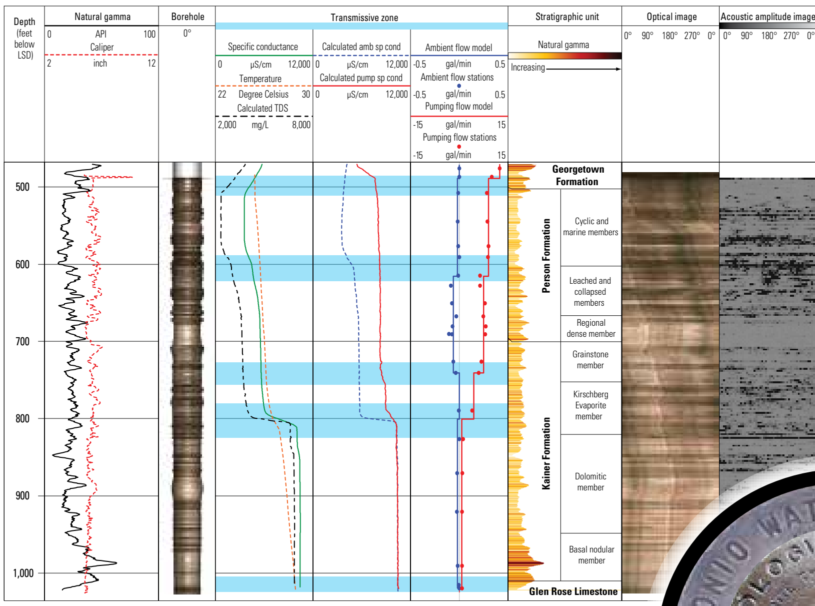
![USGS science for a changing world]

Prepared in cooperation with the San Antonio Water System

Borehole Geophysical, Fluid, and Hydraulic Properties Within and Surrounding the Freshwater/Saline-Water Transition Zone, San Antonio Segment of the Edwards Aquifer, South-Central Texas, 2010–11



Scientific Investigations Report 2012–5285

U.S. Department of the Interior
U.S. Geological Survey

Cover:

Left, Borehole geophysical suite collected at Tri-County transect well TC2, 2003–10.

Right, Photograph of a U.S. Geological Survey borehole geophysical logging truck, April 2009.

Background, Photograph of the Sun setting over the project site, San Antonio segment of the Edwards aquifer, south-central Texas, 2003.

Borehole Geophysical, Fluid, and Hydraulic Properties Within and Surrounding the Freshwater/Saline-Water Transition Zone, San Antonio Segment of the Edwards Aquifer, South-Central Texas, 2010–11

By Jonathan V. Thomas, Gregory P. Stanton, and Rebecca B. Lambert

Prepared in cooperation with the San Antonio Water System

Scientific Investigations Report 2012–5285

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

This and other USGS information products are available at http://store.usgs.gov/

U.S. Geological Survey
Box 25286, Denver Federal Center
Denver, CO 80225

To learn about the USGS and its information products visit http://www.usgs.gov/
1-888-ASK-USGS

Suggested citation:
Thomas, J.V., Stanton, G.P., and Lambert, R.B., 2012, Borehole geophysical, fluid, and hydraulic properties within and surrounding the freshwater/saline-water transition zone, San Antonio segment of the Edwards aquifer, south-central Texas, 2010–11: U.S. Geological Survey Scientific Investigations Report 2012–5285, 65 p., 3 apps.

Contents

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.59	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.207	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
	Volume	
cubic foot (ft^3)	0.02831685	cubic meter (m^3)
cubic foot (ft^3)	28.31685	liter (L)
gallon (gal)	3.785412	liter (L)
	Mass	
pound	0.45359237	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or in micrograms per liter (µg/L).

Borehole Geophysical, Fluid, and Hydraulic Properties Within and Surrounding the Freshwater/Saline-Water Transition Zone, San Antonio Segment of the Edwards Aquifer, South-Central Texas, 2010–11

By Jonathan V. Thomas, Gregory P. Stanton, Rebecca B. Lambert

Abstract

The freshwater zone of the San Antonio segment of the Edwards aquifer is used by residents of San Antonio and numerous other rapidly growing communities in south-central Texas as their primary water supply source. This freshwater zone is bounded to the south and southeast by a saline-water zone with an intermediate zone transitioning from freshwater to saline water, the transition zone. As demands on this water supply increase, there is concern that the transition zone could potentially move, resulting in more saline water in current supply wells. Since 1985, the U.S. Geological Survey (USGS), San Antonio Water System (SAWS), and other Federal and State agencies have conducted studies to better understand the transition zone.

During 2010 and 2011, the USGS, in cooperation with SAWS, conducted a study to further assess the potential for movement of the transition zone in part of the San Antonio segment of the Edwards aquifer. Equivalent freshwater heads were computed to investigate the transition from saline to freshwater zones in the San Antonio segment and evaluate the potential for lateral flow at the freshwater/saline-water interface. Data were collected within and surrounding the transition zone from 13 wells in four transects (East Uvalde, Tri-County, Fish Hatchery, and Kyle).

Hydraulic head and geophysical log data were used to calculate equivalent freshwater heads and then analyzed to identify possible horizontal gradients across the transition zone and thus flow. Unlike previous studies that used indirect methods to calculate fluid conductivity from fluid resistivity, in this study geophysical tools that directly measured fluid conductivity were used. Electromagnetic (EM) flowmeter logs were collected under both ambient and stressed (pumping) conditions and were processed to identify vertical flow zones within the borehole.

The San Antonio segment of the Edwards aquifer (the study area) is about 175 miles long and extends from the western groundwater divide near Brackettville in Kinney County to the eastern groundwater divide near Kyle in Hays County. The four transects consist of two to five wells per transect and were configured approximately perpendicular to and across the expected trace of the freshwater/saline-water interface.

The deep flow zone indicated by the EM flowmeter data for East Uvalde transect well EU2 corresponds directly with a large, negative deflection of the fluid logs, indicating an inflow of fresher water from the Devils River Limestone. To the southwest, towards the freshwater/saline-water interface, this same flow zone was observed in well EU1, but with a reduction of flow, and displayed no apparent fluid curve deflections.

The highest observed transmissivity of the study area was observed in the saline zone of the Tri-County transect, at well TC3, which had a total transmissivity of 24,900 square feet per day. Zones of high transmissivity throughout the study site were observed to not be continuous and are likely caused by localized secondary porosity such as intersecting faults or karst features.

Although analyses of daily mean equivalent freshwater heads for the East Uvalde transect indicated that the gradient across the freshwater/saline-water interface varied between into and out of the freshwater zone, the data indicate that there was a slightly longer period during which the gradient was out of the freshwater zone. Analyses of all daily mean equivalent freshwater heads for the Tri-County transect indicated that the lateral-head gradients across the freshwater/saline-water interface were typically mixed (not indicative of flow into or out of freshwater zone). Assessment of the daily mean equivalent freshwater heads indicated that, although the lateral-head gradient at the Kyle transect varied between into and out of the freshwater zone, the lateral-head gradient was typically from the transition zone into the freshwater zone.

Introduction

The freshwater zone of the San Antonio segment of the Edwards aquifer is utilized by residents of San Antonio and numerous other rapidly growing communities in south-central Texas as their primary water supply source. This freshwater zone is bounded to the south and southeast by a saline-water zone with an intermediate zone transitioning from freshwater to saline water, the transition zone. As demands on this water supply increase, there is concern the transition zone could potentially move, resulting in more saline water in current supply wells. Since 1985, the U.S. Geological Survey (USGS), San Antonio Water System (SAWS), and Federal and State agencies have conducted studies to better understand the transition zone During 1999–2007, the hydraulics of flow within and surrounding the transition zone were analyzed on the basis of water-level and borehole geophysical log data collected from 15 monitoring wells in four transects (Lambert and others, 2010).

During 2010 and 2011, the USGS, in cooperation with SAWS, conducted a study to further assess the potential for movement of the transition zone in part of the San Antonio segment of the Edwards aquifer by collecting additional water-level and borehole geophysical log data from 13 of the 15 monitoring wells from which data were collected by Lambert and others (2010). Equivalent freshwater heads were computed to further investigate the transition from saline to freshwater zones in the San Antonio segment and evaluate the potential for lateral flow at the freshwater/saline-water interface of the aquifer. Advanced borehole geophysical and fluid techniques coupled with water-level data indicating the hydraulic conditions at the time of data collection were assessed to improve the understanding of the hydrologic properties of the site. Data within and surrounding the transition zone were collected from 13 wells in four transects (East Uvalde, Tri-County, Fish Hatchery, and Kyle) (fig. 1). Compiled hydraulic head and geophysical log data were used to calculate equivalent freshwater heads and were then analyzed to identify possible horizontal gradients across the transition zone and thus potential flow. Continuous water-level measurement data from the 13 wells were assessed to identify the hydraulic conditions at the time of logging. Unlike previous studies that used indirect methods to calculate fluid conductivity from fluid resistivity, in this study geophysical tools that directly measured fluid conductivity were used. Electromagnetic (EM) flowmeter logs were collected under both ambient and stressed (pumping) conditions and were processed to identify vertical flow zones within the borehole. For this report, previously identified standards are used to define freshwater as that containing less than 1,000 milligrams per liter (mg/L) dissolved solids concentration; slightly saline water as that containing 1,000–3,000 mg/L dissolved solids concentration; moderately saline water as that containing 3,000–10,000 mg/L dissolved solids concentration; and very saline water as that containing 10,000–35,000 mg/L dissolved solids concentration (Winslow and Kister, 1956).

Purpose and Scope

This report presents the findings of a study done during 2010 and 2011 to gain a better understanding of the relation between the freshwater, transition, and saline-water zones of the San Antonio segment of the Edwards aquifer. The potential for movement of the transition zone in part of the San Antonio segment of the Edwards aquifer was evaluated, along with the potential for lateral flow at the freshwater/saline-water interface. Compared to previous studies, more precise specific-conductance profiles for the fluid column were obtained by using newer methods, and data were collected under ambient and stressed hydraulic conditions to further assess lateral flow in the transition zone. In addition to physicochemical properties (specifically, fluid conductivity and temperature), geophysical logging data collected during 2010, and water-level data collected during 2010–11, similar data collected by the USGS during 1999–2009 (physicochemical properties [fluid conductivity, specific conductance, and temperature], geophysical logging data, and water-level data) were used in a detailed analysis of hydraulics of flow of the transition zone in the Edwards aquifer. Interpreting hydrogeologic properties from the borehole geophysical logging data that were collected in 2010 within and surrounding the transition zone at four transects (East Uvalde transect, Tri-County transect, Fish Hatchery transect, and Kyle transect) from 13 wells (fig. 1) is the primary purpose of this report. To help with the interpretation of the geophysical logging data, water-level data collected at each well provided the head distribution during 1999–2011 and were used as an indicator of changes in hydrologic conditions. Daily mean water levels from continuously measured hydraulic heads in monitoring wells of the four transects were converted to equivalent freshwater heads to account for differences in salinity of water in some wells; equivalent freshwater heads were assessed as indicators of potential vertical and horizontal flow zones. This report represents an update to a previous USGS study (Lambert and others, 2010), and much of the wording and presentation of material in this report is based on Lambert and others (2010).

Previous Studies

Several investigators have studied the saline to freshwater transition zone (transition zone) of the Edwards aquifer to gain insight into the potential for movement of saline water into the freshwater zone of the aquifer, including Pavlicek and others (1987), William F. Guyton and Associates, Inc. (1986, 1988), Poteet and others (1992), Groschen (1994), Groschen and Buszka (1997), and Lambert and others (2010). William F. Guyton and Associates, Inc. (1988), described an aquifer test done near a monitoring-well transect, the

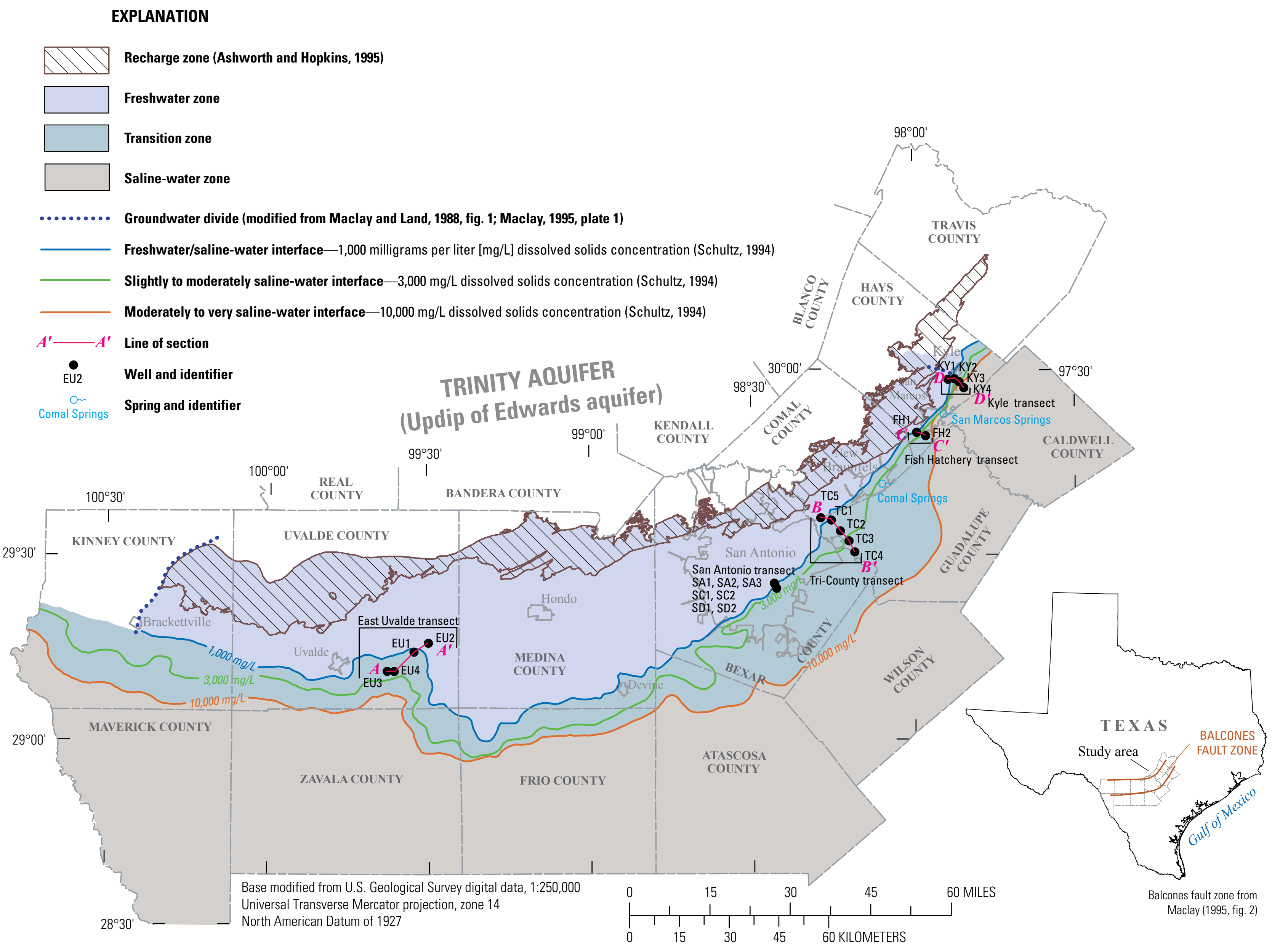


Figure 1. Areal extent of the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, and locations of monitoring wells within and surrounding the transition zone from which data were collected for this report, 2010–11 (modified from Lambert and others, 2010, fig. 1).

San Antonio transect (fig. 1), and reported calculated transmissivities and storage coefficients for each of the monitoring wells in that transect and nearby public-supply wells. Groschen (1994) concluded that the flow system in the saline-water zone probably is controlled to some extent by barrier faults that tend to restrict southeastward flow and that water movement in the saline zone generally is northeastward, parallel to flow in the freshwater zone. Groschen and Buszka (1997) used isotopic and other geochemical data from 17 wells completed in the saline-water zone to hypothesize that the saline-water zone is composed of at least two distinct hydrologic and geochemical regimes.

Previous studies have addressed different aspects of the transition zone, although they did not specifically focus on areas near the monitoring transects. Maclay (1995), in a regional analysis of the Edwards aquifer, compared the variation in mineralogy, rock texture, and diagenetic processes in the freshwater zone with those in the transition zone and the saline-water zone. Schultz (1992, 1993, 1994) used water-quality data and borehole geophysical logs to better define the extent of the transition zone. Previous publications had shown only the estimated position of the interface on maps. Schultz's (1994) work resulted in a more precise delineation of the interface and also the delineation of 3,000- and 10,000-mg/L dissolved solids concentration lines on maps. Hovorka and others (1998) explained how the structural framework and distribution of porosity and permeability influence the distribution and degree of salinity in the transition zone.

A number of studies have focused on water chemistry and the possible origin of salinity in the transition zone. An earlier geochemical study describing the regional variation in hydrocarbons in the rocks of the Edwards aquifer was done by Moredock and Van Siclen (1964). Clement (1989) and Oetting (1995) described the chemistry of the transition zone by using geochemical methods. Oetting (1995) studied the evolution of freshwater and saline water in the Edwards aquifer and focused on the geochemical and isotopic constraints on fluid-rock processes and fluid mixing. Schultz and Halty (1997) discussed the dissolution of anhydrite by freshwater movement as a principal source of high sulfate concentrations in the Edwards aquifer on the basis of geophysical log analysis. More recently, a statistical analysis of historical major ion and trace element data from the San Antonio transect (fig. 1) was done by Mahler (2008), indicating that the transition-zone wells are less connected to surficial hydrologic conditions than are the freshwater-zone wells.

Lambert and others (2010) obtained lithologic properties (rock properties associated with known stratigraphic units) and physicochemical properties (specifically, fluid conductivity and temperature) to analyze the hydraulics of flow within and surrounding the transition zone of the Edwards aquifer on the basis of water-level and borehole geophysical log data collected from 15 monitoring wells in four transects during 1999–2007. Data analyses for the report supported the hypothesis that the freshwater/saline-water interface is likely to remain stable laterally and vertically over time (Lambert and others, 2010).

Hydrogeologic Setting[1]

The San Antonio segment of the Edwards aquifer (the study area) is about 175 miles long and extends from the western groundwater divide near Brackettville in Kinney County to the eastern groundwater divide near Kyle in Hays County (fig. 1). Northeast of the eastern groundwater divide is the Barton Springs segment of the Edwards aquifer. From its outcrop (recharge zone), the Edwards aquifer dips to the southeast at about 300–400 feet per mile (ft/mi) and becomes buried and confined toward the present Gulf of Mexico coastline. From its outcrop immediately north of the Edwards aquifer recharge zone, the Trinity aquifer dips to the southeast beneath the Edwards aquifer, thus forming the northern lateral boundary and the underlying boundary of the Edwards aquifer. Depth below land surface to the top of the Edwards aquifer in the transition zone ranges from about 200 feet (ft) in the northeastern part of the study area in Hays County to more than 2,600 ft in southern Medina County (Maclay, 1995). The average thickness of the Edwards aquifer in the transition zone is about 500 ft; depths and thickness are based on data from available drillers' logs from the transect monitoring wells (John Waugh, San Antonio Water System, written commun., 2003).

The present-day Edwards aquifer formed along a crustal zone of weakness known as the Ouachita structural belt (Maclay, 1995) and encompasses three depositional provinces: the Maverick Basin, the Devils River Trend, and the San Marcos Platform (fig. 2). Structurally, the transition zone is included in the Balcones fault zone across much of the region and is bounded to the southeast by the Luling fault zone in Guadalupe and Caldwell Counties.

The Edwards aquifer comprises Cretaceous-age carbonate rocks of varying lithologies that were deposited in three depositional environments, or depositional provinces (fig. 3). These depositional environments in part influence the hydraulic conductivity and storage properties of the aquifer. In the westernmost part of the study area, the rocks of the Maverick Basin depositional province include the basinal facies of the West Nueces Formation, the McKnight Formation, and the Salmon Peak Formation (Lozo and Smith, 1964). Dividing the Maverick Basin from the Devils River Trend depositional province is the Uvalde salient (fig. 2). The Uvalde salient is a complex structural high in Uvalde County with numerous faults at the margins where the Edwards limestone has been raised to the land surface (Maclay, 1995, fig. 2) along with local volcanic rocks and igneous intrusives. In eastern Uvalde and Medina Counties, the Edwards aquifer

[1]This section modified from Lambert and others (2010, p. 5).

