissolved solids (TDS) contour lines (50,000 and 100,000 mg/L) from borehole geophysical logs, but in a relatively sparse well network.

Specific-capacity data and well information were obtained from records of state agencies: the Texas Commission for Environmental Quality (TCEQ) and TWDB. Estimating transmissivity and conductivity from specific-capacity data is not as accurate as multi-well time-drawdown data analysis but is a viable alternative in areas with few pumping tests. The mostly handwritten records for early specific-capacity tests and then scanned records were compiled into a spreadsheet, screened for incomplete and dubious entries, and imported into a GIS environment. Well locations lacking accuracy (most wells) were assigned to the centroid of the 2.5-minute U.S. Geological Survey quadrangle to which they belong. After careful examination, a total of 2474 out of 4995 specific-capacity measurement points were retained for further processing. Groundwater-level data for the Paleozoic aquifers were obtained from the TWDB groundwater database (TWDB, 2012). Each well was assigned to a stratigraphic unit (group). Well-completion intervals were compared against the developed top and bottom elevations of each geological group to check for consistency. Multiple-completion wells were excluded from the selection to avoid complicating groundwater-level interpretation. A total of 1,270 wells were retained: 922 in the Cisco Group, 237 in the Canyon Group, 72 in the Wichita Group, and 39 in the Strawn Group.

Surface-water Cl concentrations were obtained from the Surface Water Quality Monitoring Information System (SWQMIS) database (TCEQ, 2012). The database contains about 9000 monitoring stations statewide. Stream water-quality monitoring stations in the entire Paleozoic outcrop area as well as in the Trinity outcrop were selected. To avoid biased sampling, only stations that were designed for general-purpose routine measurements were selected. To correct for spatial bias, only one station was selected randomly at each sub-watershed level (Seaber et al., 1987). A total of 245 stations have surface-water Cl concentration measurements collected from the period 1968 through 2011.

Groundwater Cl and Br concentrations were obtained from the groundwater database (TWDB, 2012). Cl concentration

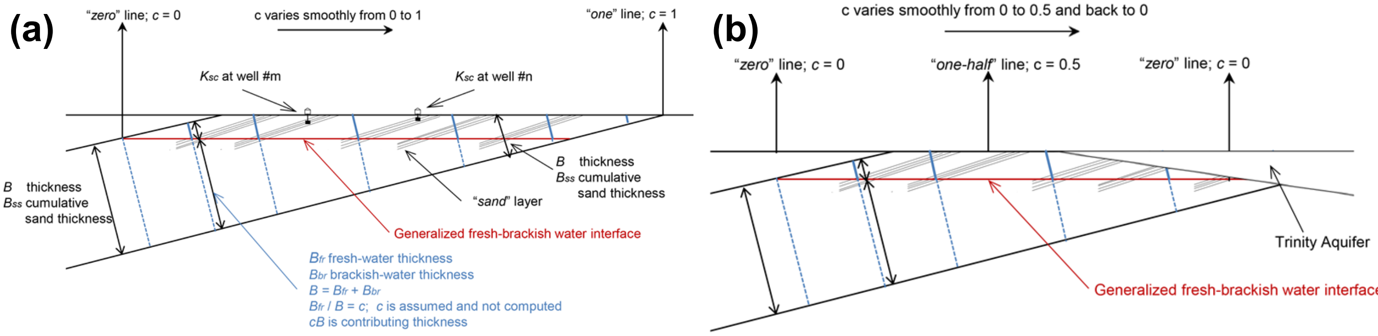



**Figure 6. (a) Diagram describing methodology to assess hydraulic conductivity (note the vertical exaggeration, dip is <1°). $K_{sc}$ is conductivity from specific-capacity tests, $B$ is the thickness of the unit (here a model layer) that decreases to 0 at the onset of the outcrop, $B_{ss}$ is the cumulative sandstone thickness, $B_{fr}$ is the thickness of the fresh-water zone, $B_{br}$ is the thickness of the brackish/saline-water zone, $c$ is the contributing coefficient that varies smoothly from 0 to 1 (see text). (b) Sketch is applied to the Strawn Group only and shows the modified approach to account for the presence of the Trinity Aquifer (see text).**

measurements were obtained from 4946 wells located in the Paleozoic aquifers (1341 wells) and the Trinity aquifer (3605 wells). A subset of 815 wells has Br concentration measurements. Measurements span from 1923 through 2011 for a total of 722 wells in the Trinity aquifer and 93 wells in the Paleozoic aquifers.

## Estimating Hydraulic Conductivity and Transmissivity from Specific-Capacity Data

Transmissivity and conductivity ($K_{sc}$) values estimated from specific-capacity data based on the Theis non-equilibrium equation (Mace, 1997, 2001) are only valid very locally in the vicinity of the well screen. Only a large number of measurements can provide a regional perspective. Combining results from the specific-capacity analysis with sandstone-thickness maps for each geological group ($B_{ss}$ is overall sand thickness for a group) guided the contouring of regional conductivity distribution. Sandstone-thickness maps were used as a reference in developing hydraulic-conductivity contour lines, under the assumption that a higher sandstone content would mean a higher hydraulic conductivity (Dutton et al., 2001; Nicot et al., 2004). Regional hydraulic conductivity ($K$) contour lines were then drawn manually on the basis of derived hydraulic conductivity $K_{sc}$ data points posted on sand-thickness maps ($K = f(K_{sc}, B_{ss})$).

However, hydraulic conductivity was also assumed to drop sharply where fresh water transitions to brackish, as documented in CLI (1972) under the assumption that groundwater >10,000 mg/L TDS is not actively recharged. Thus, portions of the study area with elevated groundwater TDS are omitted from the active groundwater flow system and not considered part of the hydrogeologic conceptual model. Assuming the brackish/fresh water interface is mostly horizontal, the thickness of the formation contributing to the aquifer decreases downdip (Fig. 6). Transmissivity of the entire layer is then $K \times (B_{ss} / B) \times c$ where $B$ is the thickness of the layer at that particular location, $c$ is defined as the *contributing coefficient*, and $B \times c$ is the *contributing thickness*. The contributing coefficient accounts for the presence of brackish water at relatively shallow depth. Its value varies from 1 where the contact with the underlying model layer intersects the surface to 0 where the entire thickness of the hydrogeological unit is brackish and goes through a maximum in between. To compute $c$, we defined a zero and a one line for each group (Fig. 6). The zero line was drawn in the subcrop west of the outcrop guided by but short of the 50,000 mg/L TDS (where $c$ vanishes to 0). The one line corresponds to the eastern edge of the outcrop (where $B$ vanishes to 0 as well). Each point in between the two lines is assigned a contributing coefficient >0 and <1 interpolated in the dip direction, using inverse-distance weighting within the GIS tool (Fig. 6). The contributing coefficient $c$ times the nominal thickness $B$ of the group represents the contributing thickness component of transmissivity. Note that the contributing coefficient $c$ is *assumed* and is not calculated from the actual depth to the fresh-brackish water interface. We followed a similar approach with the Strawn Group (Fig. 6b) but assigned it two zero lines on both sides of the outcrop whose axis corresponds to the one line. One zero line exists to the west in the downdip direction, similar to the pattern with the other formation. The other zero line occurs to the east, which is underneath by the Trinity aquifer, to account for likely flow exchange with the Trinity aquifer. The assumption of even spatial distribution of sandstones in each of the groups is a limitation of the approach.