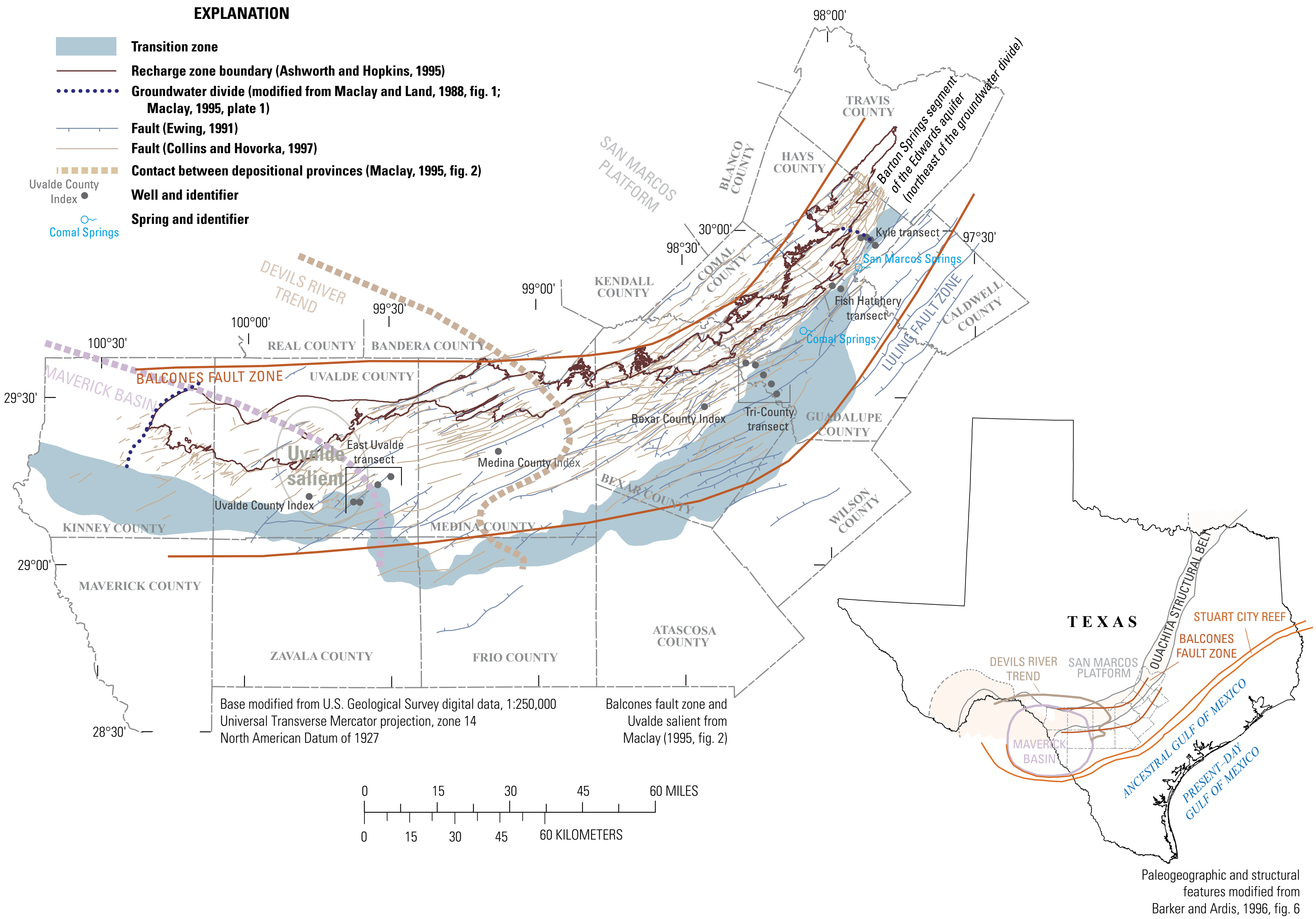
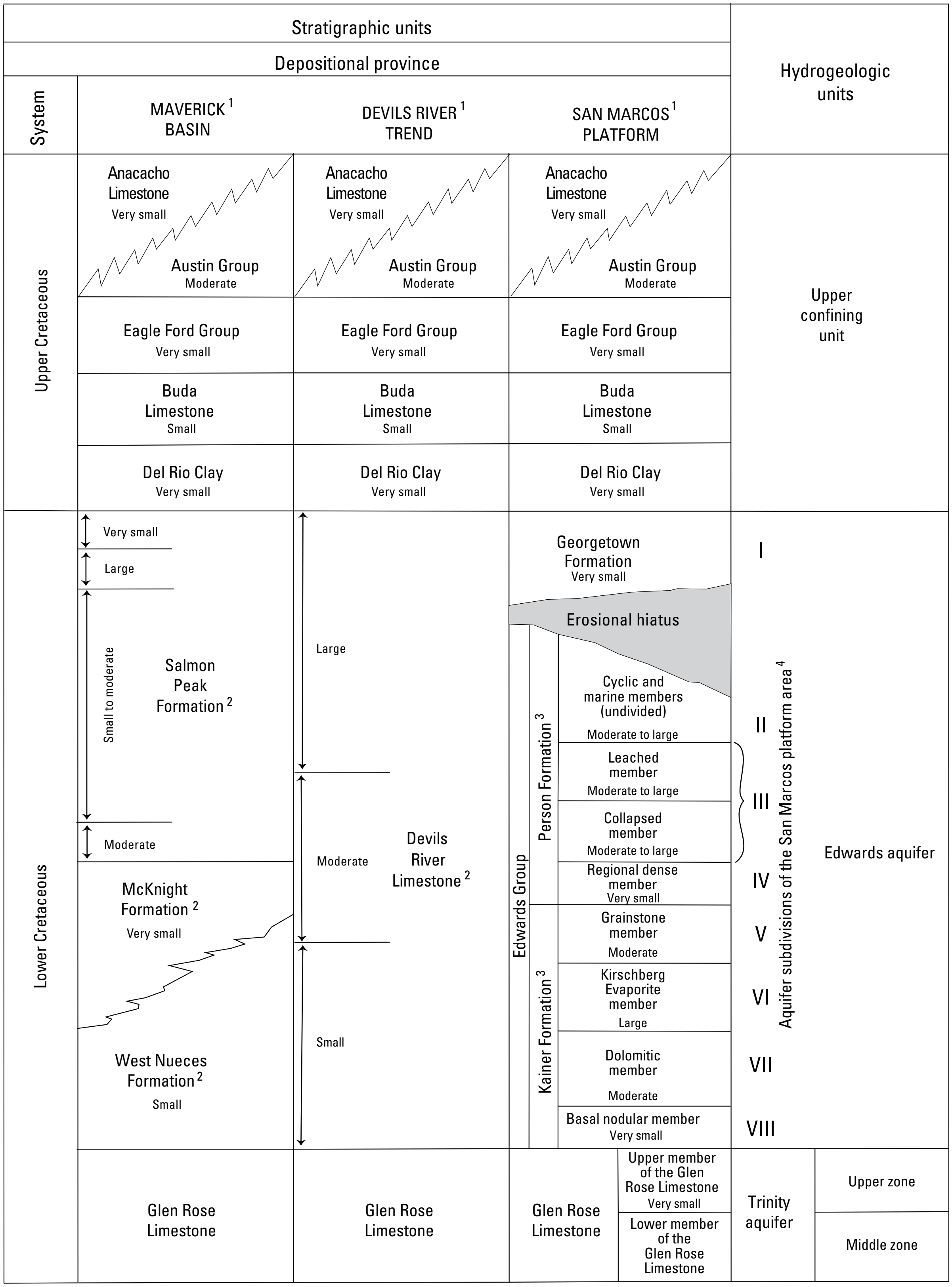


Figure 2. Structural elements and depositional provinces associated with the San Antonio segment of the Edwards aquifer, south-central Texas (modified from Lambert and others, 2010, fig. 2).



[1] Location shown on figure 1.
[2] Lozo and Smith (1964).
[3] Modified from Rose (1972).
[4] Maclay and Small (1984).

Descriptors “very small,” “small,” “moderate,” and “large” refer to relative permeability of hydrostratigraphic zones

Figure 3. Summary of Cretaceous-age stratigraphic units described with relative permeabilities and associated hydrogeologic units of the San Antonio segment of the Edwards aquifer, south-central Texas (modified from Lindgren and others, 2004, fig. 4).

is composed of reefal facies of the Devils River Limestone that were deposited in the Devils River Trend depositional province (Lozo and Smith, 1964). The Devils River Limestone grades east into shallow-water carbonate platform facies and backreef facies of the San Marcos Platform depositional province (Rose, 1972). The San Marcos Platform depositional province includes the Edwards Group (Person and Kainer Formations) and the Georgetown Formation. The Edwards aquifer regionally is confined by the overlying Del Rio Clay and the underlying Glen Rose Limestone, both of which have, for the most part, relatively low permeability (Maclay, 1995).

Recharge to the Edwards aquifer primarily results from channel losses along streams that cross the outcrop (recharge zone) and from direct infiltration of rainfall in the recharge zone (Maclay, 1995). The direction of groundwater flow is controlled in part by regional faulting (Maclay and Land, 1988). Once in the aquifer, groundwater generally moves downdip and then is directed by faults to the east and northeast toward Comal Springs and San Marcos Springs, major springs in the northeastern part of the aquifer (fig. 1) (Groschen, 1994; Maclay, 1995). An additional source of recharge to the Edwards aquifer might be groundwater inflow from the Glen Rose Limestone, the uppermost unit of the Trinity aquifer (fig. 3). Maclay (1995) indicated that Edwards aquifer model simulations showed two areas of possible inflow from the Trinity aquifer to the Edwards aquifer—one in northeastern Medina County and the other in Comal County.

Maclay and Land (1988, fig. 2) delineated four major storage and flow units in the freshwater zone of the Edwards aquifer. A storage unit is a zone of storage in the recharge zone that is unconfined and thus contains a relatively large fraction of the water stored in the aquifer. A storage unit functions independently from the remaining parts of the aquifer, in part because of faulting, and contributes water to a connected flow unit (Maclay and Land, 1988). A flow unit is a part of the aquifer that includes a storage unit and a zone in which water is transmitted from the associated storage unit to major points of discharge (fig. 4). The transition zone is adjacent to the southernmost flow units of the freshwater zone. Groundwater flow through the southern part of the freshwater zone and the transition zone of the aquifer might be influenced by local structural features in the region and by variations in hydraulic conductivity associated with differences in stratigraphic units.

Description of Transects and Monitoring Wells[2]

The monitoring wells that provided data for this report (table 1) were drilled during 1997–2001 by SAWS. Most of the monitoring wells were constructed with 6-inch-diameter steel casing extending from land surface into the upper 20 ft of the Edwards aquifer. The remaining vertical extent of the borehole was completed as open hole. Where possible, the open-hole section of each well was drilled through the entire Edwards aquifer thickness; however, because of the depth limitations of the drill rig, it was not possible for all wells to penetrate the entire thickness of the aquifer. The four transects (East Uvalde, Tri-County, Fish Hatchery, and Kyle) (fig. 1) consist of two to five wells per transect and were configured approximately perpendicular to and across the expected trace of the freshwater/saline-water interface. A well descriptor is applied to each well on the basis of water type in the borehole (freshwater, saline water, or interface [freshwater atop saline water]).

The East Uvalde transect is in the western part of the study area in southeastern Uvalde County (fig. 1). The four wells of the East Uvalde transect are completed in rocks of the Maverick Basin depositional province and the Devils River Trend depositional province (figs. 2, 5). Two of the wells, East Uvalde 1 (EU1) and East Uvalde 2 (EU2), are freshwater wells completed in the Devils River Limestone (fig. 5). The remaining two wells, East Uvalde 3 (EU3) and East Uvalde 4 (EU4), are saline-water wells completed in the West Nueces, McKnight, and Salmon Peak Formations. Although in 1988 well EU1 was drilled within the transition zone mapped by Schulz (1994), water-quality samples later collected (Lambert and others, 2009) indicated that the well was completed in the freshwater zone of the Edwards aquifer. The freshwater/saline-water interface (based on data for this report), therefore, occurs between wells EU1 and EU4.

The Tri-County transect is northeast of San Antonio in Comal and Guadalupe Counties (fig. 1). The five wells of this transect are completed in rocks of the Edwards Group and the Georgetown Formation in the San Marcos Platform depositional province (figs. 2, 6). Tri-County 1 (TC1) and Tri-County 5 (TC5) were classified freshwater wells on the basis of water-quality samples collected from these wells (Lambert and others, 2009). Tri-County 2 (TC2), designated as an interface well because it intersects the interface, contains freshwater in the upper part of the well and saline water in the lower part of the well. The freshwater/saline-water interface (based on data for this report), therefore, occurs at about the location of well TC2. Shultz (1994) located well TC1 in the transition zone before it was drilled in 1999. Tri-County 3 (TC3) and Tri-County 4 (TC4) are both saline water wells in the transition zone. Because of a blockage in the casing that occurred after drilling, no additional data collection in well TC5 was done for this report.

[2]This section modified from Lambert and others (2010, p. 8).

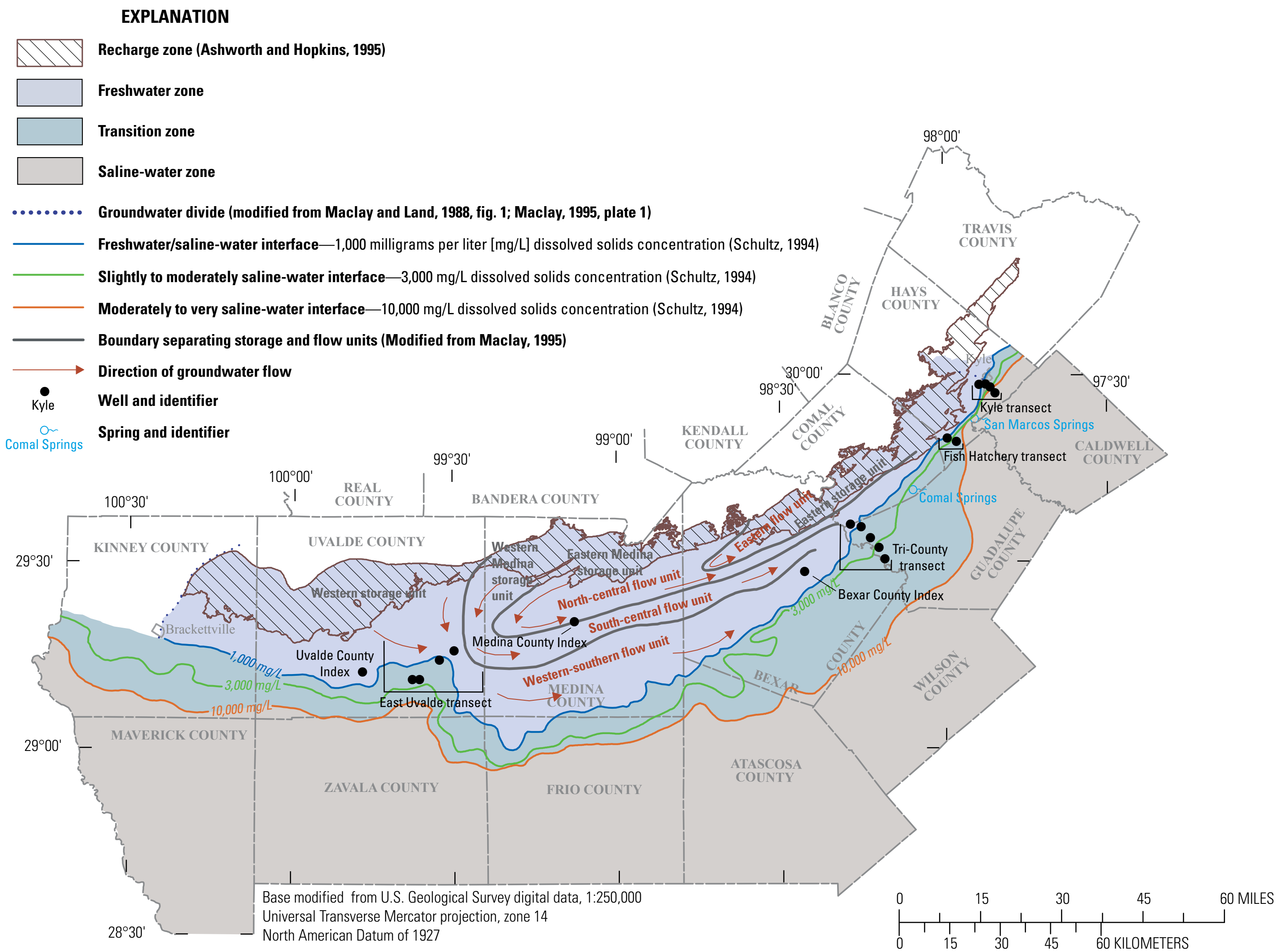


Figure 4. Major storage and flow units and regional flow patterns in the San Antonio segment of the Edwards aquifer, south-central Texas (modified from Maclay and Land, 1988, fig. 22).

Table 1. Descriptive information for monitoring wells within and surrounding the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 1999–2011.

[USGS, U.S. Geological Survey; LSD, land-surface datum; NAVD 88, North American Vertical Datum of 1988. Well descriptors: freshwater, dissolved solids concentration less than 1,000 milligrams per liter; saline water, dissolved solids concentration greater than 1,000 milligrams per liter; interface, freshwater and saline water in stratified lenses]

USGS station number	Well name	Well identifier (fig. 1)	State well number	Year drilled	Well depth (feet below LSD)	Altitude of LSD (feet above NAVD 88)	Open interval (feet below LSD)	Well descriptor based on water type
291443099325801	East Uvalde 1	EU1	YP–69–52–202	1998	1,500	874.02	985–1,500	Freshwater
291612099302001	East Uvalde 2	EU2	YP–69–44–902	1999	1,560	899.91	1,072–1,560	Freshwater
291136099375801	East Uvalde 3	EU3	YP–69–51–606	1999	1,400	877.55	768–1,400	Saline water
291133099363801	East Uvalde 4	EU4	YP–69–52–404	1999	1,463	867.02	950–1,463	Saline water
293610098152701	Tri-County 1	TC1	KX–68–30–314	1999	920	871.01	385–920	Freshwater
293424098134701	Tri-County 2	TC2	KX–68–31–403	1999	1,050	709.08	486–1,050	Interface
293245098121001	Tri-County 3	TC3	KX–68–31–511	1999	1,222	674.00	656–1,222	Saline water
293058098110501	Tri-County 4	TC4	KX–68–31–808	2000	1,562	648.92	1,000–1,562	Saline water
293632098172401	Tri-County 5	TC5	DX–68–30–315	2000	975	782.22	553–975	Freshwater
295019097592701	Fish Hatchery 1	FH1	LR–67–09–113	2000	280	714.73	216–280	Freshwater
294946097574501	Fish Hatchery 2	FH2	LR–67–09–401	2001	1,030	642.51	510–1,030	Saline water
295853097532901	Kyle 1	KY1	LR–67–01–311	1997	810	770.52	307–810	Freshwater
295858097521801	Kyle 2	KY2	LR–67–02–104	1998	975	674.32	427–975	Interface
295829097512601	Kyle 3	KY3	LR–67–02–106	1998	1,100	678.28	600–1,100	Saline water
295730097503201	Kyle 4	KY4	LR–67–02–105	1998	970	646.70	562–970	Saline water

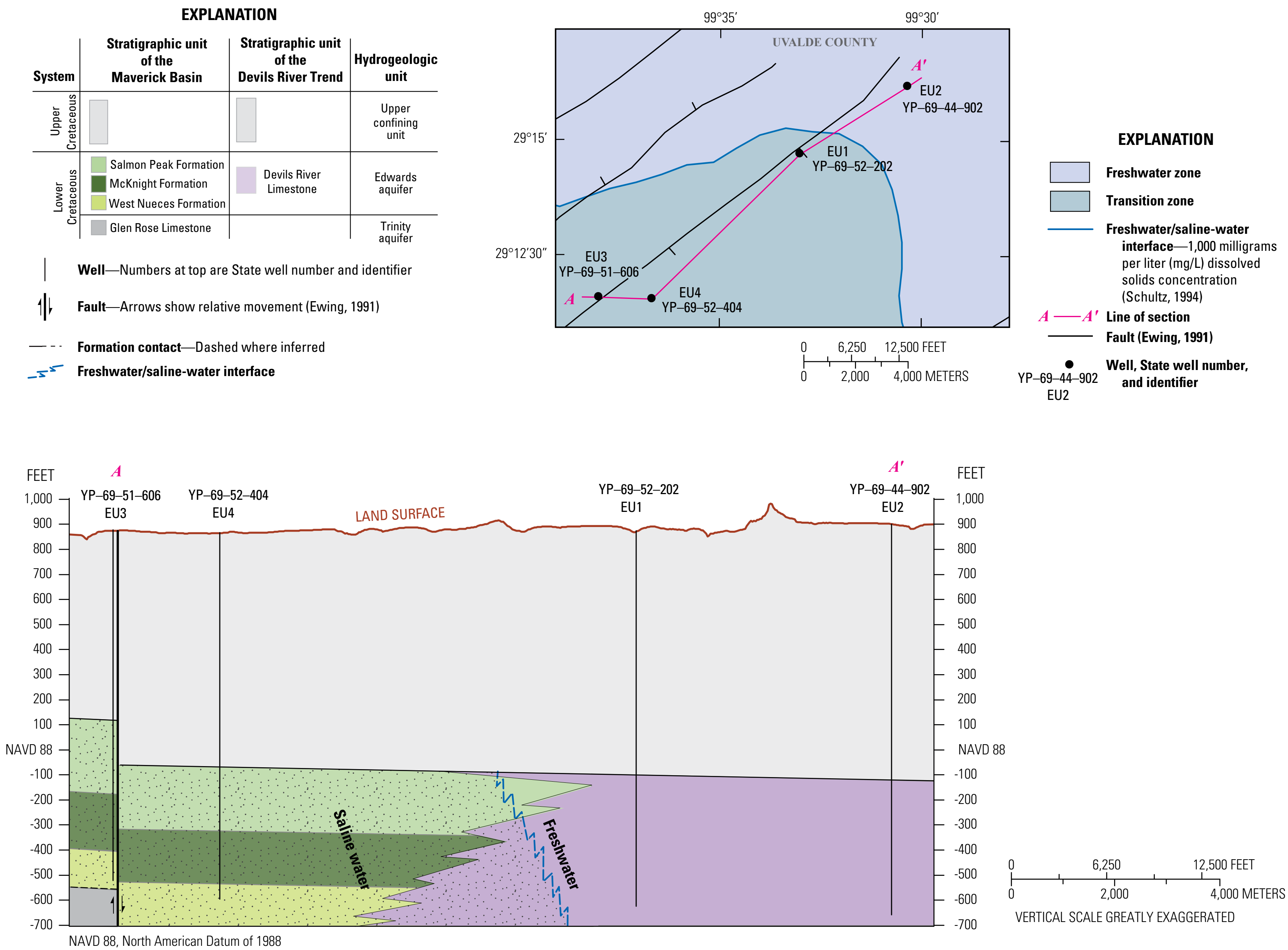


Figure 5. Hydrogeologic section of the East Uvalde transect (*A–A′*), San Antonio segment of the Edwards aquifer, south-central Texas (modified from Lambert and others, 2010, fig. 5).

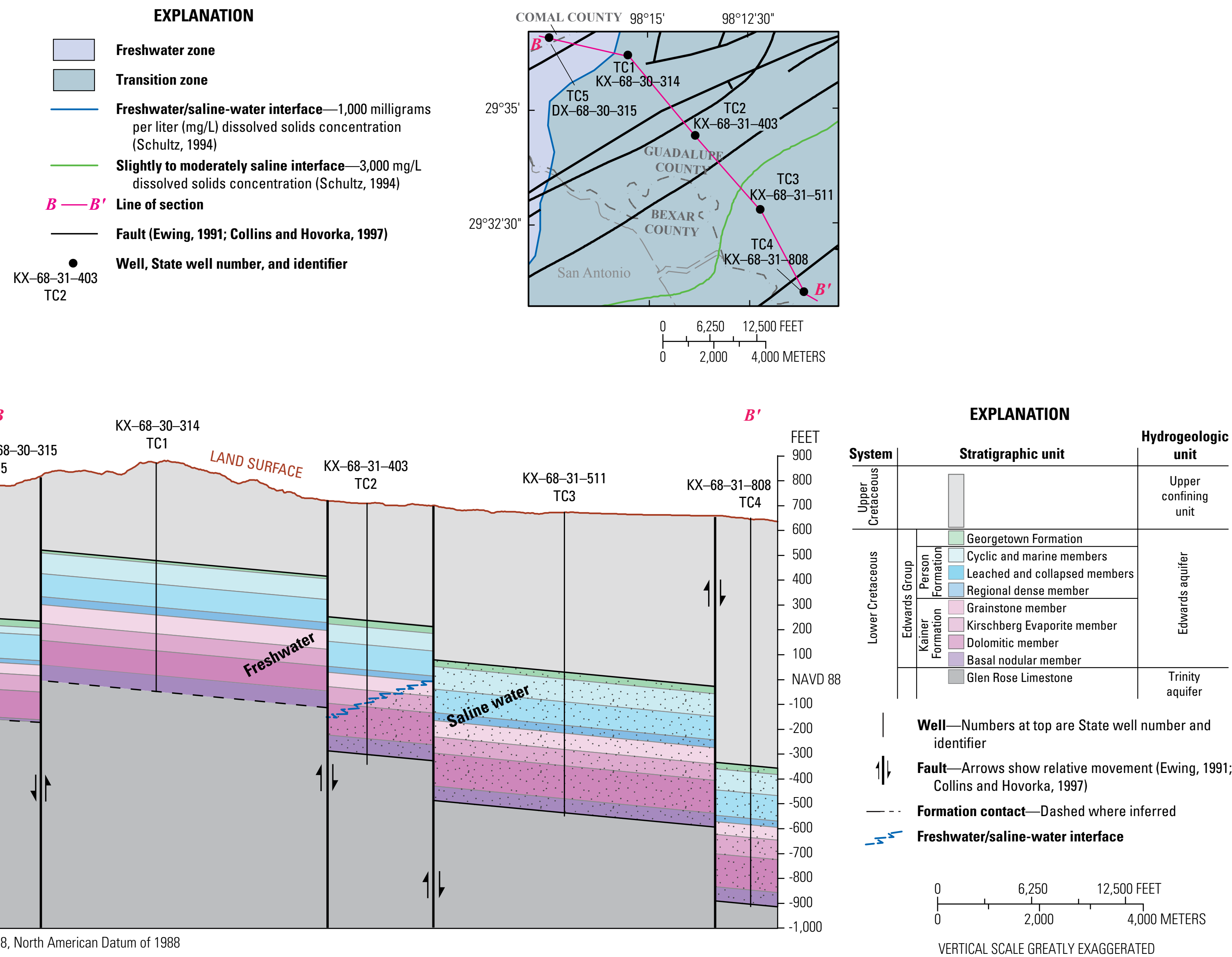


Figure 6. Hydrogeologic section of the Tri-County transect (*B–B′*), San Antonio segment of the Edwards aquifer, south-central Texas (modified from Lambert and others, 2010, fig. 6).

The Fish Hatchery transect comprises two wells and is located in the northeastern part of the Edwards aquifer in Hays County, about midway between Comal Springs and San Marcos Springs (fig. 1). Both wells are completed in rocks of the Edwards Group and the Georgetown Formation in the San Marcos Platform depositional province (figs. 2, 7). Fish Hatchery 1 (FH1) was classified a freshwater well and Fish Hatchery 2 (FH2) a saline-water well on the basis of water-quality samples (Lambert and others, 2009) (fig. 7). It is possible that well FH1 is located at the interface and contains freshwater in the upper part of the well and has saline water below the well since the wellbore does not penetrate the entire thickness of the Edwards aquifer. It was determined, however, that the well would be classified as freshwater on the basis of existing data. The freshwater/saline-water interface (based on data for this report), therefore, occurs between wells FH1 and FH2, although both were located in the transition zone by Schulz (1994) (fig. 7, inset map). Because of the relatively large difference in altitude between the open-hole sections of wells FH1 and FH2, caused by fault offset (fig. 7) and the relative shallowness of well FH1, it was judged that additional data collection at well FH1 would not be advantageous for this project.

The Kyle transect comprises four wells and is at the northeastern end of the San Antonio segment of the Edward aquifer in Hays County, northeast of Comal Springs and San Marcos Springs (fig. 1). The Kyle transect wells are all completed in rocks of the Edwards Group and the Georgetown Formation of the San Marcos Platform depositional province (figs. 2, 8). Kyle 1 (KY1) is a freshwater well, and Kyle 2 (KY2) is an interface well that intersects the interface and contains freshwater in the upper part of the well and saline water in the lower part. The freshwater/saline-water interface (based on data for this report), therefore, occurs about at the location of KY2. Kyle 3 (KY3) and Kyle 4 (KY4) were classified saline-water wells on the basis of water-quality samples (Lambert and others, 2009). Schultz (1994) located well KY3 in the transition zone (fig. 8, inset map).

Methods of Analysis

Geophysical log data were collected, including conventional methods (caliper, gamma, resistivity, fluid conductivity, and fluid temperature) and advanced EM flowmeter and multi-parameter fluid methods that directly measured specific conductance and temperature. Data collected by using the advanced geophysical logging techniques in 2010 were compared with geophysical log data collected by the USGS during 2002–2007 from the same boreholes composing the four transects evaluated in this report (all of the data in this report that were collected during previous studies are in Lambert and others [2009], which also summarizes data-collection techniques, water-quality sampling methods, analytical methods, and quality assurance for these previously collected data). The EM flowmeter logs were collected in 2010 under ambient (nonpumping) and stressed (pumping) hydraulic conditions to assess the hydraulics of flow within the aquifer. Water-level data provided hydraulic head data that were used to interpret borehole geophysical data. Equivalent freshwater heads were computed from measured water-level data (daily mean depth to water, termed environmental-water head) collected by the USGS in 2010 (entire year) and in 2011 (January through September) for 13 wells in the East Uvalde, Tri-County, Fish Hatchery, and Kyle transects (apps. 1.01–1.13). Site locations and associated information can be accessed by using the USGS National Water Information System (U.S. Geological Survey, 2012). Equivalent freshwater heads previously computed from measured water-level data collected by the USGS and SAWS from February 1999 through December 2009 for the same 13 wells were also used in the analysis (Lambert and others, 2010). The boreholes in the transect wells were open to multiple units within the aquifer. Because the boreholes in the wells were open to the entire length of the aquifer units, the measured water levels represent multiple contributing zones. The computed equivalent freshwater heads are composite heads and were corrected to determine the equivalent freshwater heads, which are the transmissivity-weighted averages of multiple flow zones in a single borehole. The measured water-levels during 2010–11 and other data used in the computation of equivalent freshwater heads during 2010–11 are listed in appendixes 1.01–1.13.

Borehole geophysical logs provide measurements from rocks saturated with water under ambient and stressed conditions without disturbing the aquifer by collecting samples (Paillet, 1994). During the previous study done by the USGS on the freshwater/saline-water transition zone in the San Antonio segment of the Edwards aquifer (Lambert and others, 2010), borehole geophysical logs were used to identify stratigraphic units penetrated by the boreholes and graphically relate these stratigraphic units with resistivity, fluid temperature, and ambient vertical flow over the lengths of the boreholes at each of the monitoring wells.

To build on the results in Lambert and others (2010), additional geophysical logs collected in 2010 for this study provided more precise specific-conductance profiles for the fluid column. Vertical flow data were collected under both ambient and stressed hydraulic conditions to calculate hydraulic properties. To assess lateral flow in the transition zone, borehole geophysical data collected in 2010 were augmented with data collected or compiled from Lambert and others (2009, 2010). The potential for lateral flow is inferred from hydraulic properties (transmissivity and hydraulic conductivity). To determine hydraulic heads, water levels were measured as the depth to groundwater subtracted from the top of the well casing elevation above the North American Vertical Datum of 1988 (NAVD 88). The environmental-water column was the measured length of the water column. Equivalent freshwater heads were computed from measured water-level data and geophysical logging data. Equivalent freshwater

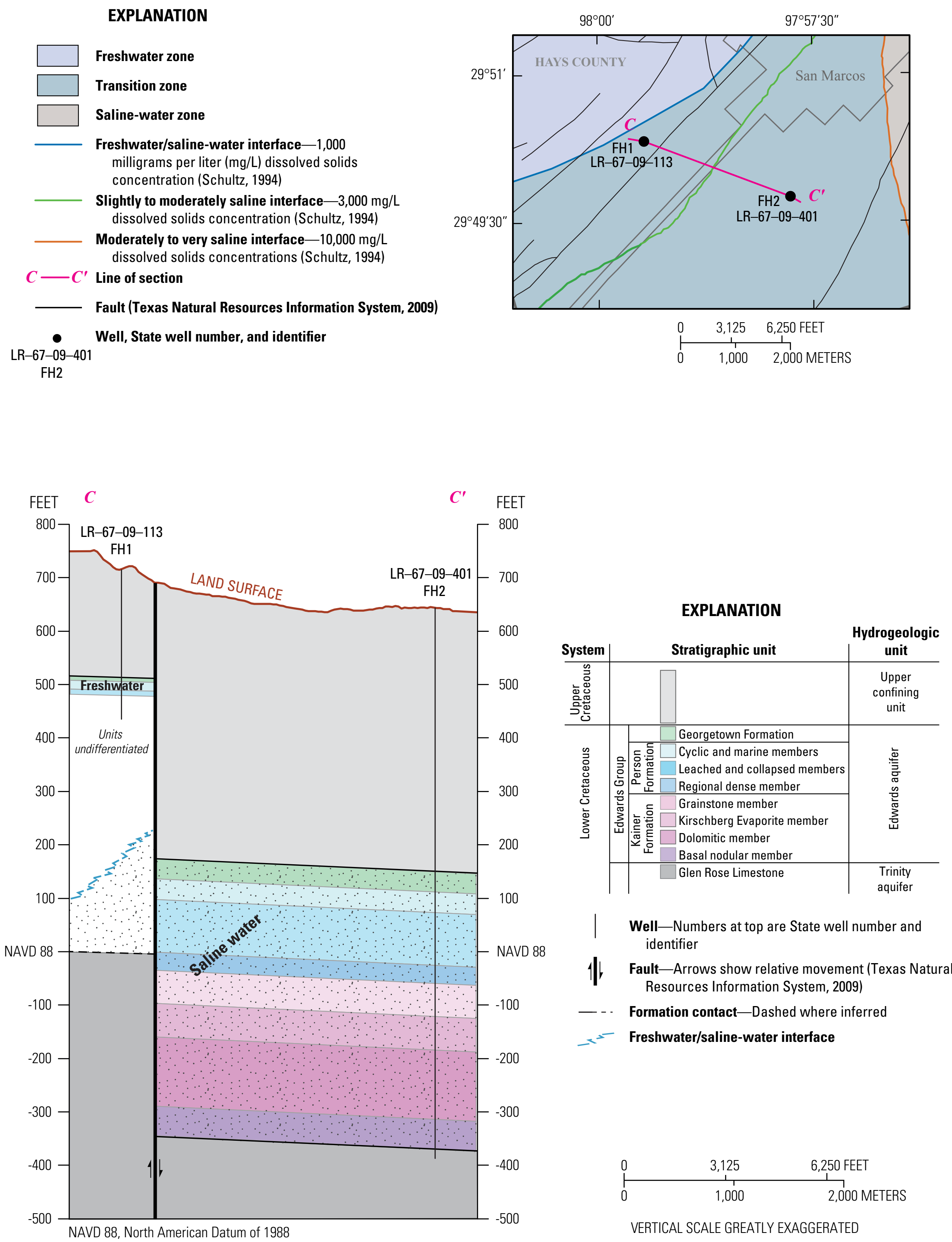


Figure 7. Hydrogeologic section of the Fish Hatchery transect (*C–C′*), San Antonio segment of the Edwards aquifer, south-central Texas (modified from Lambert and others, 2010, fig. 7).

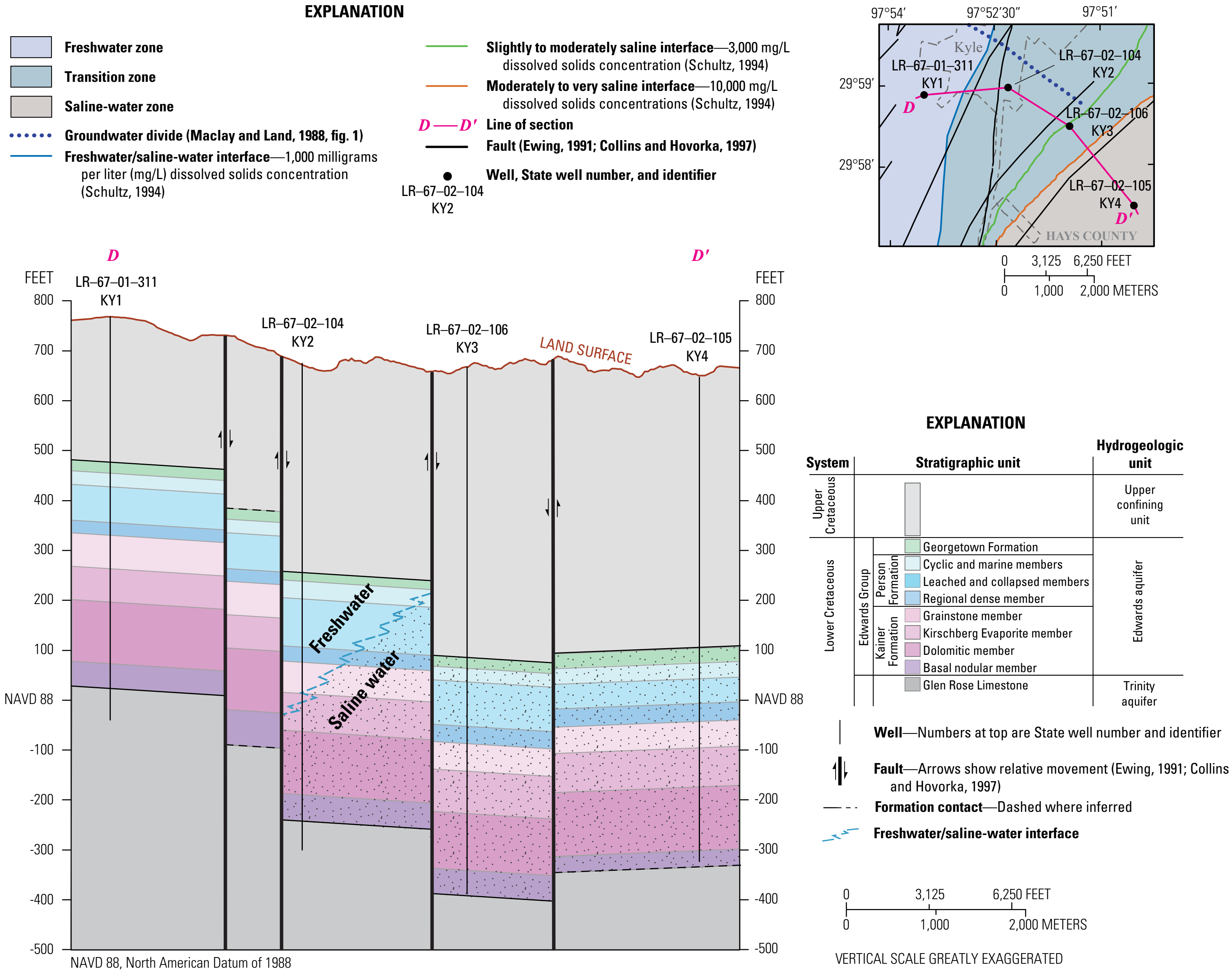


Figure 8. Hydrogeologic section of the Kyle transect (*D–D′*), San Antonio segment of the Edwards aquifer, south-central Texas (modified from Lambert and others, 2010, fig. 8).

heads were computed from measured water-level data collected by the USGS coincident with borehole geophysical data collection in 2010 and 2011 for 13 wells in the East Uvalde, Tri-County, Fish Hatchery, and Kyle transects. Daily mean equivalent freshwater heads calculated during geophysical logging periods were assessed and compared to mean daily equivalent freshwater heads (mean daily equivalent freshwater heads computed as the average of daily mean freshwater head values for the period of record shown for each well) and to other transect wells to asses hydraulic conditions and how well connected transect wells were to each other. Corrections to equivalent freshwater head and total transmissivity data collected from the 13 monitoring wells within and surrounding the freshwater/saline-water interface are listed in table 2.

Borehole Geophysical Log Data

All geophysical probes used in the data collection for this study, and in the previous studies by Lambert and others (2009, 2010) at the site, were interfaced to a Century System VI or a Mount Sopris Matrix log-acquisition system in the USGS Texas Water Science Center logging unit. The log-acquisition systems were interfaced to a personal computer and data storage by way of a digital connection. Limitations, calibration procedures, and algorithms of the geophysical probes are described by the manufacturers (Century Geophysical Corp., 2012; Mount Sopris Instruments, 2012). Additional descriptions of logging tools and their applications are in Keys (1997) and Stanton and others (2007).

Table 2. Corrections to equivalent freshwater head and transmissivity data collected from 13 monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2010.

[gal/min, gallon per minute; ft, foot; corrected drawdown, measured drawdown corrected by equivalent freshwater head correction; ft^2/day, square foot per day; ND, could not be calculated because of negative drawdown; O, could not be pumped because of overhead obstructions. Well descriptors: freshwater, dissolved solids concentration less than 1,000 milligrams per liter; saline water, dissolved solids concentration greater than 1,000 milligrams per liter; interface, freshwater and saline water in stratified lenses; values in red indicate negative drawdown measurements; water levels increased while pumping these wells because of changes in pumping at nearby wells]

Well name	Discharge rate (gal/min)	Measured drawdown (ft)	[1]Equivalent freshwater head correction (ft)	Corrected drawdown (ft)	[2]Total transmissivity (gallon/day/ft)	Total transmis-sivity (ft^2/day)	[3]Radius of influence (ft)	Well descriptor based on water type	Data collection date
East Uvalde 1	15.0	7.20	-0.002	7.20	3,130	418	192	Freshwater	8/16/2010
East Uvalde 2	11.3	5.20	-0.014	5.19	3,270	437	193	Freshwater	8/12/2010
East Uvalde 3	16.4	-0.68	-0.112	-0.79	ND	ND	ND	Saline water	8/4/2010
East Uvalde 4	16.4	-0.02	-0.143	-0.16	ND	ND	ND	Saline water	8/10/2010
Tri-County 1	O	O	O	O	O	O	O	Freshwater	6/23/2010
Tri-County 2	12.5	2.41	-1.392	1.02	18,400	2,460	177	Interface	6/14/2010
Tri-County 3	13.2	0.21	-0.104	0.11	186,000	24,900	240	Saline water	6/24/2010
Tri-County 4	12.5	9.54	-0.114	9.43	1,990	266	174	Saline water	6/16/2010
Fish Hatchery 2	18.0	6.97	-0.134	6.84	3,950	528	162	Saline water	8/2/2010
Kyle 1	11.3	7.65	-0.016	7.63	2,220	297	131	Freshwater	7/19/2010
Kyle 2	12.0	8.47	-3.376	5.09	3,530	472	192	Interface	7/12/2010
Kyle 3	18.0	8.22	-0.212	8.01	3,370	451	192	Saline water	8/21/2010
Kyle 4	20.0	1.65	-0.483	1.17	25,700	3,440	195	Saline water	7/26/2010

[1]Equivalent freshwater head corrections, or the difference in equivalent freshwater head values from ambient to stressed conditions, were used to account for changes in water densities as formation water was pulled into the borehole during pumping.

[2]$T = 1,500 * (Q/S_w)$, where T = total transmissivity (gallon/day/ft), Q = discharge rate (gal/min), and S_w = drawdown (ft) (Driscoll, 1986).

[3]Computed by using the Flow-Log Analysis of Single Holes (FLASH) (Day-Lewis and others, 2011).

Geophysical logging data (logs) collected by the USGS for this study were collected following American Society of Testing and Materials (ASTM) borehole geophysical standard procedures: (1) ASTM Standard Guide for Planning and Conducting Borehole Geophysical Logging - D5753-05 (American Society of Testing and Materials, 2010), (2) ASTM Standard Guide for Conducting Borehole Geophysical Logging: Mechanical Caliper - D6167 - 97 (American Society of Testing and Materials, 2004), and (3) ASTM Standard Guide for Conducting Borehole Geophysical Logging Electromagnetic Induction - D6726 - 01 (American Society of Testing and Materials, 2007). All logs were collected in digital format and were recorded in the proprietary formats of the data acquisition equipment used to collect the logs. These proprietary data formats were converted to and archived as Log ASCII Standard (LAS) files (Canadian Well Logging Society, 2011) for tabular data and presented as chart logs in Portable Document Format (PDF) (Adobe® Acrobat®) files.

Electromagnetic (EM) Flowmeter Data

The EM flowmeter measures the rate and direction of vertical flow in a borehole by using the principle of Faraday's law of induction. The EM flowmeter probe consists of an electromagnet and two electrodes 180 degrees apart and 90 degrees to the magnetic field inside a hollow cylinder or tube. The voltage induced by a conductor (water) moving at right angles through the magnetic field is directly proportional to the velocity of the conductor (water) through the field (Century Geophysical Corporation, 2012).