## Groundwater Levels

Collected data show that water levels were not measured regularly in wells and the coverage of groundwater-level data for a particular month or year was sparse. In order to assess groundwater-level change with time, well hydrographs with more than five measurements were selected to identify time trends. Groundwater-level contours were developed using wintertime (November to March) measurements. Pumping in wintertime for irrigation and municipal use is at minimum so its impact on groundwater level is minimized.

## Hydrochemistry

In this work, water salinity is represented by Cl concentrations because Cl is commonly measured and is the primary anion contributing to salinity in this region. Cl has been used as a tracer for flow studies because it is generally conservative. Cl can be derived from marine salts through atmospheric deposition (precipitation and dryfall) or from salt-bearing minerals (by processes such as halite dissolution). Anthropogenic sources in the shallow subsurface include brine contamination from petroleum production and agricultural sources. Similar to Cl, Br behaves generally as a conservative element in natural waters. Cl/Br ratios are commonly used as a diagnostic tool. They can be indicative of anthropogenic effects such as agricultural runoff on groundwater systems, or of natural processes such as evaporite dissolution or mixing with deeper formation water (Davis et al., 1998). Ocean water has relatively uniform Cl and Br concentrations with a Cl/Br mass ratio of ~290 (Fontes et al., 1986; Davis et al., 1998). Halite dissolution will produce a rapid increase in Cl/Br ratios (1000 to 10,000; Richter and Kreitler, 1986) with an increase in Cl concentration, whereas evaporative brines are commonly enriched in Br, translating into smaller Cl/Br ratios. We conducted a spatial analysis of Cl and Br concentrations and Cl/Br mass ratios in order to assist in regional groundwater flow interpretation.

## Recharge

The Cl mass-balance method has been widely used to estimate groundwater recharge (e.g., Wood and Sanford, 1995;

Scanlon et al., 2002). Cl concentrations in precipitation in the study area were obtained from the National Atmospheric Deposition Program (NADP, 2010). To account for dry fallout, Cl concentrations in precipitation were doubled, a calculation consistent with total Cl fallout based on pre-bomb $^{36}Cl/Cl$ ratios at Amarillo, Texas (Scanlon and Goldsmith, 1997). Cl concentration in groundwater was obtained from the TWDB database (TWDB, 2012). Cl concentrations used for recharge estimation were limited to the measurements in the period from 1951 through 2000. Cl hot spots (Cl > 500 mg/L) were excluded from the Cl mass-balance recharge computations because not representative of natural, background chloride levels. As demonstrated later, those hot spots are not linked directly to the effect of precipitation recharge. The study area was divided into 11 recharge zones, on the basis of land use, geology, and hydrology. A mean value in each zone was used to represent average groundwater Cl concentration in that zone.

## RESULTS

### Formation Geometry

We delineated sandstone bodies likely to host groundwater in extractable quantities by integrating outcrop sandstone maps and subsurface well-log data within a structural context. Initially, the four groups that comprise the Paleozoic section of north-central Texas (i.e., Strawn, Canyon, Cisco-Bowie, and Wichita-Albany) were delineated in GIS from the GAT sheets (Pearson, 2007).

The Strawn Group posed the greatest challenge to map in the subsurface because (1) it is unconformably overlain by Cretaceous-age Trinity aquifer, which limits the Strawn outcrop area to a roughly 25 mi × 50 mi portion of southeast Palo Pinto County, and (2) subsurface mapping (Cleaves, 1975) is limited to the west of the outcrop zone; thus, no subsurface data are available for the Strawn subcrop where the Strawn aquifers could be in hydrologic continuity with the base of the Trinity aquifer. We use the Dog Bend Limestone base (near the top of the Strawn Group) to infer the dip of the Strawn top. The areal extent of the Canyon Group subcrop to the west of the outcrop zone was extrapolated using a structural contour map of the Home Creek Limestone at the top of the Canyon succession (Wermund and Jenkins, 1969; Erxleben, 1975). The Cisco and Wichita-Albany groups subcrop to the west of their respective outcrops were computed using trigonometry—considering the width of the outcrop and assuming a constant regional dip. A dip of 0.5 degrees was estimated using the Home Creek Limestone top structural contour map (Wermund and Jenkins, 1969).

Subsurface sandstone distribution for the Strawn, Canyon, and Cisco Groups was compiled from maps constructed from well log analyses by Cleaves (1975), Erxleben (1975), and Brown et al. (1987). Data are lacking for the Wichita Group; therefore, we inferred subsurface sandstone distribution from the surface sandstone mapping of Hentz and Brown (1987) and the conceptual sedimentary depositional model of Hentz (1988).

Strawn sandstone content (Fig. 7a1) exhibits an overall decrease from the Red River toward the south, partly determined by the areal extent of the Bowie delta system in Clay and Montague counties and the Perrin delta in Jack, Parker, Palo Pinto, and Wise counties. Several smaller bayhead deltas deposited sands in a southeast-northwest direction in southeast Palo Pinto, Hood, and Erath counties (Cleaves, 1975; Brown et al., 1990). Canyon sandstone content (Fig. 7a2) is related to the Henrietta delta system in Clay and Wichita counties and to the Perrin system that persisted in Jack and Young counties. The former is far downdip from the outcrop, whereas the latter has a clear impact on salinity contour lines (CLI, 1972). The Cisco depositional system (Fig. 7a3) is dominated by the Bowie delta complex in Clay, Montague, Wise, and Jack Counties, with abundant fluvial sandstones. The salinity contour lines suggest that little of the confined Cisco is not brackish or saline. However, the "50,000 mg/L" contour line demonstrates the impact of the Perrin delta in the lower Cisco. The Wichita-Albany Group (Fig. 7a4) also displays abundant fluvial sandstone.

### Hydraulic conductivity distribution

We computed hydraulic conductivity distribution of the different geological units using net-sandstone maps, thickness of the fresh-water section, and conductivity estimated from specific-capacity measurements. Those wells in the compiled well database show a median diameter of ~4.5 in, a screen length of 35 ft, and a median depth of ~200 ft. The median discharge rate during the capacity test is ~11 gal/min. Hydraulic conductivity derived from the specific-capacity data varied greatly across the region: 5th and 95th percentiles are 0.03 and 10 ft/day, and median value is 0.6 ft/day. One location has an anomalous hydraulic conductivity as high as ~1000 ft/day in a Canyon Group limestone in Palo Pinto County near the Possum Kingdom reservoir. The four groups share similar median hydraulic conductivity values at ~0.5 to 1.5 ft/day. Ewing et al. (2004, his Figures 4.6.8 and 8.1.4) assigned a uniform conductivity of 2.6 ft/day to the Wichita-Albany Group that was later calibrated to 0.52 ft/day. Non-model-calibrated, estimated spatial distributions of hydraulic conductivity are shown in Figure 7. Conductivity contour lines for the Strawn Group (Fig. 7a2) are extrapolated from the Perrin delta and from smaller lateral deltas for the part overlaid by Trinity deposits. The conductivity distribution in the Canyon Group (Fig. 7b2) denotes the northwest-southeast along-strike grain of the carbonate strata with the limited downdip extent of the fresh-water zone, whereas along-dip elements of the Perrin delta allow for the deepest downdip penetration of fresh water in the study area. The Cisco Group's conductivity (Fig. 7b3) follows the orientation of the continental Bowie deposits, whereas Figure 7b4 illustrates the generally higher conductivity of continental deposits of the Wichita-Albany Group. The transmissivity map presented in Figure 8 accounts for the variable contributing thickness of the aquifers.