Generally, when using the EM flowmeter to measure low-velocity vertical flow in small-diameter (narrower than 12 inches) boreholes, rubber diverters are installed around the sensor to direct the waterflow through the open tube in the sensor. For this study a flow diverter equal to about 75 percent of the diameter of the borehole was used to help direct water through the sensor on the EM flowmeter probe and improve stability of EM flowmeter measurements (fig. 9). The diameter of the tool sensor and voltage response are calibrated, and the volume of flow is instantaneously recorded. The direction of vertical waterflow is determined by the polarity of the response, with upward flow being positive and downward flow being negative. This technique works well for flow of more than 0.1 gallons per minute (gal/min) and improves the ability to measure changes in flow during trolling logs. For flow velocities less than 0.1 gal/min, using an undersized flow diverter may result in underestimating vertical flow magnitudes or not detecting very small flow zones. In general, zones of higher hydraulic head allow flow into the borehole and upward through the tool, and the flow then exits the borehole in a zone of lower hydraulic head (fig. 9).

EM flowmeter data were collected (logged) in the borehole at various stationary locations (flow stations) throughout the water column and by trolling the EM flowmeter in a continuous run through the length of the water column. Stationary and trolling EM flowmeter data were collected during both ambient and stressed conditions. Stationary EM flowmeter measurements were collected at several intervals throughout the water column to accurately determine the ambient vertical flow within the borehole. When possible, EM flowmeter data were collected at the same depths during both ambient and stressed conditions.

Specific Conductance and Temperature Data

Specific conductance and temperature data are best recorded in boreholes containing ambient fluid that have had sufficient time to stabilize. Ideally, fluid logs are the first logs recorded downward, recording ambient conditions before other probes have passed through the borehole to avoid vertically mixing the borehole fluid. Curve deflections on the specific-conductance and temperature logs can indicate horizontal or vertical flow, stratification of borehole fluid, or screen openings in cased wells. Subsurface temperature data can provide information about groundwater flow rates. In the absence of appreciable groundwater flow, conduction is the only heat transport mechanism and results in a conductive geothermal gradient, or simply "conductive thermal gradient" (Anderson and others, 2003).

Fluid electrical conductivity, which is the reciprocal of fluid resistivity, provides data related to the concentration of dissolved solids in the fluid column and movement within the borehole (Keys, 1997). Although specific conductance can be calculated from traditional fluid resistivity logs, sensitivity is greatly reduced in highly conductive water since resistivity and conductivity are reciprocals. An Idronaut model 2IFA-1000 multiparameter probe (Idronaut probe) was used to record specific-conductance and temperature profiles. The temperature sensor consists of a platinum resistance thermometer fitted on a stainless steel housing. The conductivity sensor uses seven platinum electrodes grouped within a cell, a central electrode that emits an alternating current, and six peripheral electrodes for current return and potential (voltage) measurements (Integrated Ocean Drilling Program, 2007). The cell is mounted on a special cylindrical plastic body that guarantees thermic insulation and is filled with silicone oil (Mount Sopris Instruments, 2012). Specific conductance is calculated from the fluid conductivity and temperature values the Idronaut probe directly measures. The Idronaut probe was calibrated for temperature and specific conductance at 25 degrees Celsius. Solutions of known temperature and conductivity were used in a two-point calibration as described by the manufacturer (Mount Sopris Instruments, 2012).

In addition to measuring specific conductance with the Idronaut multiparameter probe, calculated specific-conductance values were calculated using data measured with a Century Geophysical 9721 EM flowmeter probe (Century probe), which measures fluid resistivity. Fluid conductivity logs were calculated from the EM flowmeter fluid resistivity logs and then corrected by using the Idronaut specific-conductance logs to provide ambient and stressed calculated specific-conductance logs.

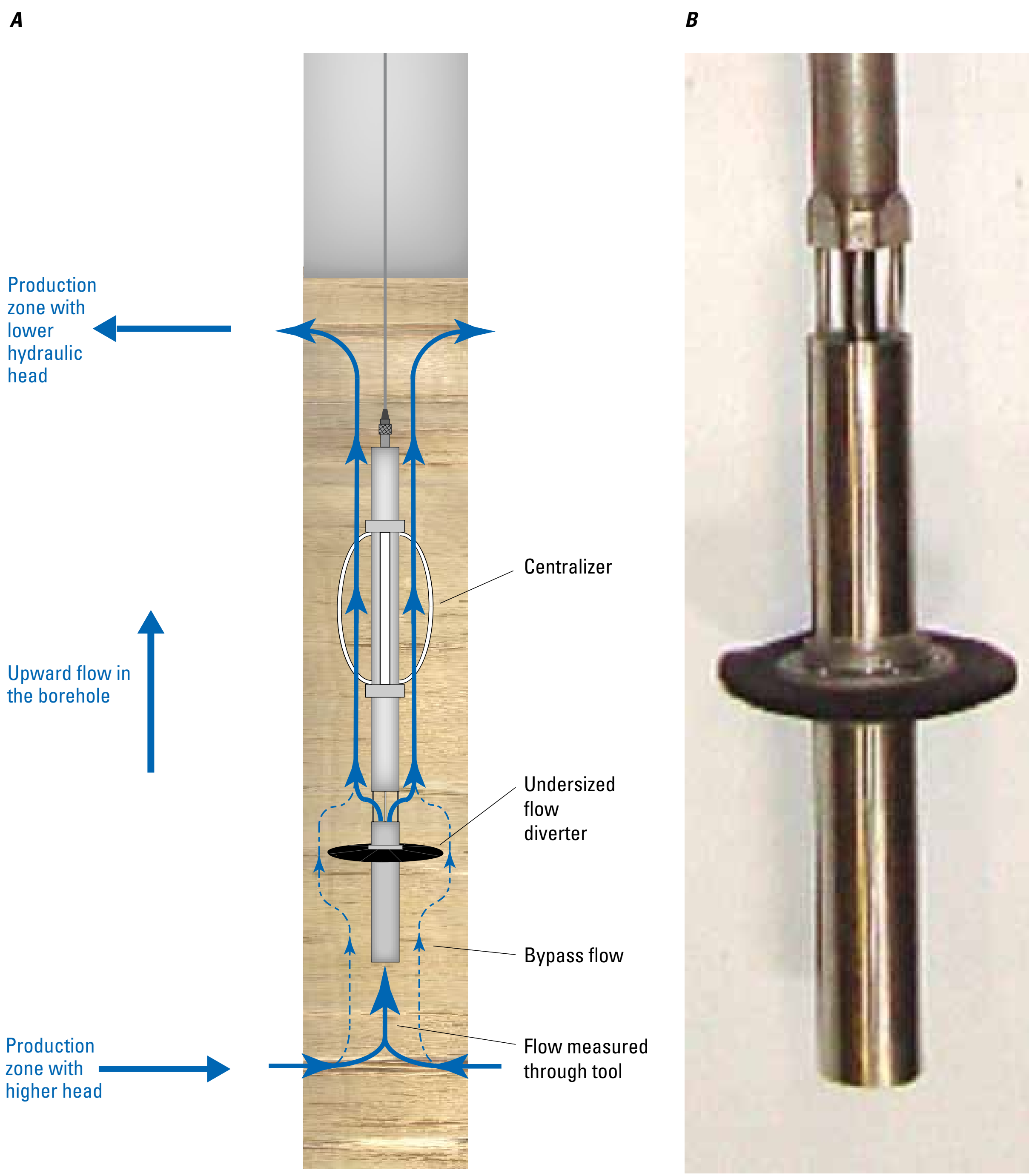


Figure 9. *A*, Diagram of an electromagnetic (EM) flowmeter, with an undersized flow diverter installed, in a borehole showing zones of differing hydraulic head and direction of flow in the borehole. *B*, Photograph of an EM flowmeter with rubber flow diverter installed.

Equivalent Freshwater Heads[3]

Equivalent freshwater heads define hydraulic gradients horizontally, and environmental-water heads define hydraulic gradients vertically (Lusczynski, 1961). Equivalent freshwater heads were used to compute lateral (horizontal) head gradients along transects to indicate whether there is a potential for lateral flow of saline-water into the freshwater zone of the San Antonio segment of the Edwards aquifer. Pressure transducers installed in monitoring wells measured environmental-water head. Environmental-water heads differ from equivalent freshwater heads by amounts corresponding to the difference in salinity between the well water and freshwater (Lusczynski, 1961). Because saline water is slightly denser than freshwater, the higher the salinity of the environmental water the greater the difference between the environmental-water head relative to the equivalent freshwater head.

The use of equivalent freshwater heads to infer groundwater flow in structurally sloping aquifers containing water of variable density can lead to errors (Davies, 1987). In the case of the Edwards aquifer, normal faulting has resulted in fault blocks that are offset, which might result in slopes large enough to challenge the assumption of a horizontal aquifer; nevertheless, the judgment was made that equivalent freshwater heads provide the best data from which to compute lateral-head gradients for this report.

Measured water-level altitudes can be converted to equivalent freshwater heads by applying the following equation:

$$p = \rho g l, \qquad (1)$$

(Cooper and others, 1964, p. C28)
where

- p is the pressure at the bottom of the well,
- ρ is the density of the water in the well,
- g is the acceleration of gravity, and
- l is the length of the water column in the well.

Equating the right-side term of equation 1 for environmental-water and freshwater columns and solving for the length of the freshwater column yields the following:

$$l_f = (\rho_s/\rho_f)(l_s), \qquad (2)$$

where

- l_f is the length of equivalent freshwater column, in feet;
- ρ_s is the density of environmental water, in milligrams per cubic centimeter;
- ρ_f is the density of freshwater, in milligrams per cubic centimeter;
- ρ_s/ρ_f is the density correction factor (unitless); and
- l_s is the length of environmental-water column (total depth of the well minus the depth from land surface to the water level in the well), in feet.

The density of the environmental water was obtained by using a Web-based JavaScript calculator from the Johns-Hopkins University Applied Physics Laboratory (2005). Three variables were entered into the Web-based calculator to compute the density of environmental water: length of the environmental water column converted to meters (the units required by the calculator), average specific conductance of the water column at 25 degrees Celsius in microsiemens per centimeter, and average temperature in the water column in degrees Celsius. These variables were measured by using the Idronaut multiparameter geophysical log or from a manual water-level measurement made by using an electrical water-level indicator at the time of logging. The specific conductance and temperature logs for the entire water column were used to compute average specific conductance and temperature values representative of the entire water column. Freshwater density values (temperature dependent) for each well, assumed to be representative of the period 2010–11, were calculated by using a Web-based JavaScript (Copyright© 1995, 2010, Oracle and/or its affiliates. All rights reserved.) calculator from Frostburg State University Chemistry Department (2011). Density correction factors for each well were thus computed as the average density of environmental water divided by the average density of freshwater. After the length of the equivalent freshwater column was computed by using equation 2, the equivalent freshwater head was computed as follows:

$$h_f = h_s + (l_f - l_s), \qquad (3)$$

where

- h_f is the equivalent freshwater head, in feet above the land surface datum (LSD) referenced to the North American Vertical Datum of 1988;
- h_s is the environmental-water head, in feet above LSD;
- l_f is the length of equivalent freshwater column, in feet; and
- l_s is the length of environmental-water column, in feet (total depth of the well minus the water-level depth measured from land surface of the well).

Environmental-water head was computed as altitude of LSD minus water-level depth below land surface measured at the time of logging. Equivalent freshwater head calculations were made for the 13 monitoring wells at the four transects to assess potential horizontal-head gradients across the transition zone.

[3] This section modified from Lambert and others (2010, p. 14).

Borehole Geophysical, Fluid, and Hydraulic Properties

During 2010, the USGS collected borehole geophysical data consisting of vertical flow rates, specific conductance, and fluid temperature from 13 wells within and surrounding the transition zone of the Edwards aquifer (fig. 1). EM flowmeter data were analyzed to determine the direction and magnitude of vertical flow in the open intervals of the boreholes and the distributions of transmissivity in the adjacent section of the aquifer. Specific-conductance and temperature logs were used to calculate equivalent freshwater heads (table 3), and these heads were assessed as indicators of potential vertical and horizontal flow zones.

In addition to the logs collected throughout this study, the wells were logged by using similar geophysical methods by the USGS between 2002 and 2007 (Lambert and others, 2009). The years logged varied by well. Among the logs collected during that study were 16- and 64-inch normal resistivity, single-point resistance, spontaneous potential, three-arm caliper, optical televiewer (OBI), acoustic televiewer (ABI), EM induction, EM flowmeter (under ambient conditions), and natural gamma. In-depth explanations of each additional method may be found in Keys (1997) and Stanton and others (2009). All geophysical logs for each borehole were analyzed collectively to enhance the understanding of the hydrogeologic properties of the transition zone.

Borehole Geophysical Properties

Borehole geophysical data such as natural gamma, formation resistivity, and caliper are commonly used to characterize and identify stratigraphic units. These data were collected by the USGS at all 15 transect wells during a previous study (Lambert and others, 2009; 2010) and utilized to determine the stratigraphy of each well. Optical and acoustic televiewer logs were also collected and used to confirm the tops and bases of hydrostratigraphic subdivisions (stratigraphic picks) and assess voids and faulting identified in the rocks surrounding each well.

East Uvalde Transect

The East Uvalde Transect wells were logged by using geophysical methods periodically from 2002 through 2007 (Lambert and others, 2009) and in 2010. For the freshwater well EU1, the natural gamma log is consistent with relatively pure carbonate rocks, showing a lack of contrast and low gamma counts, which indicate low clay content in the upper interval of the log and increasing silt or clayey material in the lower interval, as indicated by the greater count rate and variability in the gamma counts (fig. 10). In contrast, the gamma logs for freshwater well EU2 and saline-water wells EU3 and EU4 (figs. 11–13) show greater variation in lithology in the upper interval than that in well EU1, indicating more silty or clayey intervals interbedded with carbonate rocks. The bottom silty or clayey intervals were common and correlated in the bottom parts of wells EU3 and EU4 corresponding to the McKnight Formation and the West Nueces Formation of the Maverick Basin depositional province. The increased apparent thickness of the McKnight Formation in well EU3 could be caused by the possibility of faulting intersecting the well EU3 borehole in the southwest part of *A–A'*(fig. 5). Wells EU3 and EU4 are completed in the basinal facies of the Maverick Basin depositional province, and wells EU1 and well EU2 are completed in the reefal facies of the Devils River Limestone in the Devils River Trend depositional province (fig. 5) (Lambert and others, 2010).

The caliper logs for all the East Uvalde transect wells confirm that the boreholes are about 6 inches in diameter along most of the lengths, except in some intervals where the boreholes were enlarged beyond 6 inches to 7–9 inches in diameter. In wells EU1 and EU2, the larger-diameter intervals correspond to vuggy (cavity-filled) sections in the Devils River Limestone (figs. 10–11). In wells EU3 and EU4, the diameters of the boreholes were enlarged in the upper sections of the boreholes that correspond to the Salmon Peak and upper McKnight Formations (figs. 12–13). The caliper logs and the gamma logs, indicate that most of the porosity and permeability in the East Uvalde wells are associated with cleaner (less silty or clayey content) limestone sections and are the result of secondary porosity development.

The optical televiewer and acoustic televiewer logs (hereinafter image logs) for well EU1 show that the borehole was competent in the upper sections and vuggier and fractured in the lower sections, with the greatest number of vugs, or enlarged pores, occurring at the bottom of the well (fig. 10). In well EU2, the image logs show secondary porosity development in the form of bedding-plane fractures and vugs in the Devils River Limestone (fig. 11). The image logs for wells EU3 and EU4 show numerous vugs and bedding-plane fractures in the borehole associated with enlarged intervals shown on the caliper logs. The highest concentrations of these vugs and bedding-plane fractures was in the Salmon Peak Formation in well EU3 and in the Salmon Peak and West Nueces Formations in well EU4 (figs. 12–13). The vertical striping effects on the image logs were an artifact of poor centralization, or nonuniform borehole roundness, and not necessarily an indicator of vugs.

Table 3. Summary of hydraulic property data for 13 monitoring wells within and surrounding the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2010.

[ft, feet; LSD, land-surface datum; NAVD 88, North American Vertical Datum of 1988; h_s, environmental-water head; l_s, length of environmental-water column; t, depth-averaged water temperature; °C, degrees Celsius; C, depth-averaged specific conductance; µS/cm, microsiemens per centimeter at 25 °C; ρ_s, environmental-water density; g/cm³, grams per cubic centimeter; ρ_f, freshwater density; l_f, length of equivalent freshwater column; h_f, equivalent freshwater head. Well descriptors: freshwater, dissolved solids concentration less than 1,000 milligrams per liter; saline water, dissolved solids concentration greater than 1,000 milligrams per liter; interface, freshwater and saline water in stratified lenses]

Well name	Data collection date	Ambient water level (ft below LSD)[1]	Time of ambient water-level measurement	Altitude of LSD (ft above NAVD 88)	Well depth (ft below LSD)	h_s (ft above NAVD 88)	l_s (ft)	t (°C)	C (µS/cm)[2]	ρ (g/cm³)[3]	ρ (g/cm³)[4]	Density correction ratio (ρ_s/ρ_f)	l_f (ft)[5]	l_f-l_s (ft)[5]	h_f (ft above NAVD 88)[6]	Well descriptor based on water type
East Uvalde 1	8/16/2010	119.96	0805	874.02	1,490	754.06	1,370.04	29.74	748	997.85	995.73	1.002	1,372.95	2.91	756.97	Freshwater
East Uvalde 2	8/12/2010	145.13	0728	899.91	1,553	754.78	1,407.87	23.14	466	999.64	997.51	1.002	1,410.88	3.01	757.79	Freshwater
East Uvalde 3	8/4/2010	128.95	0856	877.55	1,397	748.60	1,268.05	29.80	3,800	998.79	995.71	1.003	1,271.98	3.93	752.53	Saline water
East Uvalde 4	8/10/2010	125.41	0833	867.02	1,442	741.61	1,316.59	35.77	3,340	996.59	993.77	1.003	1,320.32	3.73	745.34	Saline water
Tri-County 1	6/23/2010	205.27	0736	871.01	860	665.74	654.73	24.52	897	998.41	997.17	1.001	655.55	0.82	666.56	Freshwater
Tri-County 2	6/14/2010	37.17	0720	709.08	1,025	671.91	987.83	25.36	6,830	1,001.10	996.96	1.004	991.93	4.10	676.01	Interface
Tri-County 3	6/24/2010	10.93	0920	674.00	1,170	663.07	1,159.07	26.35	10,900	1,002.78	996.69	1.006	1,166.15	7.08	670.15	Saline water
Tri-County 4	6/16/2010	-2.67	0736	648.92	1,550	651.59	1,552.67	29.14	11,700	1,002.59	995.91	1.007	1,563.08	10.41	662.00	Saline water
Fish Hatchery 2	8/2/2010	51.03	0745	642.51	980	591.48	928.97	25.96	13,500	1,003.80	996.80	1.007	935.50	6.53	598.01	Saline water
Kyle 1	7/19/2010	176.00	0740	770.52	802	594.52	626.00	24.75	1,150	998.40	997.11	1.001	626.81	0.81	595.33	Freshwater
Kyle 2	7/12/2010	93.23	0906	674.32	920	581.09	826.77	24.34	8,040	1,001.75	997.22	1.005	830.53	3.76	584.85	Interface
Kyle 3	8/21/2010	100.92	0800	678.28	1,042	577.36	941.08	24.83	27,800	1,011.22	997.09	1.014	954.41	13.33	590.69	Saline water
Kyle 4	7/26/2010	69.65	0945	646.70	947	577.05	877.35	25.18	24,800	1,009.45	997.00	1.012	888.30	10.95	588.00	Saline water

[1]Water level measured with a electric-tape water-level meter.

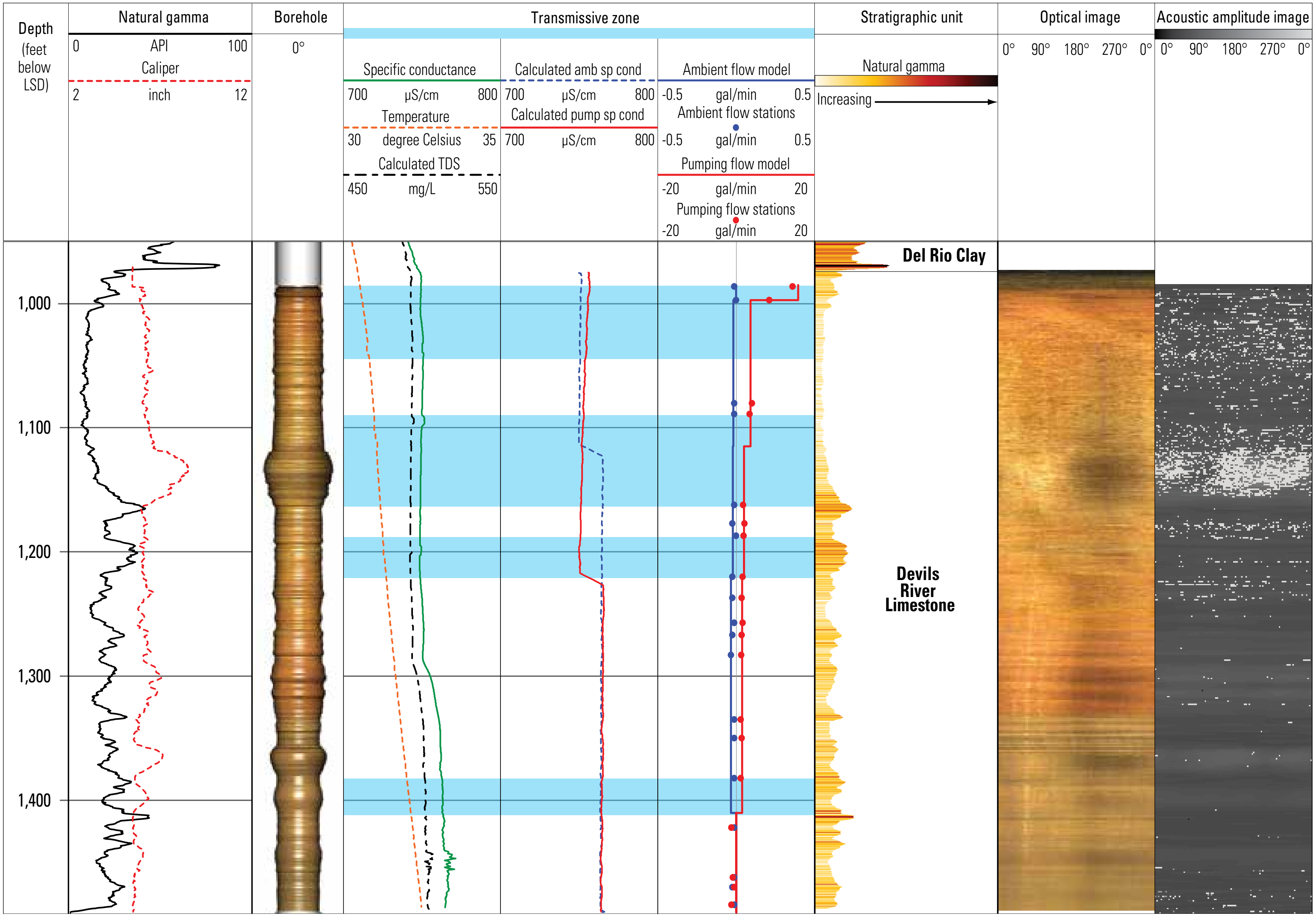
[2]Depth-averaged value from Idronaut log data collected at each well.