### Head Distribution and Regional Groundwater Flow

Of 1270 Paleozoic wells with some records, only 65 have more than five groundwater-level measurements. A visual inspection of their hydrographs indicated ~50% do not display systematic time variations, 25% show an upward time trend, 10% show a downward time-trend, and the rest are indeterminate as a result of time-data scarcity (Fig. 9). Hydrographs of two wells with observational data going back to the 1960s illustrate gradual groundwater-level increases (Fig. 10). These increases might be caused by increased precipitation in the region in the sampling period, or, more likely, by changes in land use and land cover (Scanlon et al., 2005). Generalized groundwater-level contours were created using multiyear wintertime (November through March) groundwater-level observations (Fig. 11). Note that groundwater withdrawal amounts are limited to ~18,000 ac-ft/yr (Nicot et al., 2012b) with pumping centers to the north of the study area but this current effort did not analyze their distribution in detail. Although local variations exist because of dynamics in aquifer groundwater levels, the general groundwater flow direction is along strike towards the northeast, with higher heads in interfluvial areas and lower heads in valleys.

### Salinity Variation in Surface Water and Groundwater

Stream Cl concentration is highly variable. The mean value for all measurements is 379 mg/L, whereas the 90th percentile is 880 mg/L. A summary of Cl concentration by river basin and aquifer (Table 1) shows the highest mean value occurs in the Red River basin (704 mg/L), followed by the Brazos River basin (434 mg/L). Cl concentrations in the Colorado River basin (174 mg/L) and the Trinity River basin (45 mg/L) are much lower. The Red, Brazos, and Colorado River basins extend upstream far beyond the study area. Average concentration for each river basin described here reflects the condition of the stream segments in the study area. A general trend of decreasing stream-water salinity from upstream to downstream (roughly northwest to southeast) can be observed in all three river basins (Trinity, Brazos, and Colorado) (Fig. 12). The salinity originates from

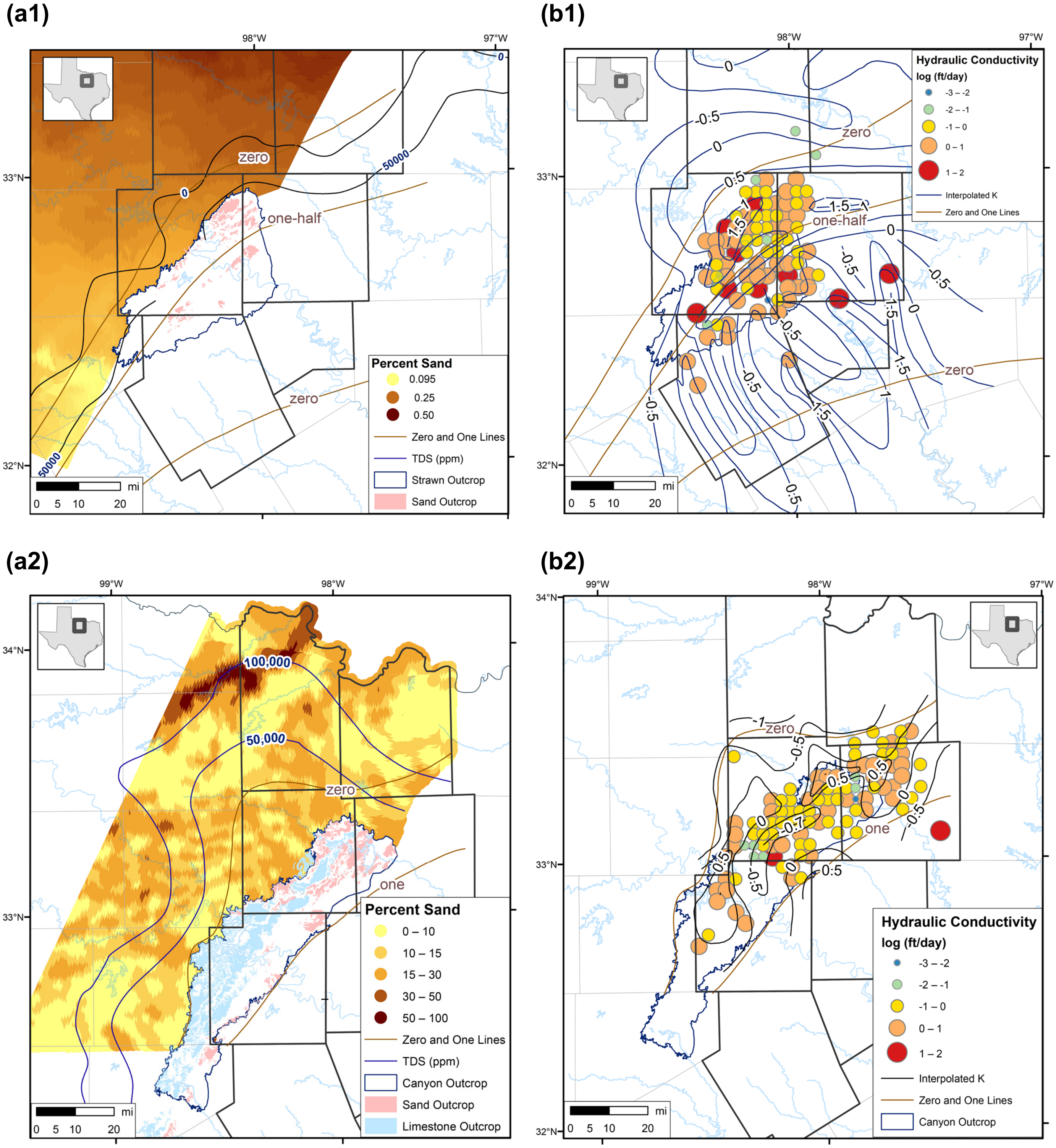



**Figure 7. Location of zero and one lines and (a) sandstone content and (b) estimated generalized hydraulic conductivity (not model-calibrated) for (1) Strawn, (2) Canyon, (3) Cisco, and (4) Wichita-Albany groups. For Wichita-Albany Group, sandstone fraction extrapolated in GIS assuming a sandstone fraction of 40 percent on eastern portion of outcrop of Nocona Formation, grading smoothly to sandstone fraction of 10 percent in western portion of outcrop in study area. Based on data presented in Hentz (1988).**

upstream saline seeps outside of the study area; these seeps are made saline by the leaching of halite layers with meteoric groundwater (Richter and Kreitler, 1986) as well as by the input of gypsum from the Blaine Formation and others.

Cl concentrations in groundwater in sampled locations range from fresh to brackish and vary by aquifer (Table 2). Average Cl concentration in the Paleozoic aquifers (364 mg/L) is about twice that in the Trinity aquifer (119 mg/L). In contrast to the surface-water salinity trend, there is a general trend of increasing Cl concentration from younger to older formations (W–E) in the Paleozoic aquifers as evidenced by the mean and median concentration values of each group, although groundwater Cl concentration in

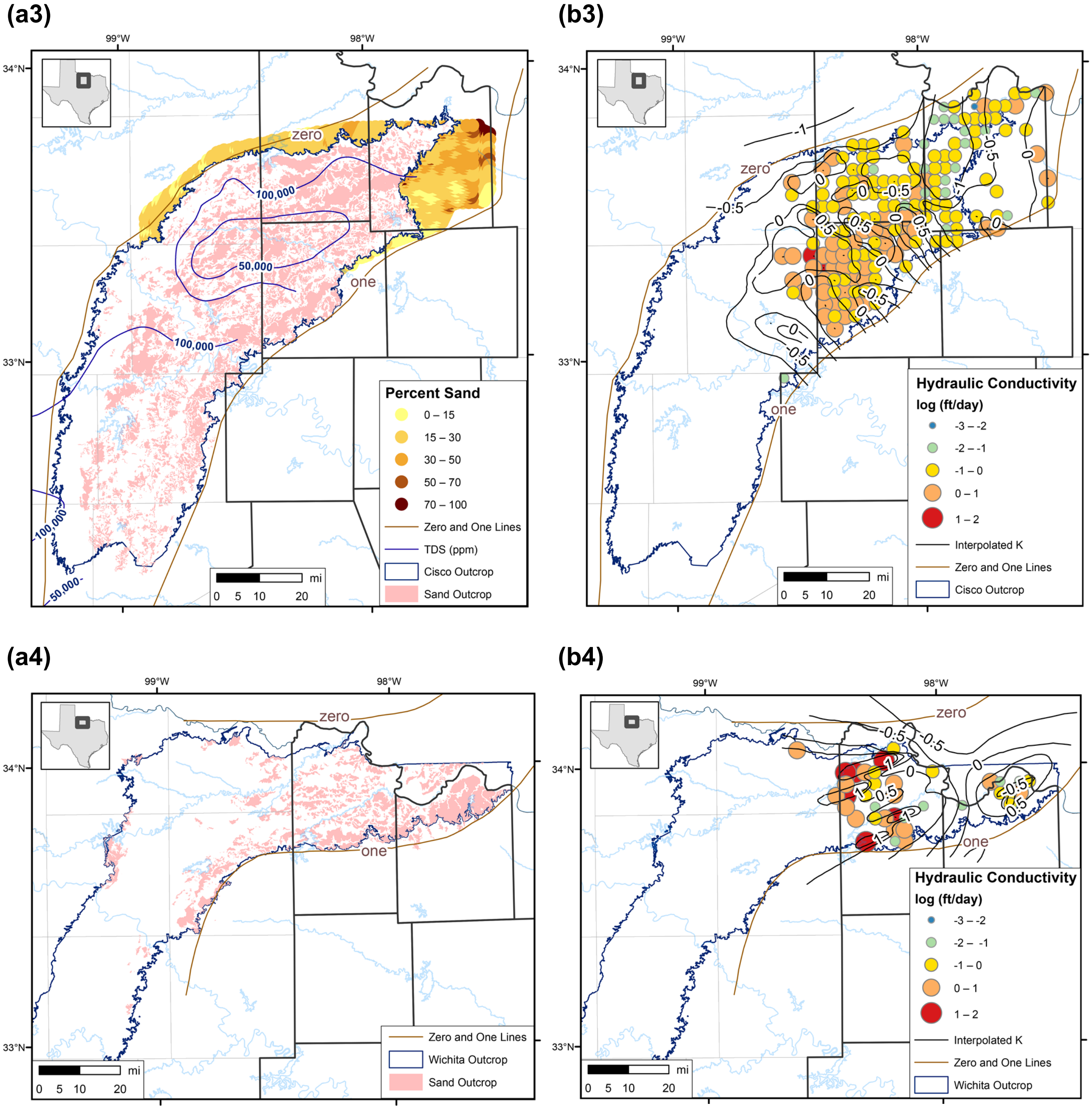



**Figure 7 (continued from adjacent page).**

the Strawn is lower than that in the Canyon. The reversal of groundwater salinity trend in the Strawn suggests cross-formational flow between the Trinity and Strawn in the overlapping area, with the primary direction of the Trinity recharging the Strawn.

Spatial distribution of Cl concentration in the Paleozoic aquifers and the Trinity aquifer is shown in Figure 13. Hot spots (average Cl concentration > 600 mg/L) are more prevalent in the Paleozoic aquifers than in the Trinity aquifer. Many hot spots in the Trinity aquifer footprint are along the border with the Paleozoic aquifers and correspond to sampling of the underlying Paleozoic formations overlaid there by thin Cretaceous deposits. High values correspond to inadvertent sampling from the brackish downdip section or, just as likely, oilfield brine contamination. Hot spots in the Paleozoic aquifers do not occur along main stream channels, so surface-water input is not the likely source of high Cl content in the Paleozoic aquifers. Instead, they indicate halite dissolution or surface contamination. Further analysis using Br suggests that surface contamination is the most likely cause, as demonstrated below.

## Bromide and Cl/Br Ratios

Br concentrations in groundwater range from 0.01 to 41 mg/L with a mean value of 0.76 mg/L, a median value of 0.32 mg/L, and a 90th percentile of 1.69 mg/L (Table 3). Average Br con-

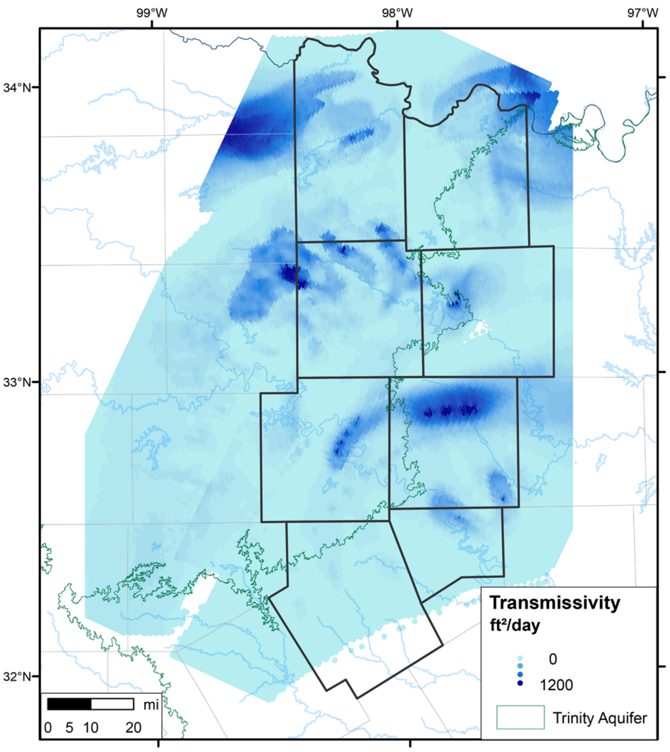



**Figure 8. Generalized transmissivity maps of Paleozoic aquifers). Individual values for overlapping layers were added together.**