[3]Computed by using the Johns-Hopkins equation of state calculator (Johns-Hopkins University Applied Physics Laboratory, 2005) with l_s, t, and C.

[4]Computed by using the Frostburg State University water density calculator (Frostburg State University Chemistry Department, 2011) with t.

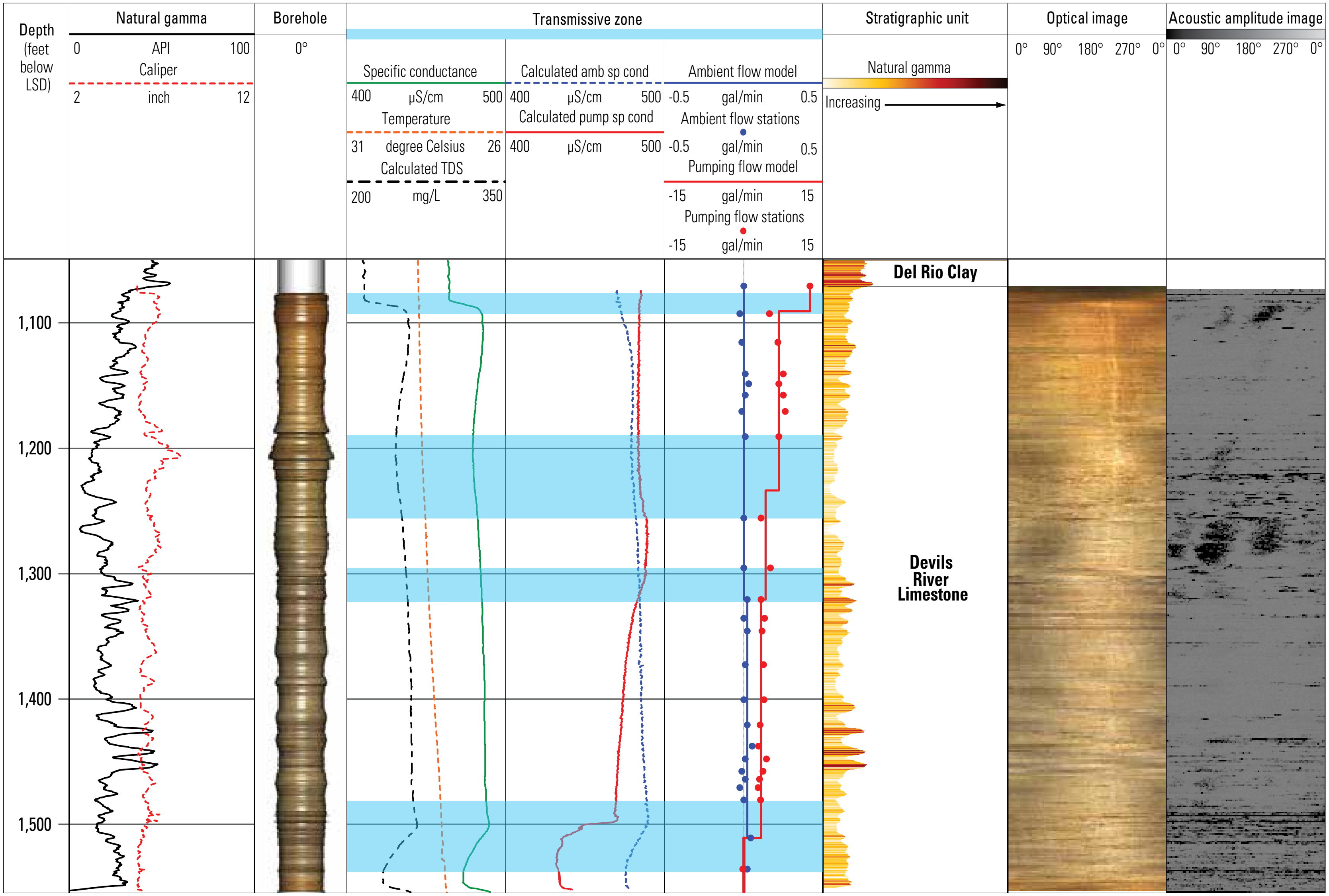
[5]$l_f = (\rho_s/\rho_f)\ (l_s)$ from Cooper and others (1964, p. C28).

[6]$h_f = h_s + (l_f - l_s)$.



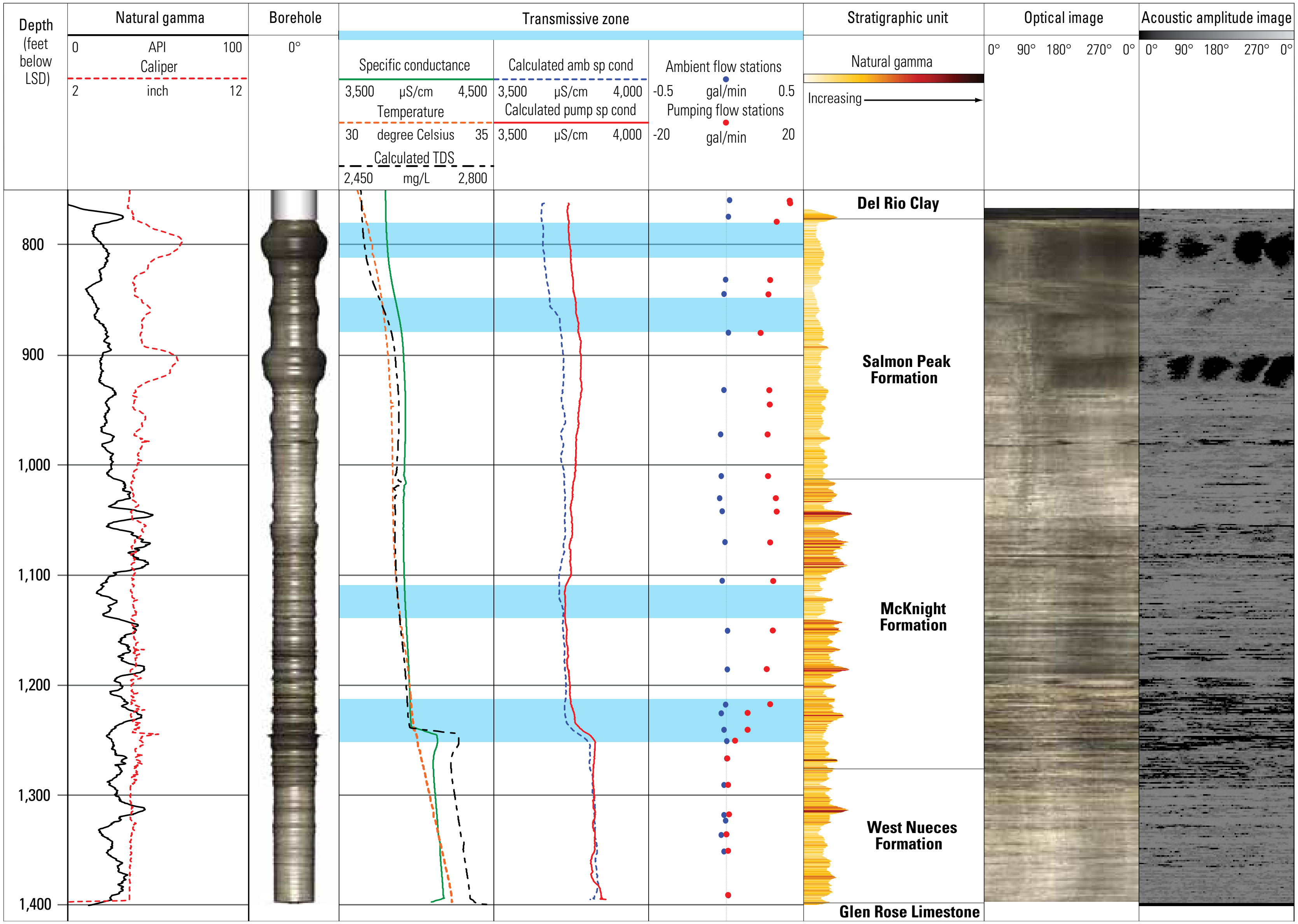
API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 10. Borehole geophysical data from East Uvalde transect well EU1 (YP–69–52–202), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.



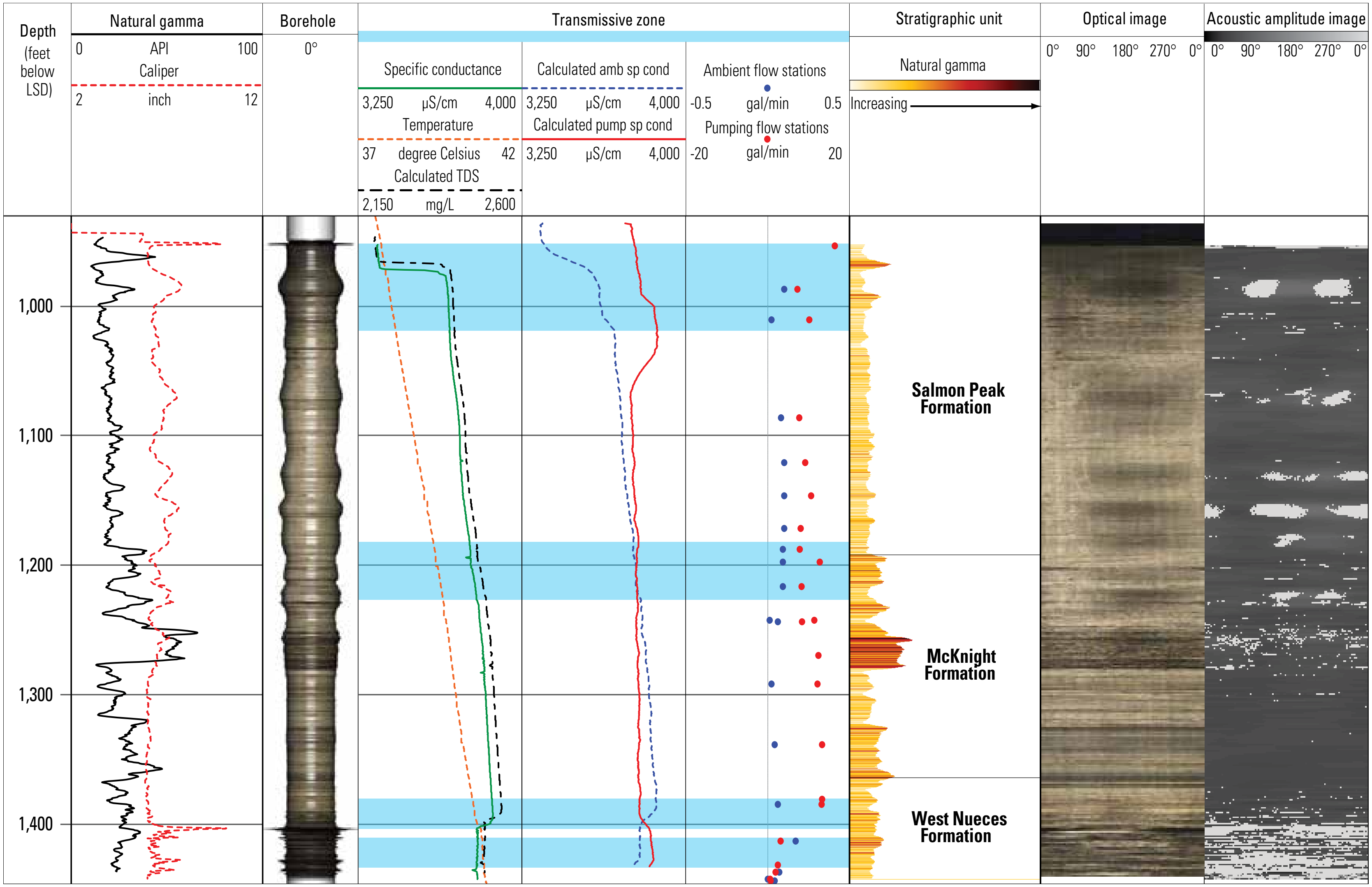
API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 11. Borehole geophysical data from East Uvalde transect well EU2 (YP–69–44–902), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.



API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 12. Borehole geophysical data from East Uvalde transect well EU3 (YP–69–51–606), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.



API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

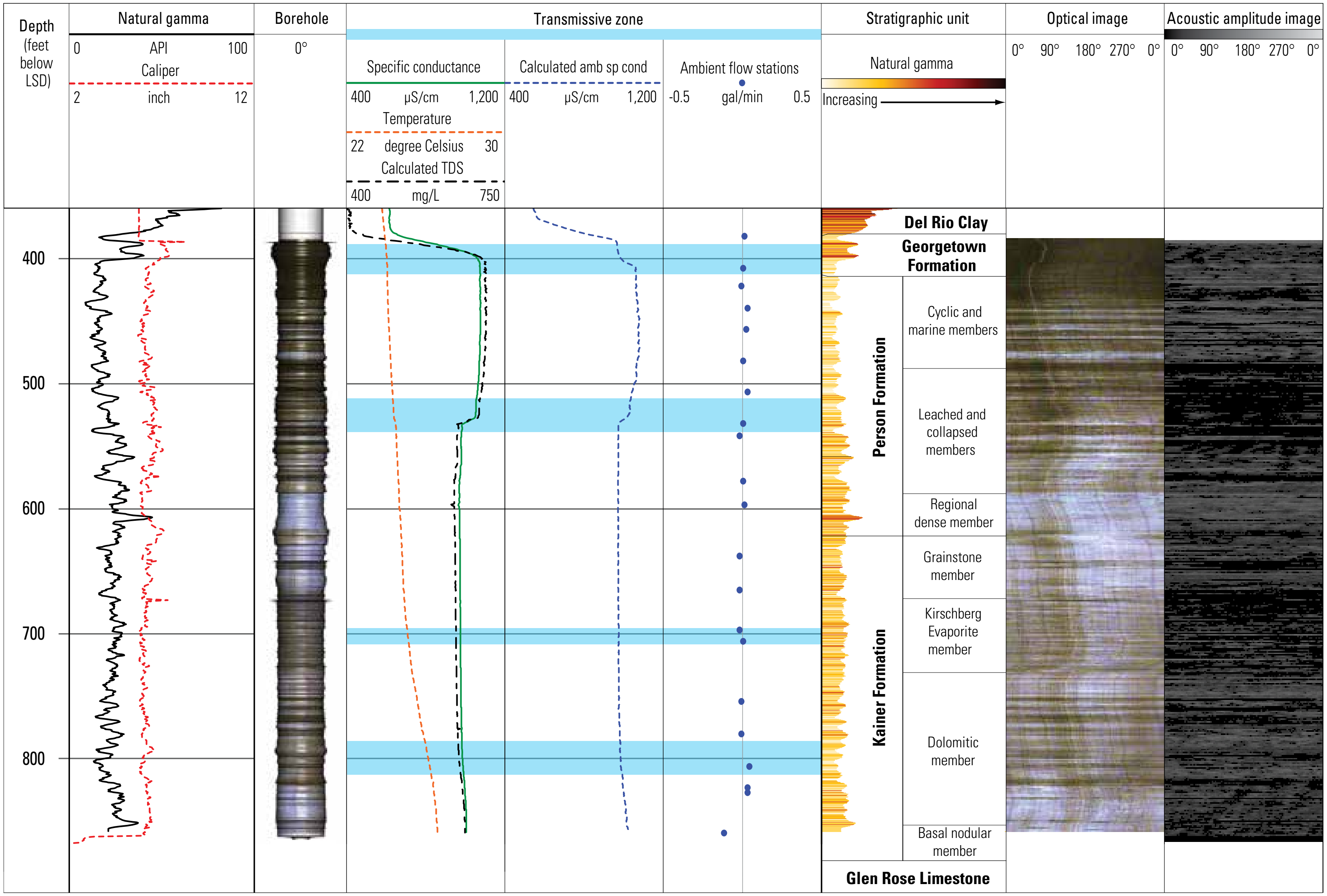
Figure 13. Borehole geophysical data from East Uvalde transect well EU4 (YP–69–52–404), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.

Tri-County Transect

The Tri-County transect wells were logged by using geophysical methods periodically from 2003 through 2007 with the exception of well TC3, which was logged during 2003 through 2006 (Lambert and others, 2009), and in 2010. The natural gamma logs for freshwater well TC1, interface well TC2, and saline-water wells TC3 and TC4 (figs. 14–17) are consistent with Edwards aquifer rocks that are composed predominantly of limestone with a few minor clayey sections without any major contrast in lithology, despite the layered structure in the San Marcos Platform depositional province reflected by the members (hydrogeologic subdivisions) of the Person and Kainer Formations (fig. 3).

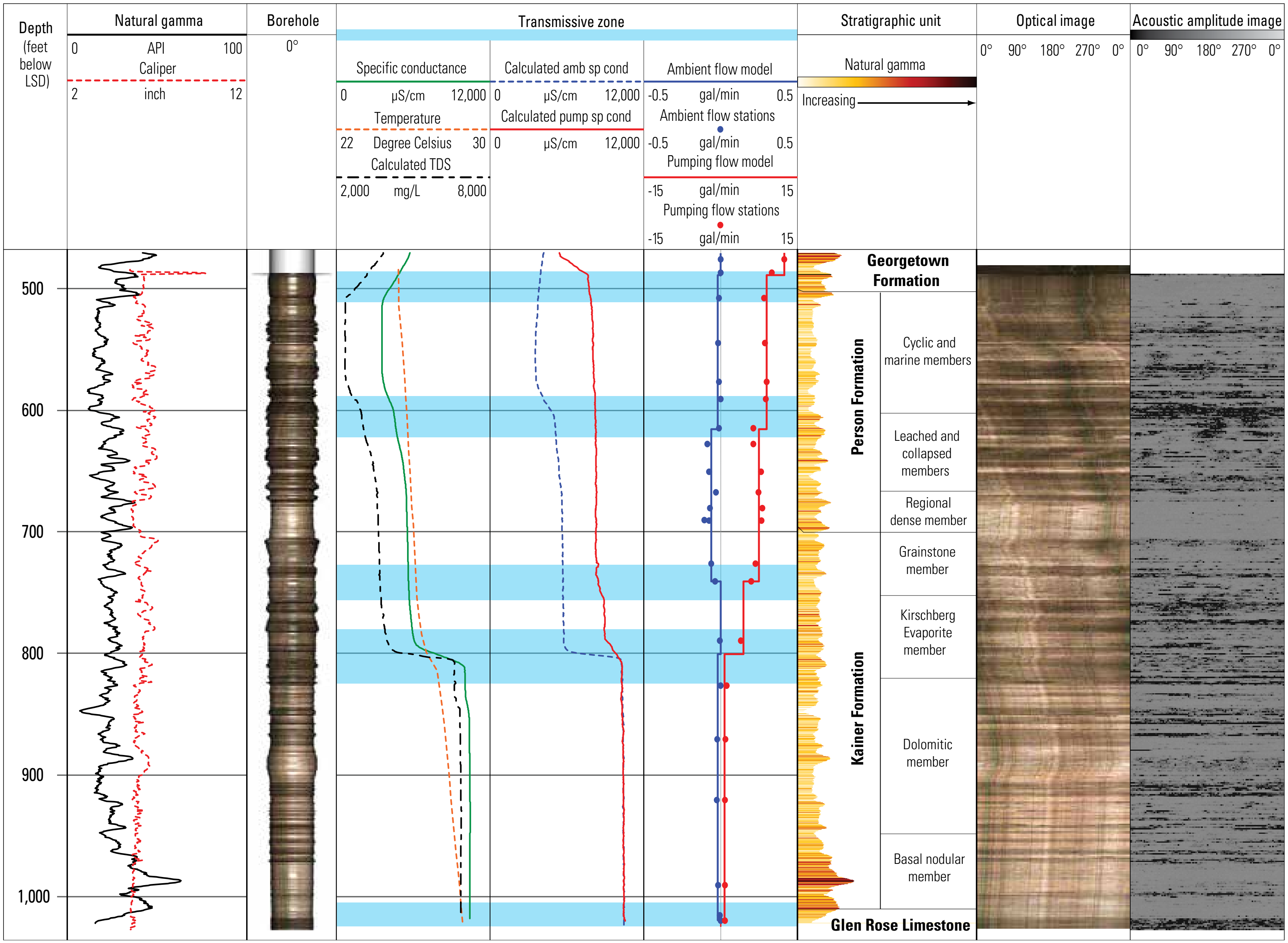
The caliper logs for these wells show numerous enlargements of the boreholes beyond their 6-inch diameters, some extending to nearly 10 inches in diameter. The enlargements are irregularly shaped and pitted and are prevalent in all sections except the regional dense member, the basal nodular member, and the upper part of the Glen Rose Limestone.

The image logs of the Tri-County wells show fractures and vuggy intervals that correspond to the enlarged intervals measured by the caliper logs. The fractures and vuggy intervals are commonly present in all sections except in the regional dense member, the basal nodular member, and the upper part of the Glen Rose Limestone. Small bedding-plane fractures and vugs are interspersed throughout the remaining sections of the boreholes. The vertical striping effect on the image logs for well TC2 near about 600–620 ft were artifacts of poor centralization, or nonuniform borehole roundness, and not necessarily an indicator of vugs.



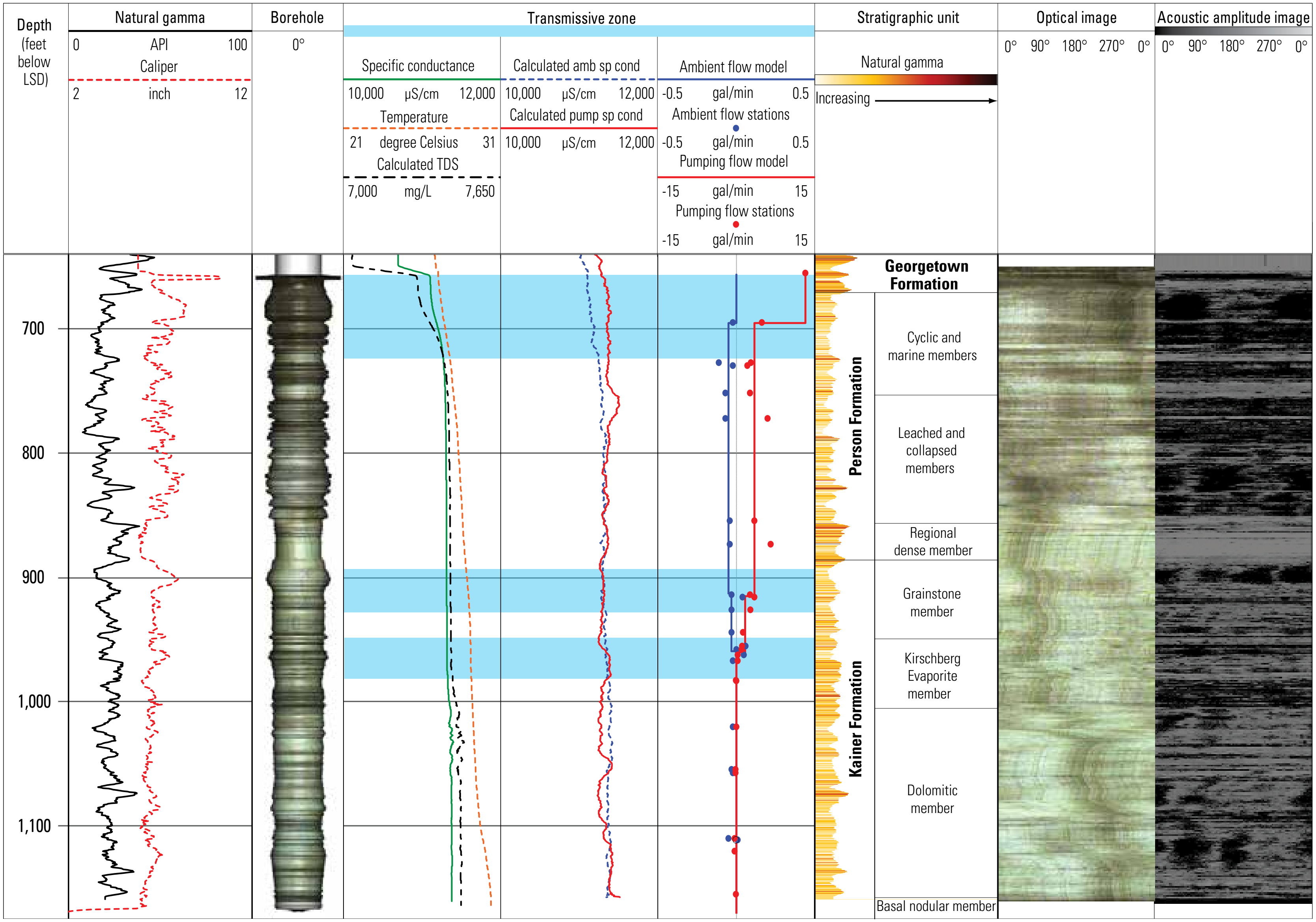
API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 14. Borehole geophysical data from Tri-County transect well TC1 (KX–68–30–314), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–10.



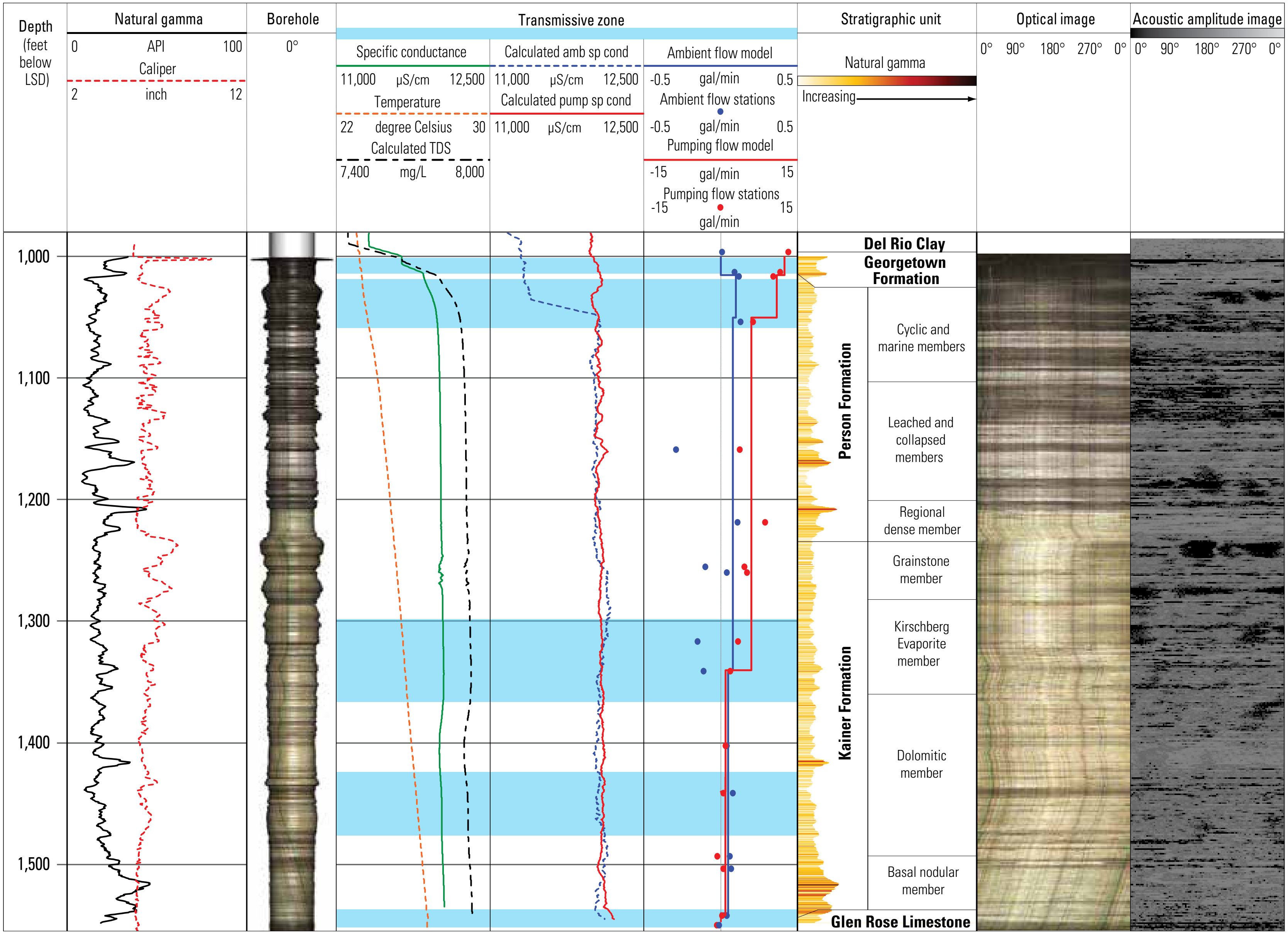
API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 15. Borehole geophysical data from Tri-County transect well TC2 (KX–68–31–403), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–10.



API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 16. Borehole geophysical data from Tri-County transect well TC3 (KX–68–31–511), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–10.

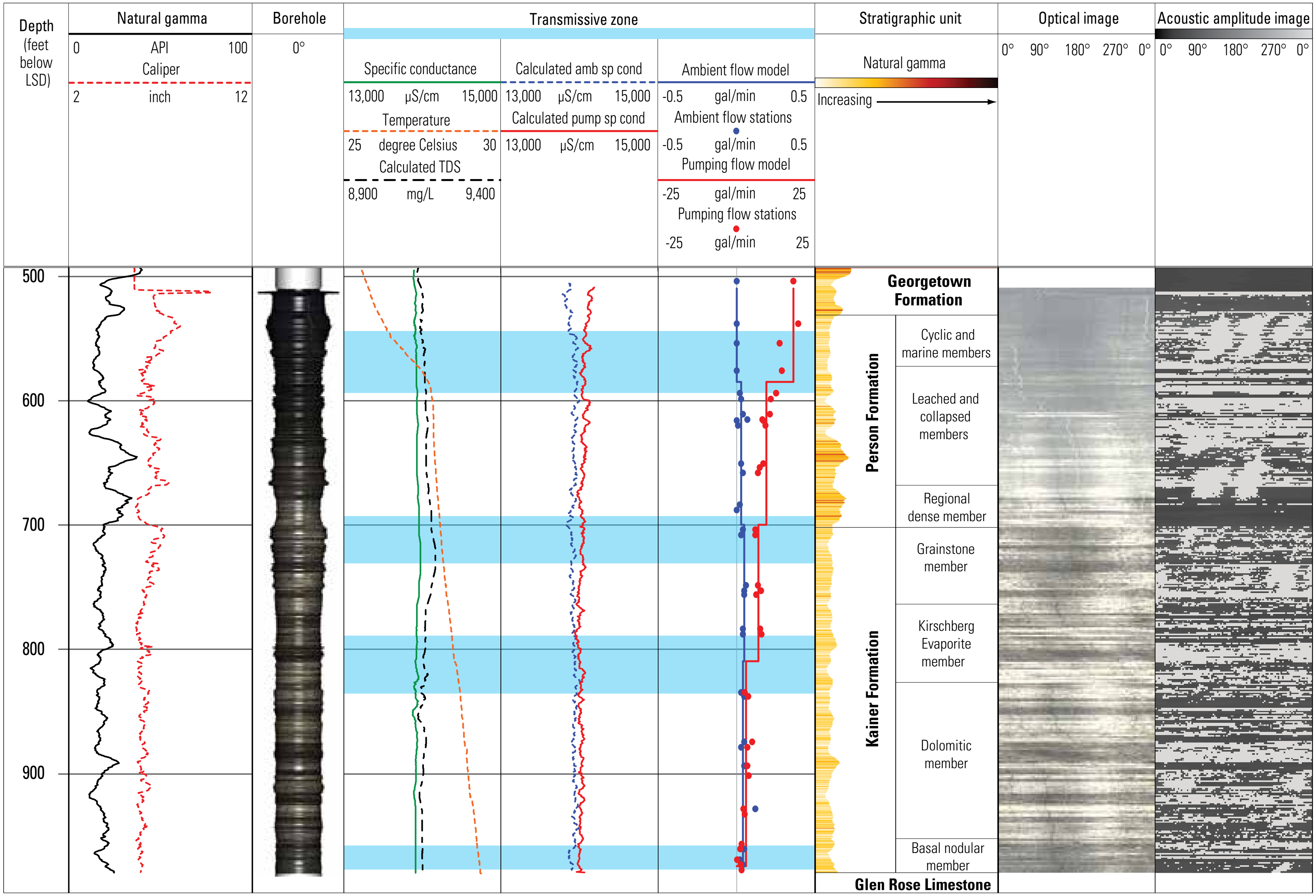


API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 17. Borehole geophysical data from Tri-County transect well TC4 (KX–68–31–808), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–10.

Fish Hatchery Transect

The Fish Hatchery Transect well FH2 was logged by using geophysical methods periodically from 2002 through 2007 (Lambert and others, 2009) and in 2010. The natural gamma log for the Fish Hatchery transect saline-water well FH2 (fig. 18) is consistent with fairly clean limestone, interbedded with silt or clayey lenses through the borehole sections. This well is completed in rocks of the San Marcos Platform depositional province (figs. 2–3). At well FH2, the natural gamma log indicates clayey intervals that correspond to the leached and collapsed members and parts of the Kirschberg Evaporite, dolomitic, and basal nodular members of the Edwards Group. The caliper and image logs show enlargements of the borehole diameter with rough intervals in the lower part of the Georgetown Formation, cyclic and marine members, leached and collapsed members, and the grainstone and Kirschberg Evaporite members, as well as small bedding-plane fractures in the Kirschberg Evaporite and dolomitic members. The vertical striping effects on the image logs for well FH2 were artifacts of poor centralization of the logging instrument, nonuniform borehole roundness, or large diameter of the borehole and were not necessarily an indicator of vugs (fig. 18). Because of the relatively large difference in altitude between the open-hole sections of wells FH1 and FH2, caused by fault offset (fig. 7), and the relative shallowness of well FH1, it was judged that additional data collection at well FH1 would not be advantageous for this project.



API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 18. Borehole geophysical data from Fish Hatchery transect well FH2 (LR–67–09–401), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.

Kyle Transect

The Kyle Transect wells were logged by using geophysical methods periodically from 2002 through 2007 (with the exception of well KY2, which was first logged in 2003) (Lambert and others, 2009) and in 2010. The natural gamma logs for freshwater well KY1, interface well KY2, and saline-water wells KY3 and KY4 are consistent with clean limestone with some silty or clayey intervals in the cyclic and marine members and the leached and collapsed members of the Person Formation in the upper part of the Edwards aquifer and in the dolomitic and basal nodular members of the Kainer Formation, which compose the lower part of the Edwards aquifer (figs.3 and 19–22). Wells KY1, KY2, and KY3 also are open to the Glen Rose Limestone (Trinity aquifer) at the base of the wells (fig. 8). The gamma logs for these wells indicate that the Glen Rose Limestone has greater silt or clay content than do the formations of the overlying Edwards aquifer (figs. 19–22).

The caliper logs from wells KY1, KY2, and KY3 indicate borehole enlargement to diameters greater than the nominal 6 inches in all sections of the borehole except the regional dense member of the Person Formation, the basal nodular member of the Kainer Formation, and the upper part of the Glen Rose Limestone (figs. 19–22). In well KY4, the caliper log indicates that the borehole is enlarged along most of its length from the cyclic and marine members to the upper part of the dolomitic member (fig. 22).

The image logs from the Kyle wells confirm the enlarged diameter areas that were recorded by the caliper logs. Some of the enlarged intervals are relatively more porous and vuggy as compared to other intervals, and other enlarged intervals show small zones of bedding-plane fractures and vugs. The vertical striping effects on the image logs for well KY4 were artifacts of poor centralization of the logging instrument, nonuniform borehole roundness, or large diameter, and were not necessarily an indicator of vugs (fig. 22).

Borehole Fluid and Hydraulic Properties

Curve deflections of fluid logs in ambient conditions can indicate horizontal or vertical flow, stratification of borehole fluid, or screen openings in cased wells. For this report, a change in specific conductance at 10 ft intervals was used to define small deflections as changing less than 10 microsiemens per centimeter (µS/cm); moderate deflections as changing 10–100 µS/cm; and large deflections as changing more than 100 µS/cm. Fluid property logs were utilized as indicators of possible flow zones, calculations of equivalent freshwater head, and as a characterization of the borehole fluid. Borehole fluid was classified on the basis of total dissolved solids (TDS) concentration. To correlate specific-conductance values with the salinity descriptors for TDS concentration as specific conductance, observations of specific conductance and TDS concentration from Lambert and others (2009) were related by regression to yield threshold values of specific conductance corresponding to the threshold values of TDS concentrations that describe freshwater and categories of saline water (slightly, moderately, or very saline) (table 4).

A correlation between TDS and specific conductance transecting the transition zone was established by linear regression (app. 2) (Helsel and Hirsch, 2002) from 62 samples collected from 15 monitoring wells (table 1) during 1999–2007 (Lambert and others, 2009). The coefficient of determination for the regression (r^2) was 0.99. The r^2 is the fraction of the variance explained by the regression, where values closer to 1 indicate a stronger relation. Specific-conductance logs were then used to calculate estimated TDS profiles for each well by using the following equation:

$$E_{TDS} = (0.6522)(C_f), \quad (4)$$

where

E_{TDS} is the estimated TDS, in milligrams per liter; and

C_f is the specific conductance, in microsiemens per centimeter at 25 degrees Celsius.

The EM flowmeter probe in addition to flow rates, measures fluid resistivity data, and fluid resistivity was measured fluid resistivity under both ambient and stressed (pumping) hydraulic conditions during logging. These data were then converted into logs of fluid conductivity by using the following equation:

$$C_{fc} = (1 / R_f)(10{,}000), \quad (5)$$

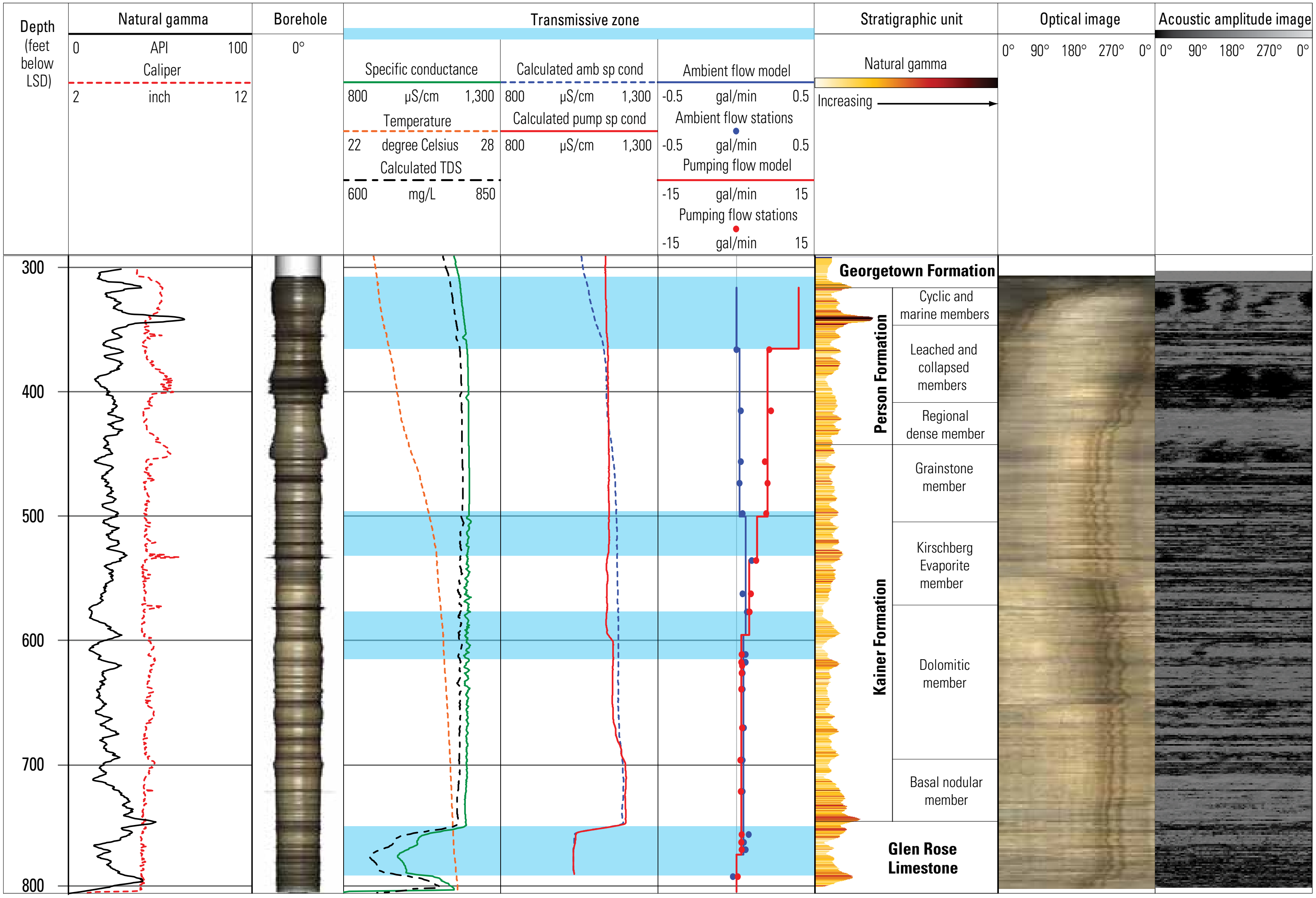
where

C_{fc} is the fluid conductivity, in microsiemens per centimeter; and

R_f is the fluid resistivity, in ohm-meters.