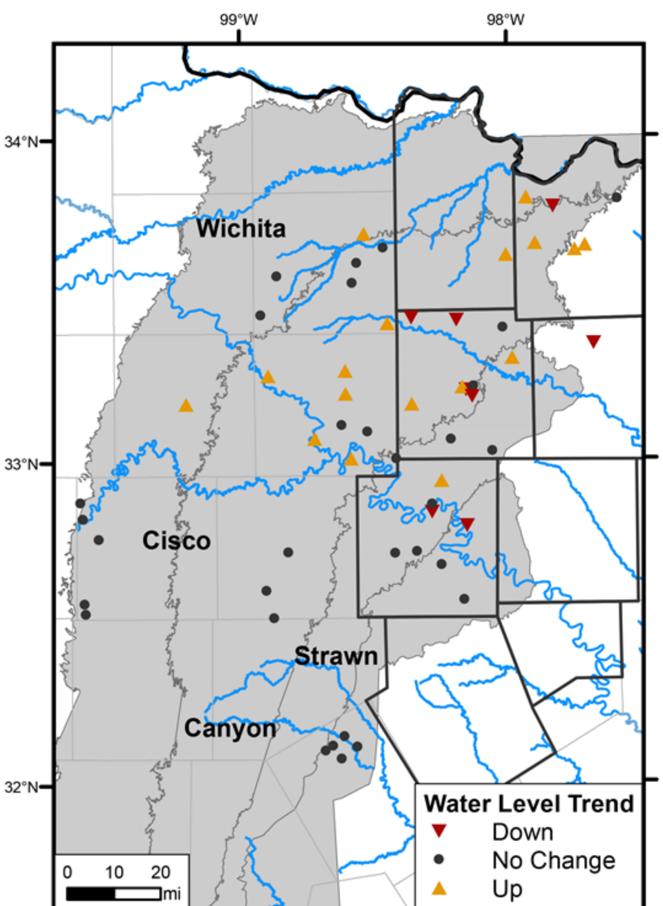



**Figure 9. Paleozoic aquifer groundwater-level trend through time.**

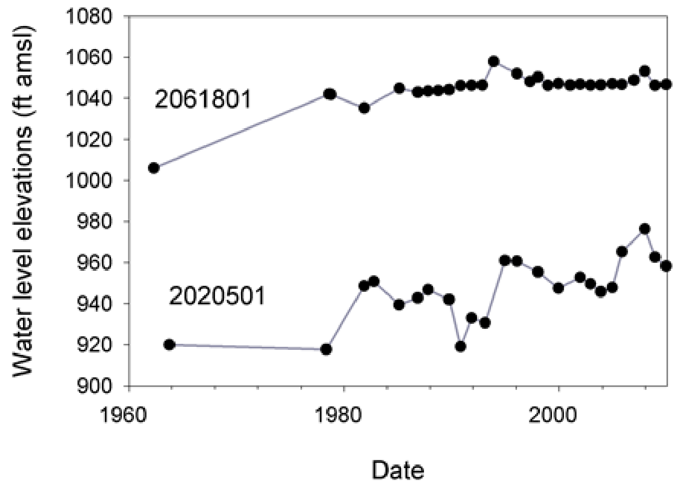



**Figure 10. Groundwater-level hydrographs with long-term observations. Top well is well #2061801 (Young County); bottom well is well #2020501 (Archer County).**

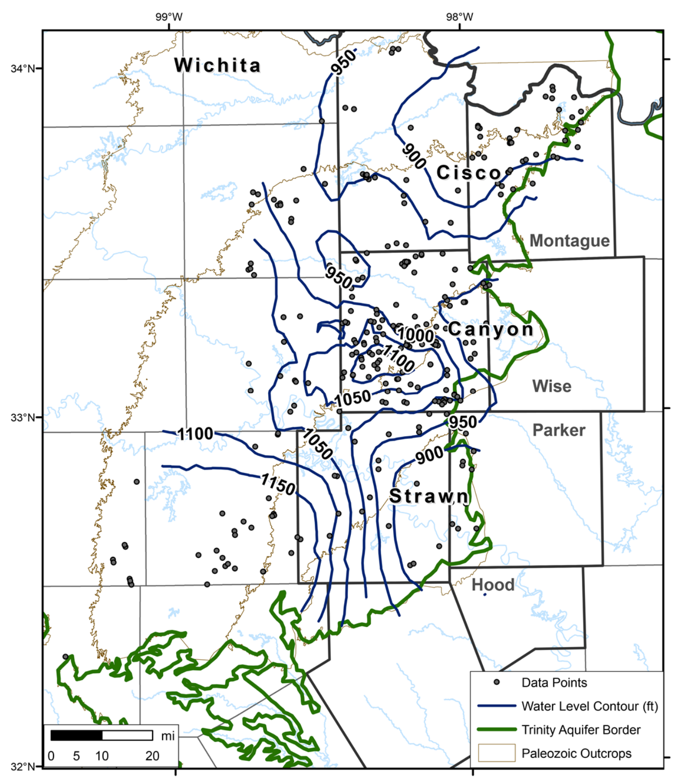



**Figure 11. Generalized groundwater-level elevation contours of Paleozoic aquifers. Area in Clay and Montague counties just south of Red River and north of 900-ft line contains multiple cones of depression. Water withdrawal from Wichita-Albany sandstones and recent alluviums used for municipal water use and irrigation.**

centration in the Paleozoic aquifers (1.58 mg/L) is about twice that of the Trinity aquifer (0.69 mg/L). Unlike the trend in Cl concentration, Br concentration decreases from west to east, but, similar to the trend of Cl concentration, it shows a reversal in the Strawn.

Cl/Br ratios range from 8 to 7900, with a mean of 212 and a median of 189. These figures are consistent with Davis et al. (2004, their Figures 1 and 4a) for groundwater. Cl/Br ratios in

**Table 1. Surface-water Cl concentration by basin and aquifer (mg/L).**

| River Basin | Aquifer | # Obs. | Mean | Mean |
|---|---|---|---|---|
| Red | Paleozoic | 82 | 704 | 704 |
| Trinity | Paleozoic | 138 | 106 | 45 |
| Trinity | Trinity | 2366 | 42 | |
| Brazos | Paleozoic | 1839 | 942 | 434 |
| Brazos | Trinity | 3257 | 141 | |
| Colorado | Paleozoic | 1809 | 174 | 174 |

**Table 2. Groundwater Cl concentration by aquifer (mg/L)**

| System | Aquifer | # Obs. | Mean | Min. | Max. | Median | Mean |
|---|---|---|---|---|---|---|---|
| Paleozoic | Wichita-Albany | 228 | 284 | 6 | 3058 | 148 | 364 |
| Paleozoic | Cisco | 915 | 332 | 3 | 4760 | 153 | |
| Paleozoic | Canyon | 239 | 532 | 3 | 5200 | 238 | |
| Paleozoic | Strawn | 124 | 431 | 9 | 4910 | 205 | |
| Cretaceous | Trinity | 6608 | 119 | 2 | 1624 | 53 | 119 |