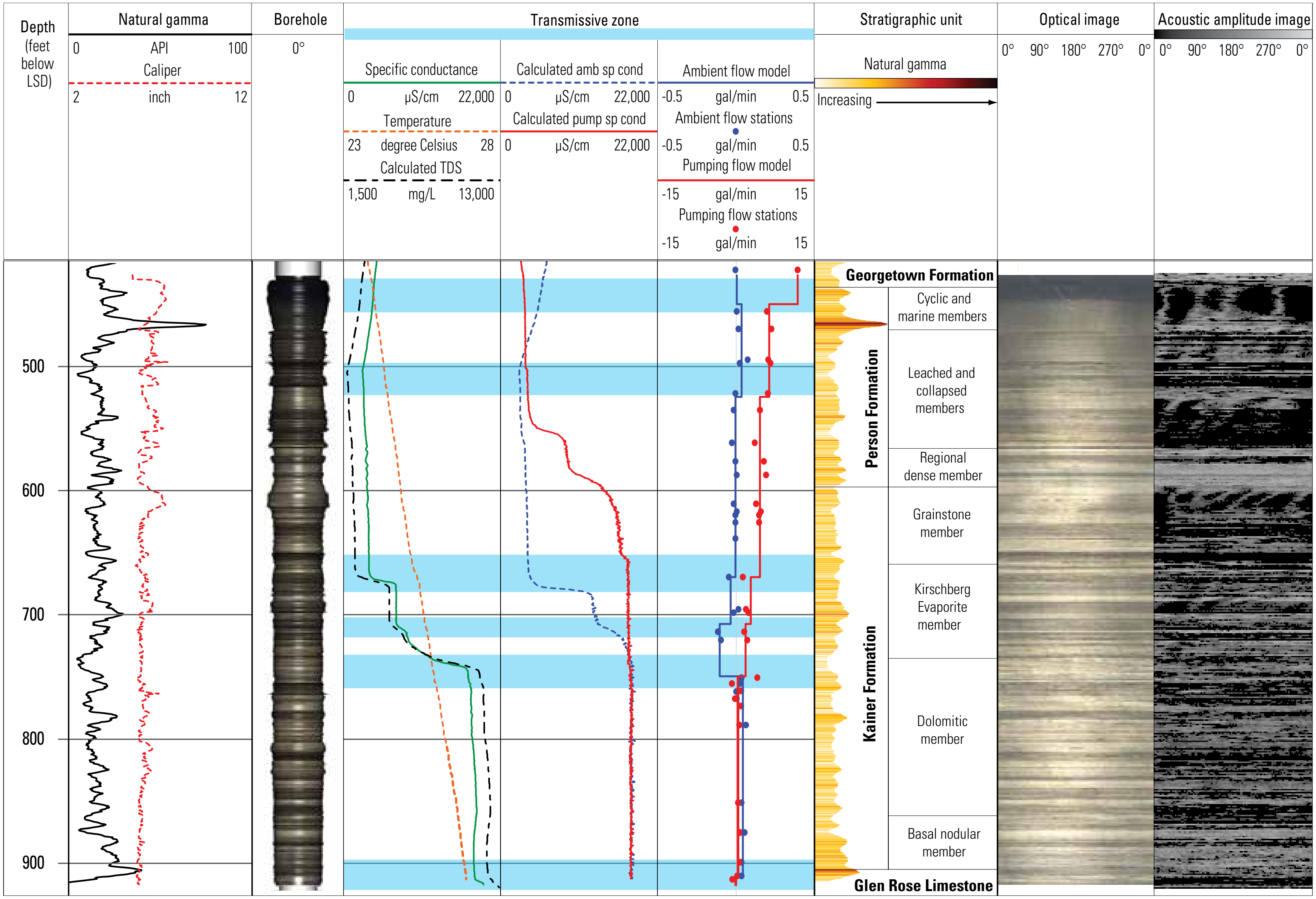
Then, the logs of calculated specific conductance obtained during ambient and stressed hydraulic conditions were adjusted by applying correction factors derived from specific-conductance data collected with the Idronaut fluid properties geophysical probe, to yield calculated specific-conductance logs. Changes between ambient and stressed calculated specific-conductance logs were analyzed to identify possible vertical or horizontal flow zones and direction of flow and to establish the relation between the ambient water in borehole and the formation water entering the borehole during pumping.

Fluid properties, EM flowmeter data, and well-completion data were used to assess vertical flow within the borehole. Completion data for the wells were compiled from a previous report (Lambert and others, 2009) and confirmed by geophysical logs. A numerical model, Flow-Log Analysis of Single Holes (FLASH) (Day-Lewis and others, 2011), was used to process the EM flowmeter data and calculate different zones of transmissivity and hydraulic heads for the open interval of each borehole.



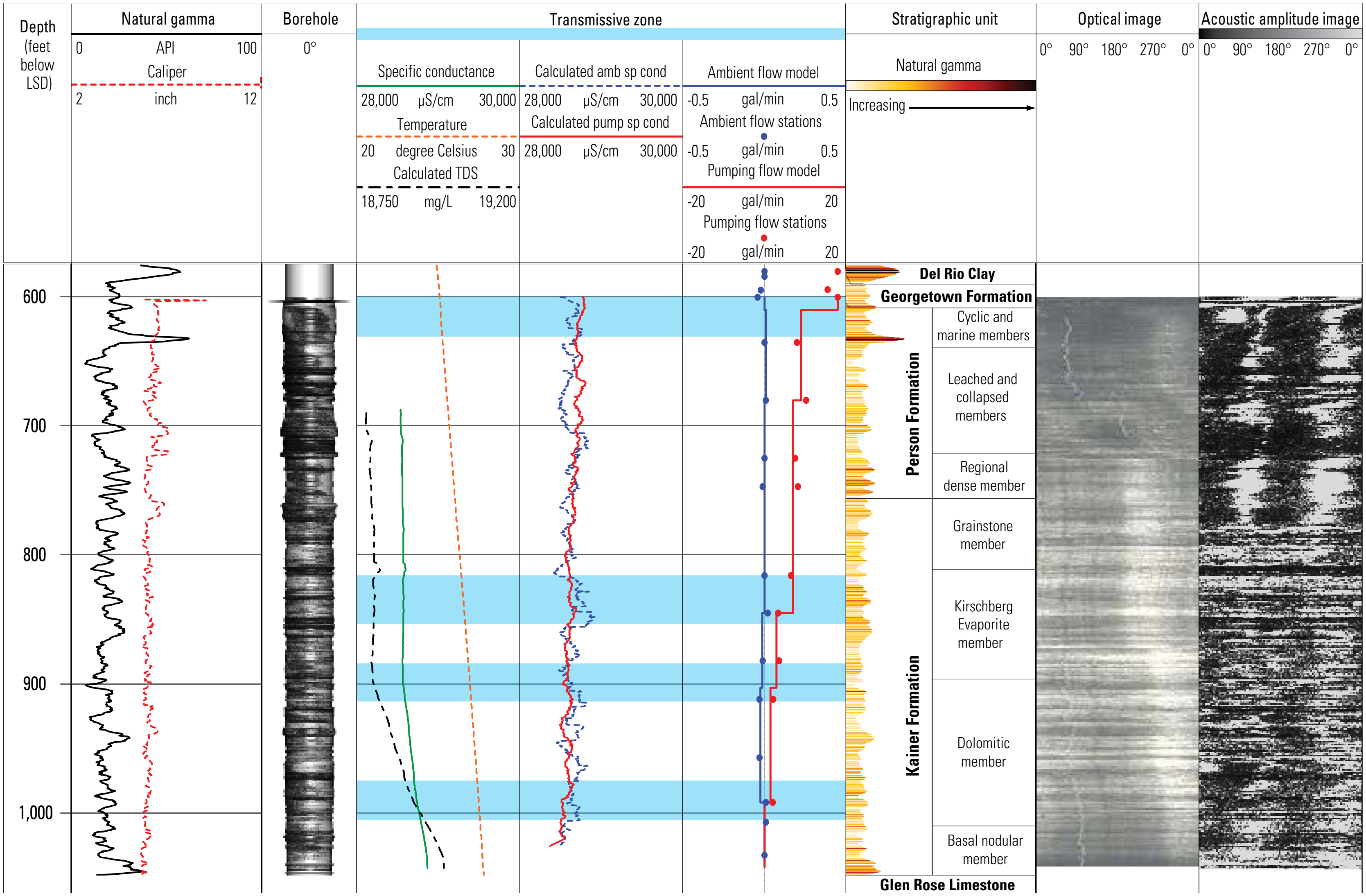
API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 19. Borehole geophysical data from Kyle transect well KY1 (LR–67–01–311), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.



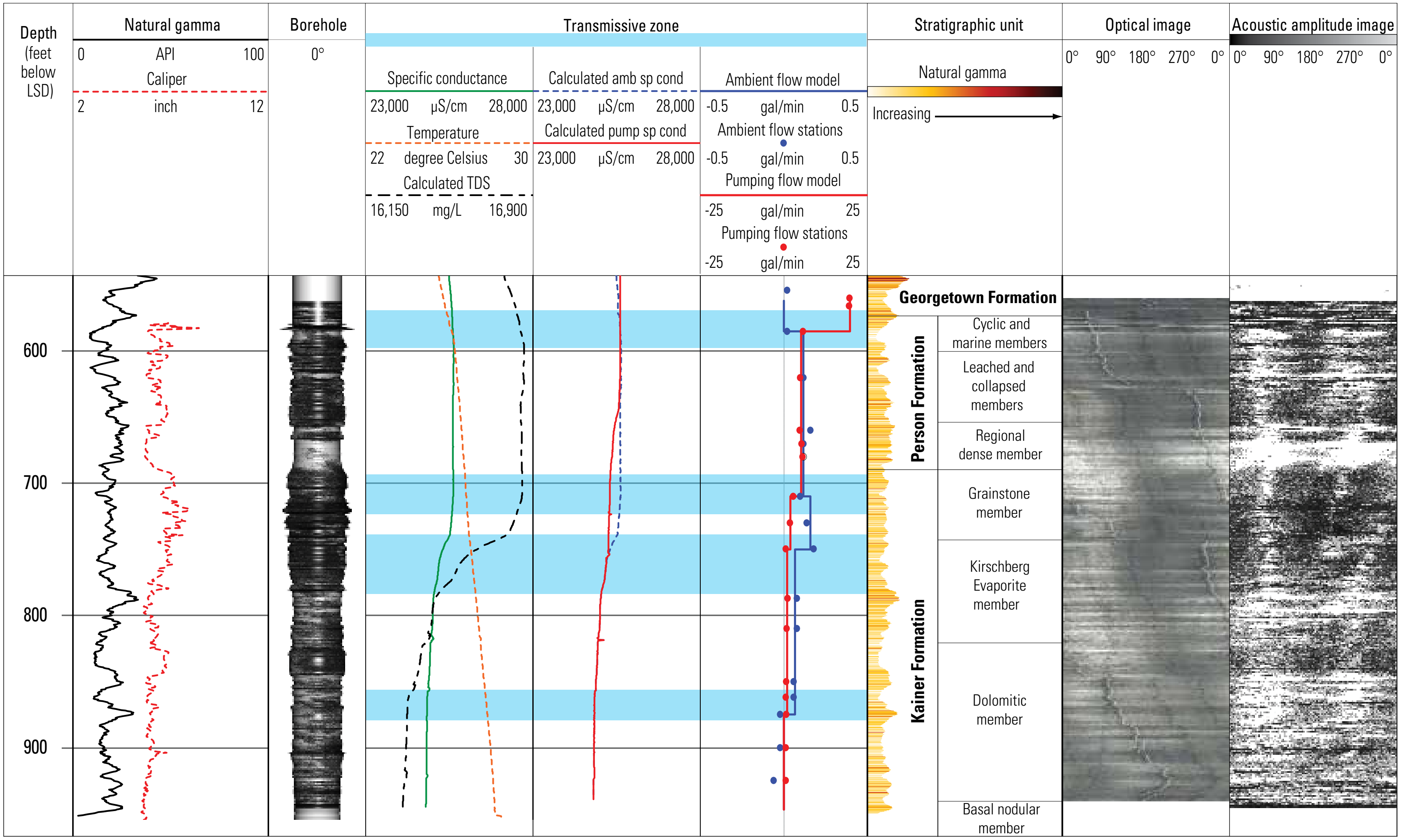
API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 20. Borehole geophysical data from Kyle transect well KY2 (LR–67–02–104), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–10.



API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 21. Borehole geophysical data from Kyle transect well KY3 (LR–67–02–106), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.



API, American Petroleum Institute; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; gal/min, gallons per minute; TDS, total dissolved solids; Calculated amb sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the electromagnetic (EM) flowmeter probe under ambient conditions; Calculated pump sp cond, Specific conductance logs calculated from fluid resistivity logs collected with the EM flowmeter probe under pumped conditions; Calculated TDS, estimated total dissolved solids profile calculated from the specific conductance log; LSD, land-surface datum referenced to the North American Vertical Datum of 1988; °, degree.

Figure 22. Borehole geophysical data from Kyle transect well KY4 (LR–67–02–105), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–10.

Table 4. Specific-conductance values corresponding to the thresholds of total dissolved solids concentrations that define freshwater and different categories of saline water in monitoring wells within and surrounding the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas.

[mg/L, milligrams per liter; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius]

Well descriptor	Total dissolved solids concentration (mg/L)	Specific conductance (µS/cm at 25 °C)[1]
Freshwater	1,000	1,520
Slightly saline water	3,000	4,560
Moderately saline water	10,000	15,200
Very saline water	35,000	53,200

[1]Determined from data collected from 15 monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas (Lambert and others, 2009).

FLASH is a spreadsheet-based graphical user interface (GUI) that supplies multilayered Thiem modeling results for steady-state flow of a borehole (Day-Lewis and others, 2011). FLASH generates a borehole flow log representing the flow that would be measured in a borehole given the specified number of transmissive zones and head values for parts of the aquifer not affected by pumping (referred to as "farfield head values" in FLASH). FLASH modeling results also provide estimates of the difference between the open-hole water level under ambient and stressed conditions and transmissivities and hydraulic heads for two or more water-producing (flow) zones intersecting a single interval of an open borehole under typical field conditions. The input and output data from FLASH are in appendixes 3.01–3.10.

Several hydraulic properties are entered into FLASH to solve the multilayered Thiem analytical model and calculate the output values (radius of influence, transmissivities, and hydraulic heads). The analytical model can estimate either total transmissivity or the radius of influence (the distance for which the well can affect or be affected by its surroundings) for a single well.

Using the Jacob modified formula (Cooper and Jacob, 1946), Driscoll (1986) developed an approximating formula for estimating transmissivity from specific capacity in confined and unconfined aquifers. All of the wells used in this study penetrate unconfined aquifers, and all required data (including ambient water-level, pumping rate, and water-level drawdown) were collected at the time of logging. Transmissivity was estimated from specific capacity by using Driscoll's equation for an unconfined aquifer (Driscoll, 1986, app. 16D):

$$T = 1{,}500 \times Q/s \quad (6)$$

where

T is transmissivity, in gallons per day per foot of drawdown;

Q is well yield or pumping rate, in gallons per minute;

s is drawdown at any point in the vicinity of a well discharging at a constant rate, in feet; and

Q/s is specific capacity, in gallons per minute per foot of drawdown.

In some boreholes, the density of the water column varied as formation water was pulled into the wellbore during pumping, and corrections had to be made to accurately calculate drawdown values. To determine accurate drawdown values, the differences between equivalent freshwater heads, calculated for ambient and stressed conditions, were used as the corrected drawdown values (table 2). These equivalent freshwater heads were calculated by using the calculated specific-conductance data (calculated from fluid resistivity logs from the EM flowmeter probe) collected under ambient and stressed conditions. The hydraulic property data for the 13 monitoring wells transecting the freshwater/saline-water interface are presented in table 3.

East Uvalde Transect

Specific-conductance values measured during ambient conditions in well EU1 on August 16, 2010, were less than 800 µS/cm, which indicated there was freshwater throughout the entire fluid column (table 4). Small deflections in the specific-conductance and temperature curves were identified near 1,290 ft below LSD, indicating that changing flow conditions near this depth in the borehole are possible. The calculated ambient specific-conductance values indicated that, during pumping, freshwater enters the borehole from the Devils River Limestone at approximately 1,220 ft below LSD. The change between the ambient and stressed calculated specific-conductance logs near 1,120 ft below LSD indicates that the flow zone at this depth during ambient conditions is likely more saline compared to flow zone near 1,220 ft below LSD (fig. 10).

Well EU2 is located in the freshwater zone (fig. 1), and fluid logs also indicated freshwater, with specific-conductance values of less than 500 µS/cm for the entire fluid column (table 4). Three small deflections in the ambient specific-conductance and temperature curves at depths near 1,190, 1,240, and 1,502 ft below LSD were identified, indicating possible flow zones. The decrease in the specific-conductance curve for well EU2, near the bottom of the borehole, indicated flow of fresher water into the borehole. Calculated specific-conductance logs also indicated that fresher water was entering the borehole during pumping from near the bottom of the well. This freshwater entering the bottom part of the borehole creates an interesting effect on the calculated stressed specific conductance curve. Moving upward from the bottom part of the borehole, the pumping specific conductance curve shows the decrease in conductivity as the freshwater entered and moved upward in the borehole from about 1,500 to about 1,310 ft below LSD (where higher conductivity water entered the borehole and mixed with the upward flow, increasing the conductivity), and then fresher water entered the borehole at about 1,240 ft below LSD and mixed with the upward-moving water, again reducing the conductivity of pumped water moving upward (fig. 11).

Fluid logs in the range of slightly saline water were measured at well EU3, located in the transition zone; the specific conductance ranged from approximately 3,800 to more than 4,200 µS/cm (table 4). One moderate fluid curve deflection was observed during ambient conditions at approximately 830 ft below LSD; a small curve deflection was also observed near 890 ft below LSD, followed by a larger deflection near 1,240 ft below LSD, indicating possible flow zones. The calculated specific-conductance logs also indicated that, during pumping, the specific conductance of the water entering the borehole from the base of the McKnight Formation increased at about 1,240 ft below LSD (fig. 12).

The fluid logs for well EU4 (located near well EU3) displayed a similar range of specific-conductance values compared to well EU3 and were within the range of slightly saline water; the specific conductance at well EU4 ranged from about 3,300 to 3,800 µS/cm (table 4). There were four small curve deflections in the fluid logs near 1,040, 1,080, 1,140, and 1,230 ft below LSD, indicating possible flow zones. A large deflection at about 970 ft below LSD (near the top of the uncased part of the borehole) and a moderate deflection at about 1,400 ft below LSD (near the bottom of the borehole) were also observed. The large deflection near the top of the uncased part of the borehole around 970 ft below LSD likely indicates a small flow zone. The moderate deflection at about 1,400 ft below LSD corresponded with a large void in the borehole recorded by the caliper as about 11 inches in diameter. The calculated specific-conductance logs likely indicate that, under ambient conditions, slightly saline water enters from the West Nueces Formation near the bottom of the borehole at about 1,400 ft below LSD. When stressed by pumping, the logs indicate that slightly saline water enters the borehole at approximately 1,400 ft below LSD (fig. 13) and moves up the borehole.

Similar total transmissivities of 418 and 437 square feet per day (ft^2/d) were calculated at the two freshwater wells in the East Uvalde transect (wells EU1 and EU2, respectively) in August 2010. In the boreholes for wells EU1 and EU2, the two upper flow zones in both wells had hydraulic head differences near zero (apps. 3.01–3.02), indicating that the upper flow zones in both wells are relatively well connected. Compared to the upper zones, the lower zones displayed greater magnitudes of hydraulic head changes, indicating that the lower flow zones were not as well connected vertically. Because of negative drawdown (water levels increased while measuring hydraulic heads during pumping because of changes in pumping at nearby wells), transmissivity and head values could not be computed for transition zone wells EU3 and EU4. A second round of EM flowmeter logging and pumping was attempted for well EU3 approximately 1 month later; however, a negative drawdown during pumping was again observed (water levels rose while pumping the well), so once again it was not possible to calculate transmissivity and head values. It is hypothesized that the increase in water level during pumping at the two wells was caused by large variability of groundwater pumping in the area.

Ambient EM flowmeter data for the East Uvalde transect varied both in magnitude and direction of flow throughout the transect (fig. 23). All observed ambient flow measurements were small (less than 0.1 gal/min) and similar to measurement accuracy range of the EM flowmeter probe (plus or minus 0.1 gal/min).

Pumping data from the freshwater zone (wells EU1 and EU2) indicated there are three main zones that contribute vertical flow to each well (a fourth flow zone with markedly lower transmissivities values was identified) (fig. 23). All of the flow zones are in the Devils River Limestone; the two main flow zones are near the top of the formation, and a third zone that also contributes appreciable flow is near the bottom of each well. The natural gamma log for well EU1 indicates that the two main flow zones are in a part of the formation that contains relatively clean limestone with little silt or clay. FLASH analyses of ambient and stressed EM flowmeter data from well EU1 indicated that the two uppermost flow zones contributed about 87 percent of the total flow and that the flow zone near the bottom of the borehole contributed about 10 percent. For the other freshwater well in this transect, EU2, flow analyses indicated that the two flow zones in the upper Devils River Limestone contributed about 67 percent of the total flow and the deep flow zone contributed about 26 percent of the total flow (apps. 3.01–3.02). Hydraulic heads in wells EU1 and EU2 changed little from one flow zone to the next deepest one (particularly for the two upper flow zones), indicating that the flow zones are vertically somewhat connected. The deep flow zone indicated by the EM flowmeter data for well EU2 corresponds directly with a large, negative deflection of the fluid logs, indicating an inflow of fresher water from the Devils River Limestone. To the southwest, towards the interface, this same flow zone was observed in well EU1 (with a reduction of flow, however) and displayed no apparent fluid curve deflections. Transmissivity of this zone decreased from 115 ft^2/day at well EU2 to 42.6 ft^2/day at well EU1. These results appear to indicate that this flow zone is spatially connected, although it decreases toward the freshwater/saline-water interface.

In the two transition zone wells, EU3 and EU4, the main zones that contribute vertical flow are likely in the McKnight Formation (well EU3) and in the West Nueces Formation (well EU4). The negative drawdown measurements obtained during pumping of these wells indicate that the variable pumping of other nearby wells was likely affecting the hydraulic conditions in the flow zones contributing groundwater to wells EU3 and EU4 at the time these wells were logged.