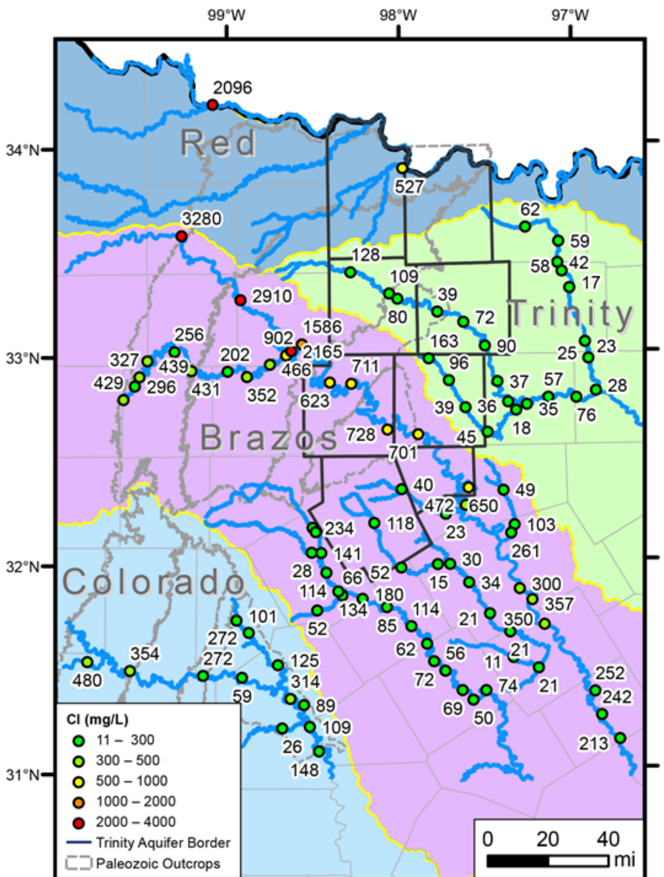



**Figure 12. Spatial distribution of stream Cl concentration in study area. Note the salinity downstream decrease. Data summarized from TCEQ SWQMIS database (TCEQ, 2012).**

groundwater vary by aquifer (Table 4) but we observed no spatial trend. About 3% of samples (37 out of 1278) have Cl/Br ratios less than 50; the locations of these 37 samples are scattered. The maximum Cl concentration in those 3% samples is 300 mg/L, suggesting likely anthropogenic addition of Br in those locations from sources such as surface runoff containing artificial sources of Br such as ethylene dibromide, septic waste, or oil and gas byproducts. About 1% of samples have Cl/Br ratios greater than 1000 (Fig. 13). These sample locations are grouped together but none were situated within the Cl hot spots. This distribution suggests the influence of halite dissolution, possibly associated with surface contamination.

Cl/Br mass ratio versus Cl concentration (Fig. 14) is consistent with typical recharging aquifers with low Cl concentration (<500 mg/L) and Cl/Br mass ratio below 300 representing recent recharge water and not much influence of halite dissolution. The relatively small variation of Cl/Br ratios with increasing Cl concentration indicates evapotranspiration and mixing processes with deeper water.

## Groundwater Recharge

Average recharge across the Paleozoic outcrops is about 0.1 in/yr, corresponding to 0.3% of the annual mean precipitation (which varies from 26.4 to 37.4 in) (Fig. 15). Lower recharge rates were observed in the southwest of the study area, and higher recharge rates were observed in the area close to the Trinity outcrop and in the north, a distribution consistent with the regional precipitation gradient (northeast to southwest) and potential influence of cross-formational flow from the Trinity aquifer. However, spatial pattern is not consistent across the entire study region. For example, one recharge zone of the Canyon Group shows much higher recharge (0.22 in/yr), indicating probable data bias. Recharge estimates using this approach were interpreted as long-term net distributed recharge from precipitation. The estimates from Cl mass-balance in this study appear low in comparison to those in some previous studies. For example, Keese et al. (2005) estimated approximately 0.4 to 1.2 in/yr distributed recharge using unsaturated zone modeling in the general area that includes the Paleozoic outcrops. However, the estimates of Keese et al. were extrapolations from simulations of more permeable media—the Trinity aquifer to the east and Seymour aquifer to the west, which, in addition, also sustain more cultivated land (Fig. 3), an element known to enhance recharge (Scanlon et al., 2004).

## CONCEPTUAL GROUNDWATER FLOW

A qualitative conceptual groundwater flow and surface-water–groundwater interaction can be formulated on the basis of the observations detailed above. Overall, Paleozoic aquifers represent a shallow flow system, mostly unconfined and discontinuous, with general flow toward the northeast mostly discharging into rivers and receiving water input through limited distributed recharge and likely from the overlying Trinity aquifer when present (Fig. 16). To the north, the Red River, a major river with extensive alluvium deposits, is a likely relatively constant head boundary for the Paleozoic aquifers, whereas the topographic high of Cretaceous remnants in Eastland County likely forms a no-flow boundary to the south of the Paleozoic system. To the east, cross-formational flow from the Trinity to the Strawn and Canyon Group sandstones is clearly present, although this study did not uncover the amount or geographic extent of the interaction. No obvious geologic or geographic marker exists to impose a boundary to the system to the west except perhaps the Bend Arch toward which thicknesses decrease. The study area is in continuity with Paleozoic aquifers present to the west of the study area and described in Ewing et al. (2004).

Streams are believed to be mostly gaining. Slade et al. (2002) summarized gain-loss studies performed in Texas by the U.S. Geological Survey in previous decades. Only a second-order tributary to the Brazos River in Shackelford County, upstream of Lake Daniel, slightly outside of the area of study, is included in the compilation. Five studies suggest that the investigated reaches are mostly gaining. Although not evidence for mostly gaining streams in the area of study, the conceptual model

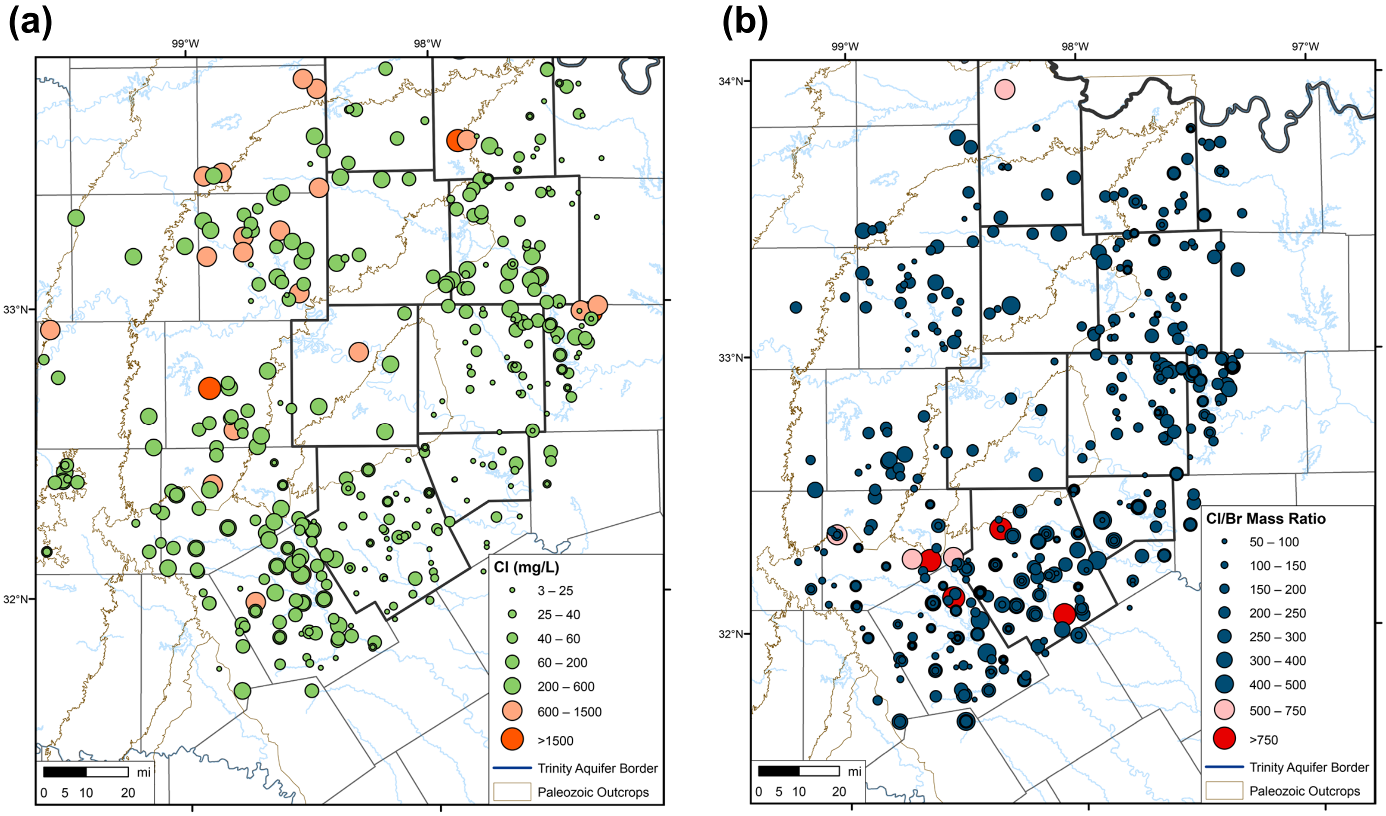



**Figure 13. Spatial distribution of (a) groundwater Cl concentration and (b) Cl/Br mass ratio in Paleozoic and Trinity aquifers. Data from TWDB groundwater database (TWDB, 2012).**

**Table 3. Groundwater Br concentration by aquifer (mg/L).**

| System | Aquifer | # Obs. | Mean | Min. | Max. | Median | Mean |
|---|---|---|---|---|---|---|---|
| Paleozoic | Wichita-Albany | 13 | 1.97 | 0.30 | 5.25 | 2.00 | 1.58 |
| Paleozoic | Cisco | 64 | 1.64 | 0.12 | 17.68 | 0.89 | |
| Paleozoic | Canyon | 13 | 0.98 | 0.10 | 3.68 | 0.59 | |
| Paleozoic | Strawn | 3 | 1.20 | 0.62 | 1.77 | 1.22 | |
| Cretaceous | Trinity | 1185 | 0.69 | 0.01 | 41.00 | 0.30 | 0.69 |

**Table 4. Groundwater Cl/Br mass ratio by aquifer (mg/L).**

| System | Aquifer | # Obs. | Mean | Min. | Max. | Median | Mean |
|---|---|---|---|---|---|---|---|
| Paleozoic | Wichita-Albany | 13 | 233 | 27 | 536 | 211 | 215 |
| Paleozoic | Cisco | 64 | 196 | 27 | 476 | 197 | |
| Paleozoic | Canyon | 13 | 305 | 26 | 1605 | 229 | |
| Paleozoic | Strawn | 3 | 168 | 18 | 264 | 221 | |
| Cretaceous | Trinity | 1185 | 212 | 8 | 7900 | 189 | 212 |

presented by Ewing et al. (2004, their p. 4–73 and Figure 8.2.3) in an area slightly west of our study area also relied on discharge to streams as base flow and through springs to balance recharge. The lack of gain-loss studies led us to rely on indirect elements to understand surface water-groundwater interactions. Well-documented saline seeps to the west of the study area have a shallow meteoric origin (Richter and Kreitler, 1986), which is more evidence of gaining reaches. In the study area, the saline river water, in particular that containing Cl, coming from upstream can be used as a tracer. Long-term, mostly losing reaches would render the aquifers at least as saline as river water. Maps of salinity in aquifers and in rivers (Figs. 12 and 13a) strongly suggest that streams do not recharge the aquifers regionally. However, data from the TWDB and other sources show that aquifer salinity markedly increases with depth. The increase could be mistaken for the effect of a losing stream. The two effects can be discriminated through the Cl/Br ratio. Stream salinity is due to halite dissolution and therefore should have a high mass ratio (>1000), whereas brackish-section salinity in the study area is due to regular rock-water interaction and possibly mixing with deeper brine or due to oil and gas activities; this brackish-section salinity should display a much lower mass ratio (<400). Progressive dilution of surface-water concentration from upstream to downstream is likely primarily due to increased surface runoff, although Nance (2006), on the basis of observations in his study site farther upstream, suggested that baseflow contribution is the primary factor.

The Trinity aquifer may provide cross-formational flow to the Paleozoic aquifers. In general, increasing groundwater Cl concentration from west to east is not correlated with the change in surface-water salinity. The general groundwater salinity trend and its reversal in the Strawn suggest that cross-formational flow exists between the Trinity and Strawn when they overlap, with the primary flow direction from the Trinity to the Strawn. Through Cl/Br ratio analysis, we observed that proportionally more recharge water and higher degree of mixing exist in the neighboring Trinity aquifer than in the Paleozoic aquifers.

The amount of distributed groundwater recharge (that is, infiltration after removing evapotranspiration) through outcrops is limited but consistent with that of neighboring areas. On the basis of data from shallow pumping wells (data not shown), we observed no systematic change in Cl concentration with depth in the Paleozoic aquifers; that is, in the shallow fresh-water zone, groundwater is not stratified. Because salinity sharply increases downdip, we expect a stable salinity stratification and limited mixing restricting deep recharge, unlike processes described in the upper Gulf Coast aquifers (Huang et al., 2012). Lack of deep recharge can be attributed to low recharge and low conductivity of a heterogeneous subsurface, but interactions between topography and formation structural dip also plays a role. In the Gulf Coast, general slope of the topography and structural dip are generally coincident, whereas topographic slope of the Paleozoic aquifers is regionally both along strike and counter to the structural dip. This favors along strike flow to discharge to rivers and also to limit downdip flow through a geometric effect. Only in Montague and Clay Counties, where topographic slope and structural dip coincide, are the aquifers productive (Nicot et al., 2012b).

## CONCLUSIONS

The Paleozoic aquifer system contains fresh water to a limited depth, with generally limited well yield, reflecting a low-permeability shallow system that is mostly unconfined and discontinuous. The regional flow pattern indicates that the flow is controlled by a combination of topography, geologic structure, and regional discharge features in valleys. Surface-water salinity decreases downstream toward the Gulf of Mexico. Groundwater salinity increases from younger to older formations toward the east but there is a reversal in the Strawn Group, whose formations are in hydraulic contact with the overlying Trinity aquifer. The primary direction of water exchange is from the Trinity to the Strawn Group. Spatial changes in surface-water salinity do not correlate with changes in groundwater salinity, and Cl/Br ratios suggest flow from the aquifers to mostly gaining streams and rivers. Distributed recharge is about 0.1 in/yr across the Paleozoic outcrops. The limited downdip flow in the Paleozoic aquifers can be explained by low permeability, flow along strike, and opposite topographic slope and structural dip generating a stable salinity configuration. Elements presented in this investigation enabled us to formulate a conceptual model of groundwater flow in the study area and formed the basis for a regional modeling study (Nicot et al., 2012b).

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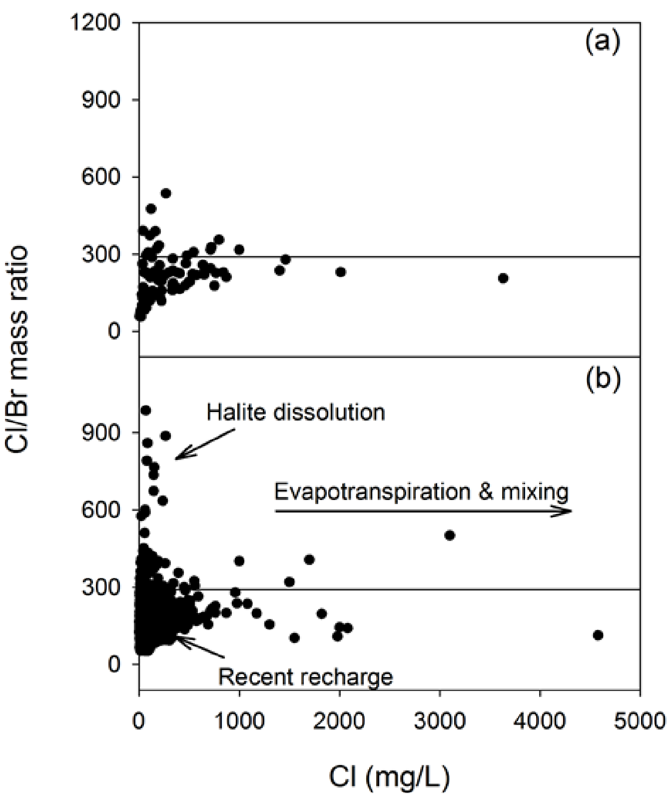


**Figure 14. Cl/Br mass ratio vs. Cl concentration in groundwater in two adjacent aquifers (a) Paleozoic aquifers and (b) Trinity aquifer. Reference line is for oceanic water, which has Cl/Br mass ratio of 290.**

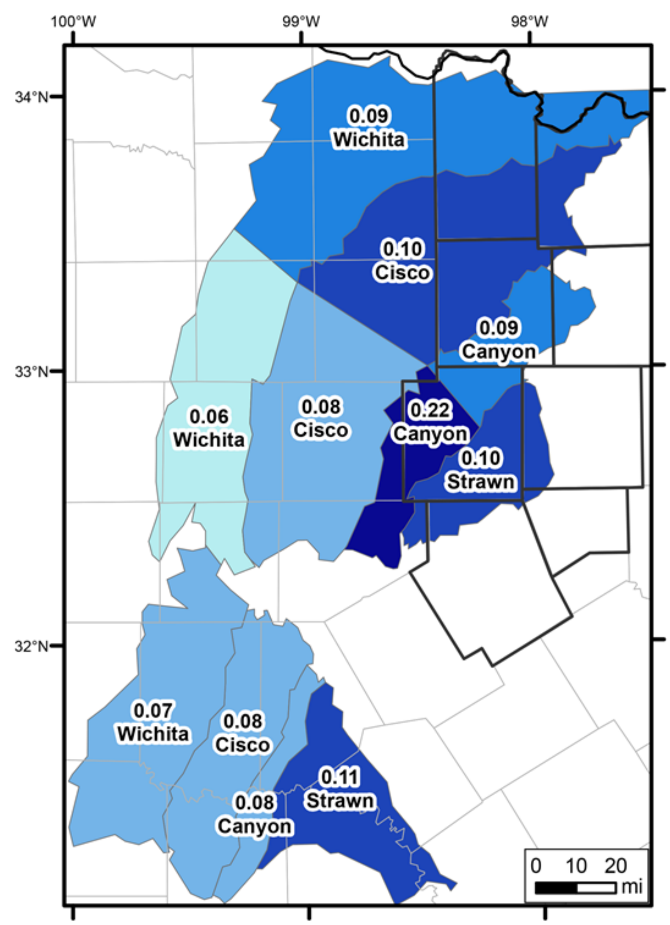


**Figure 15. Distributed recharge (in/yr) to Paleozoic aquifers, estimated using the Cl mass-balance approach.**

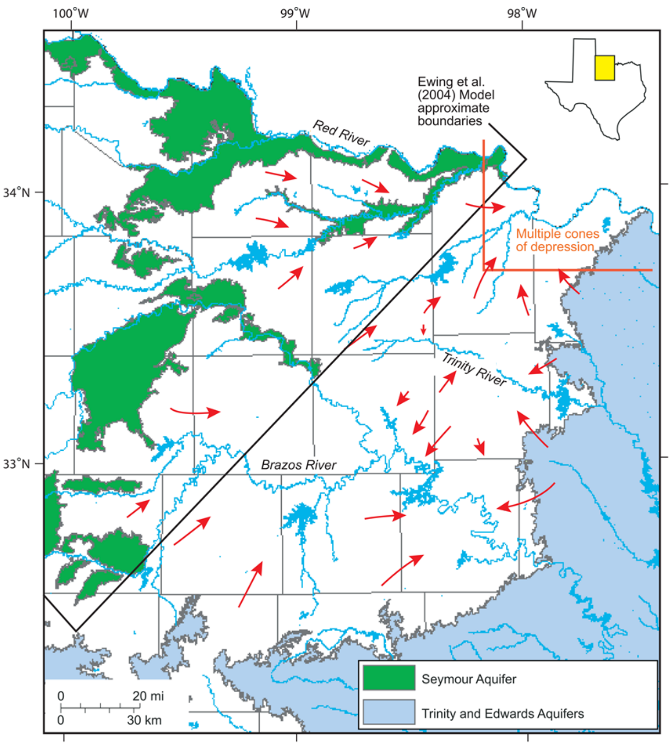


**Figure 16. Conceptual model of flow in Paleozoic aquifers of north-central Texas.**

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