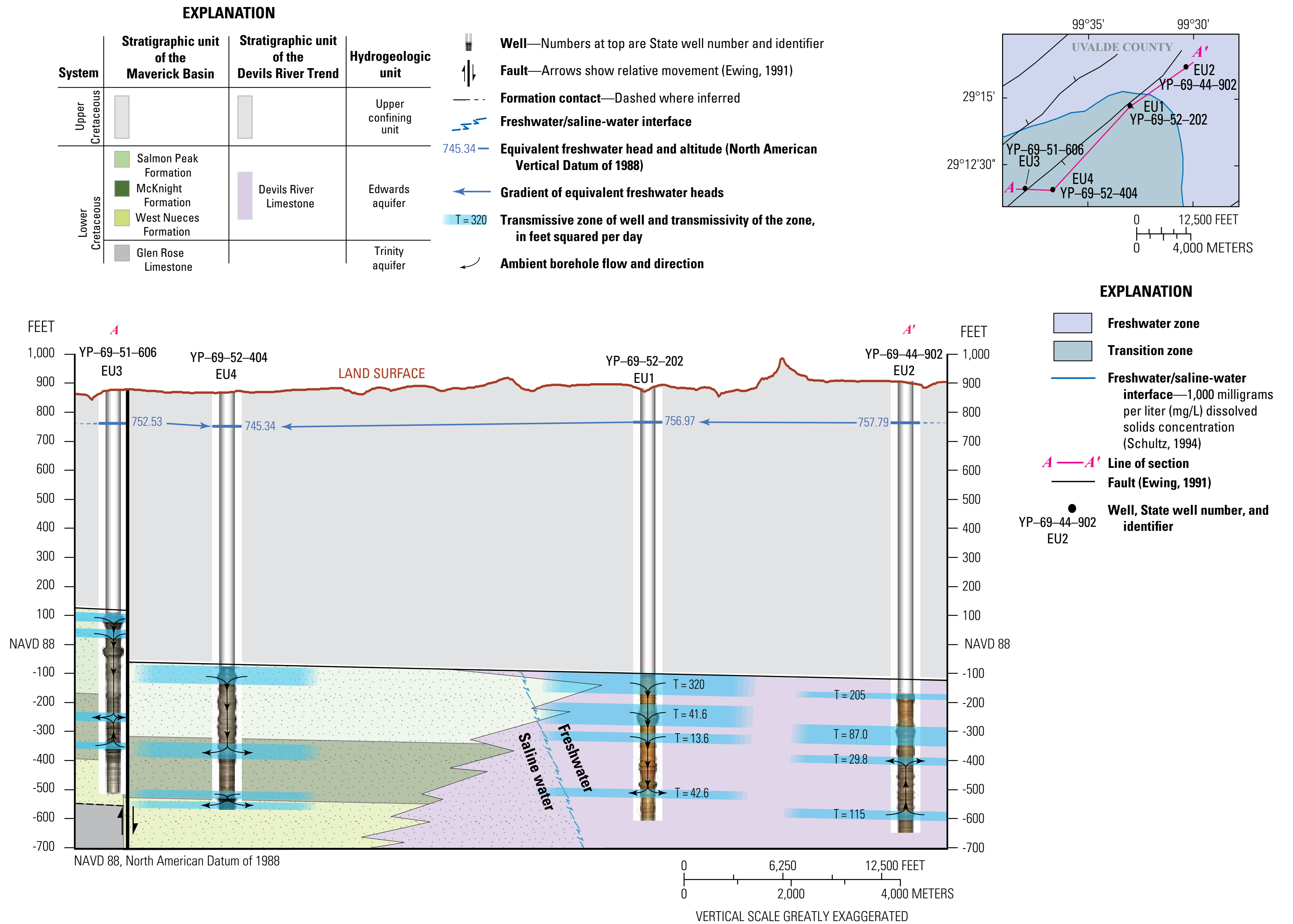


Figure 23. Conceptual diagram showing ambient flow, transmissive zones, and equivalent freshwater head in monitoring wells in the East Uvalde transect, San Antonio segment of the Edwards aquifer, south-central Texas, 2010.

Tri-County Transect

Although in 1988 well TC1 was drilled within the transition zone mapped by Schulz (1994), water-quality samples later collected (Lambert and others, 2009) indicated that the well was completed in the freshwater zone of the Edwards aquifer. For this report, well TC1 is the northernmost borehole in the Tri-County transect and is located in the freshwater zone (fig. 6). The specific conductance ranged from approximately 600 to 1,100 µS/cm, indicative of freshwater throughout the well (table 4). Other than near the top of the log (bottom of casing), there was one moderate deflection of the fluid logs at about 530 ft below LSD, in the leached and collapsed members. Two small deflections were identified, one at about 730 ft below LSD and one at about 830 ft below LSD, indicating additional possible zones of flow (fig. 14).

Located at the freshwater/saline-water interface, well TC2 ranged from slightly saline water to moderately saline water with specific conductance that ranged from 3,550 to 10,400 µS/cm. There were four large fluid curve deflections identified, near 510, 575, 625, and 800 ft below LSD, with the largest near 800 ft below LSD, and one moderate curve deflection identified near 840 ft below LSD, indicating possible flow zones. The lack of ambient fluid conductivity deflections below about 850 ft below LSD is consistent with the upward flow observed on the ambient EM flowmeter geophysical log, indicating water of similar quality moving upward from the bottom of the borehole. Analyses of the calculated specific-conductance logs indicate that, during pumping, water higher in specific conductance was pulled upward from below the freshwater/saline-water interface or that water possibly entered the borehole near the largest identified deflection at a depth near 800 ft below LSD, from the Kirschberg Evaporite member (fig. 15).

Located in the transition zone, near the freshwater/saline-water interface, well TC3 was within the range of moderately saline water with the specific conductance ranging from 11,100 to 11,400 µS/cm in the open interval of the borehole. Other than near the top of the log (bottom of casing) there was little variability in the fluid logs; however, some minor variability in specific conductance was evident near about 1,010 to 1060 ft below LSD, and two moderate deflections in specific-conductance values were identified near 670 and 715 ft below LSD, identifying possible zones of flow. The logs of calculated ambient specific conductance derived from fluid resistivity, although somewhat “noisy” because of the low resistivity of the water, showed similar patterns compared to the logs of measured specific conductance. The logs of calculated ambient specific conductance generally indicated that water entering the borehole during pumping was of similar specific conductance compared to the borehole fluid (fig. 16).

Similar to the fluid logs for well TC3, fluid logs for well TC4 were within the range of moderately saline water with the specific conductance ranging from 11,600 to 12,000 µS/cm in the open interval of the borehole. There was minimal variability in the fluid logs, and only two small specific-conductance curve deflections were identified near 1,050 and 1,418 ft below LSD. A moderate deflection was identified near 1,365 ft below LSD. The two minor deflections and one moderate deflection identify possible zones of flow. Calculated specific-conductance logs, although once again somewhat noisy because of the low resistivity of the water, indicated that the inflow of water during pumping was of similar chemical composition to the borehole fluid (fig. 17).

Total transmissivity values varied widely throughout the Tri-County transect (table 2). The largest observed transmissivity of the study area was observed in the saline zone of the Tri-County transect, at well TC3, which had a total transmissivity of 24,900 ft^2/day (fig. 24). Zones of high transmissivity were observed to not be continuous across the site and are likely caused by localized secondary porosity such as intersecting faults or karst features. At well TC1, within the freshwater zone of the transect, pumping could not be completed because of overhead obstructions preventing mobilization of equipment. Since pumping could not be completed, only ambient EM flowmeter data were collected, and calculations of transmissivities and heads were not possible.

Ambient flow data for the Tri-County transect varied throughout the transect, both in magnitude and direction. All observed ambient flow measurements were relatively small with the largest ambient flow of -0.29 gal/min, observed in well TC4, entering the borehole near the cyclic and marine members and exiting the borehole into the grainstone member. Ambient EM flowmeter data from well TC1 indicated a small vertical flow upward from the dolomitic member to the Kirschberg Evaporite member and from the leached and collapsed members to the Georgetown Formation.

Analyses of EM flowmeter data collected in three wells of the transect indicated five common stratigraphic units—the Georgetown Formation, leached and collapsed members, Kirschberg Evaporite member, cyclic and marine members, and grainstone member—that contributed the majority of the flow. Processing the data with FLASH indicated that, for all three wells, one of the highest transmissive zones was within the Kirschberg Evaporite member. For the two transition zone wells, TC3 and TC4, the largest transmissive zone was within the cyclic and marine members; however, in the interface well (TC2), data indicated that the highest transmissivity was in the Kirschberg Evaporite member and that the second highest was in the Georgetown Formation. Calculated differences in head values for flow zones of the Tri-County transect were relatively small in all zones with the exception of the transition zone well (TC4) and indicated that well TC4 was less hydraulically connected vertically than were the other wells in the Tri-County transect. This larger head difference in well TC4 between transmissive zones is likely the hydraulic force causing the ambient flow.

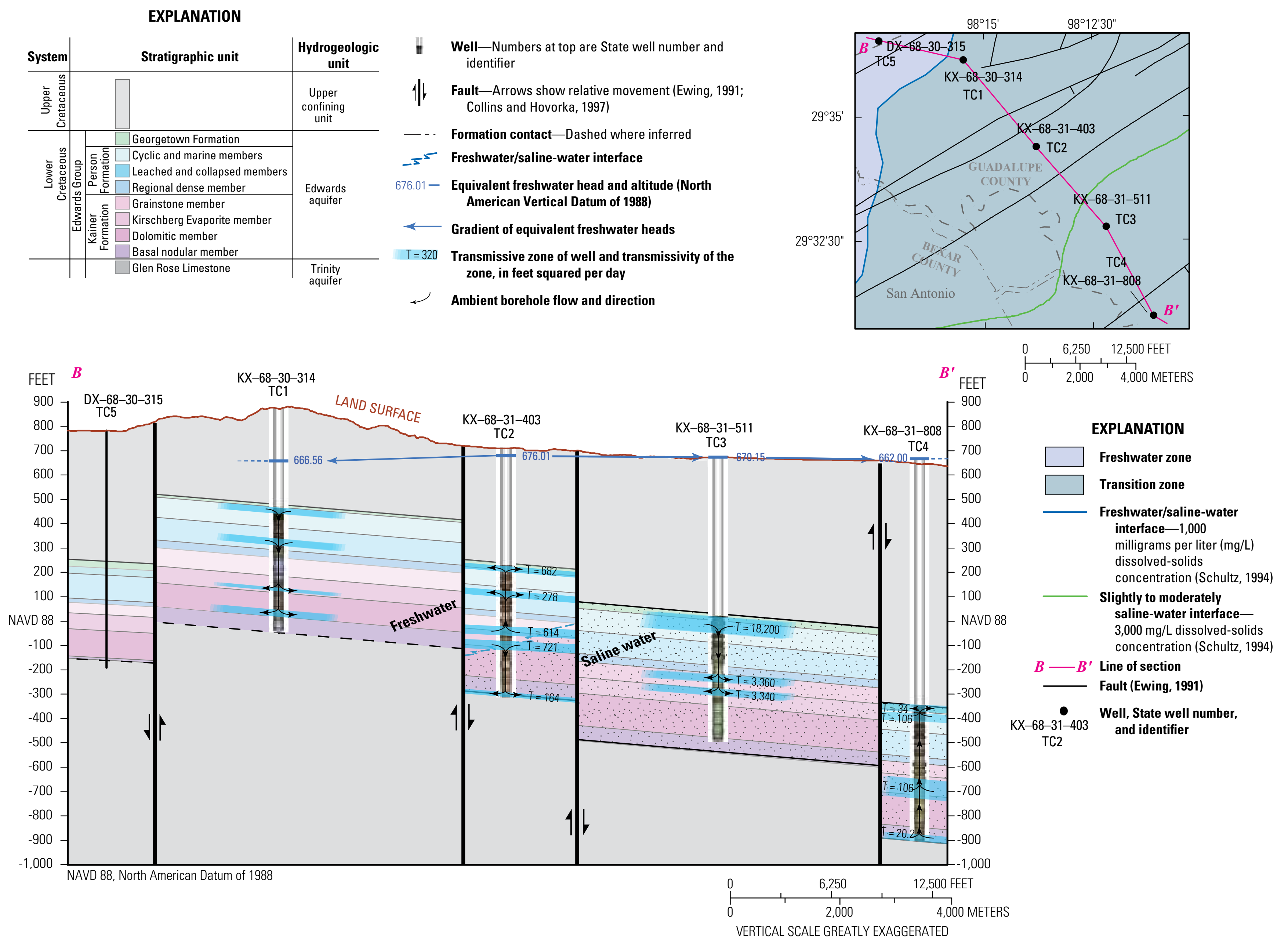


Figure 24. Conceptual diagram showing ambient flow, transmissive zones, and equivalent freshwater head in monitoring wells in the Tri-County transect, San Antonio segment of the Edwards aquifer, south-central Texas, 2010.

Collectively evaluating the EM flowmeter data for the Tri-County transect indicates that, while the Kirschberg Evaporite member remains one of the most transmissive zones throughout the transect, transmissivities of the other zones change with spatial location. Data appear to indicate that for the freshwater and transition wells (TC1 and TC2) the Georgetown Formation and the leached and collapsed members are two of the highest transmissive zones, but to the southeast in the transition zone, data for wells TC3 and TC4 indicate that they are less transmissive and that the cyclic and marine members and the grainstone member are more transmissive.

Fish Hatchery Transect

Fluid logs for well FH2 indicated that the borehole fluid was within the high range of moderately saline water with the specific conductance ranging from about 13,800 to 14,000 μS/cm within the open interval of the borehole. A small specific-conductance curve deflection was identified near 730 ft below LSD, and two moderate deflections were identified near 810 and 580 ft below LSD as possible flow zones. Although the fluid temperature curve displayed these deflections well, there was very little variability in the specific-conductance log, indicating that the flow was likely from similar fluid types. Calculated specific-conductance logs, although somewhat noisy because of the low resistivity of the water, indicated that water entering the borehole was of similar chemical composition to the borehole fluid and displayed minimal deflections. Due to the relatively large difference in altitude between the open-hole sections of wells FH1 and FH2, caused by fault offset (fig. 7), and the relative shallowness of well FH1 it was judged that additional data collection at well FH1 would not be advantageous for this project (fig. 7).

The total transmissivity measured in well FH2 was 528 ft^2/day (fig. 25; table 2). Under ambient conditions, EM flowmeter data indicated minimal flow within well FH2 with no flow magnitudes of more than 0.04 gal/min. The main ambient flow identified was a slight flow from near the bottom of the Georgetown Formation downward into the grainstone member.

During pumping of well FH2 several flow zones were identified within the Georgetown Formation, cyclic and marine members, grainstone member, Kirschberg Evaporite member, and dolomitic member. Analyses of the EM flowmeter data with FLASH indicated a range of transmissivities for these zones from the highest, 250 ft^2/day near the bottom of the Georgetown Formation, to the lowest, 73.9 ft^2/day in the grainstone member (fig. 25). Differences in head values for the different flow zones were estimated to be minimal and indicated that the flow zones were vertically well connected at well FH2.

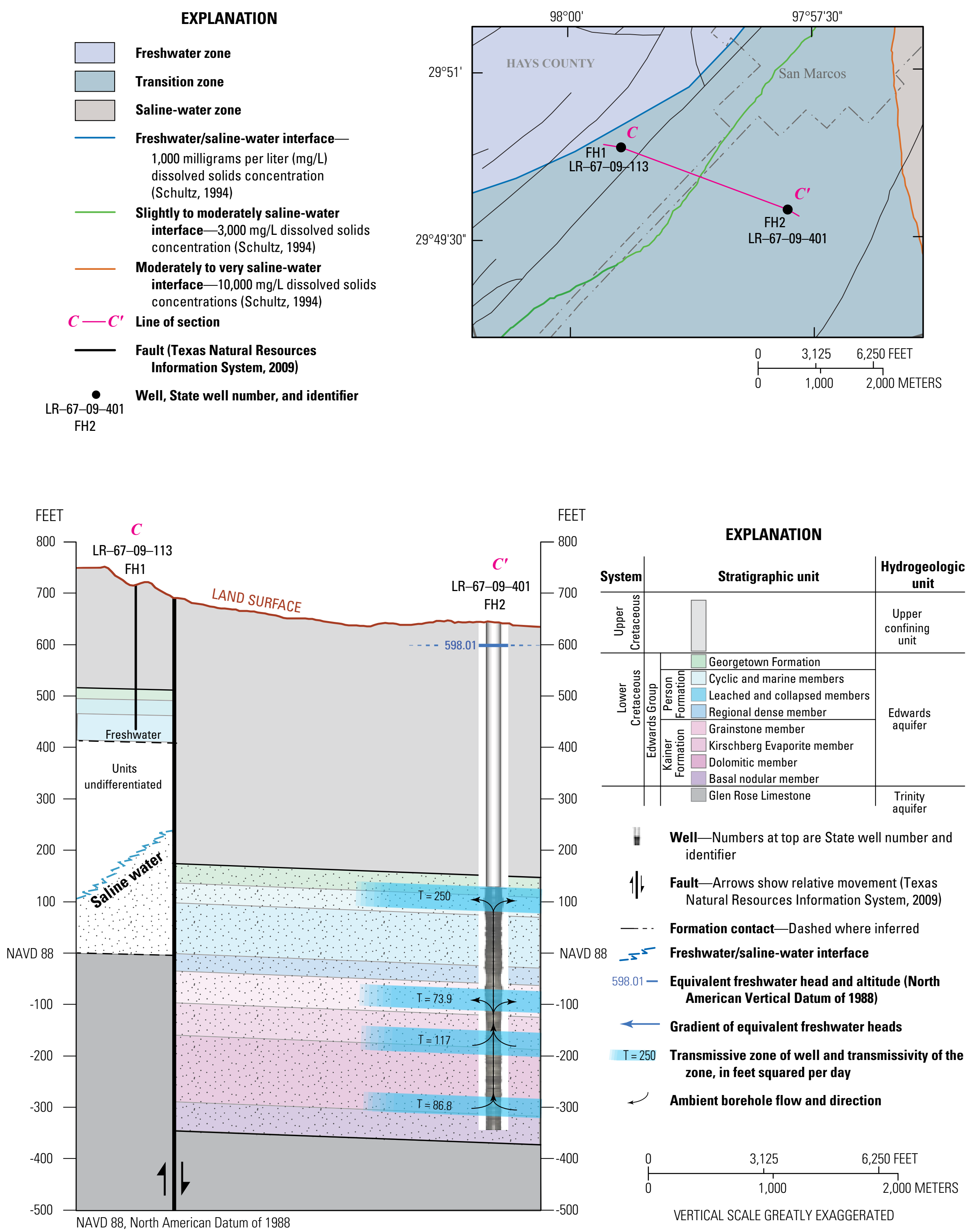


Figure 25. Conceptual diagram showing ambient flow, transmissive zones, and equivalent freshwater head in monitoring wells in the Fish Hatchery transect, San Antonio segment of the Edwards aquifer, south-central Texas, 2010.

Kyle Transect

Located within the freshwater zone, fluid properties for well KY1 were within the freshwater range, with specific-conductance values ranging from approximately 965 to 1,230 µS/cm within the open interval of the borehole. Possible flow zones were identified at three small specific-conductance curve deflections, one near 420 ft below LSD and two others confirmed by the EM flowmeter at 365 and 500 ft below LSD, one moderate deflection near 772 ft below LSD (also confirmed by the EM flowmeter), and one large deflection near 750 ft below LSD. Analysis of the calculated specific-conductance logs indicated that fresher water was entering the borehole during pumping from the dolomitic member at approximately 590 and 715 ft below LSD. There is a contrasting freshwater zone that is evident on all of the specific-conductance logs during both stressed and ambient conditions in the bottom 40 ft of well KY1, in the Glen Rose Limestone. Although there is some evidence of intrazone fluid movement on the EM flowmeter inclusive of the Glen Rose Limestone freshwater zone under ambient conditions, the freshwater does not appear to move upward during ambient or stressed conditions, as shown by the sharply increasing specific conductance and pumping flow logs just above the Glen Rose Limestone (fig. 19).

To the east, at the freshwater/saline-water interface, well KY2 ranged from slightly saline water near the top of the open interval to very saline water near the bottom of the Kirschberg Evaporite member with a specific conductance range of 2,650–19,600 µS/cm within the open interval of the borehole. Four large specific-conductance curve deflections near 672, 710, 730, and 745 ft below LSD and one moderate deflection near 505 ft below LSD were identified as possible flow zones and confirmed by the EM flowmeter. Analysis of the calculated specific-conductance logs indicated that, during pumping, moderately saline water entered the borehole at a depth below 730 ft below LSD from the dolomitic member and moved upward (fig. 20).

At well KY3, fluid logs indicated that the entire fluid column was within the midrange of very saline water with a specific conductance range of 28,500–29,100 µS/cm within the open interval of the borehole. Two deflections of the specific-conductance curve were identified, a large one near 680 ft below LSD and a moderate one near 910 ft below LSD, as possible flow zones. The large deflection of the specific-conductance log near 680 ft below LSD was not observed on the either of the calculated specific-conductance logs and did not correlate to any temperature curve deflections; therefore, the specific conductance data shallower than 680 ft were removed from the log for this report (fig. 21). It is not known what caused the sharp curve deflection, but it is hypothesized that it was caused by some kind of malfunction of the Idronaut probe, which is capacitively coupled and susceptible to electric noise. The calculated specific-conductance logs, although noisy, displayed very little variability between the ambient and stressed conditions and indicated that water entering the borehole was likely of similar chemical composition to the borehole fluid (fig. 21).

Fluid logs at well KY4 also indicated that the entire fluid column was within the midrange of very saline water with a specific conductance range of 24,600 to 25,600 µS/cm within the open interval of the borehole. Several specific-conductance curve deflections were identified, a large one at approximately 735 ft below LSD and five moderate ones near 585, 755, 787, 825, and 865 ft below LSD, as possible flow zones. An inflow of very saline water during pumping was indicated by the calculated specific-conductance logs, from near the top of the Kirschberg Evaporite member (fig. 22).

The Kyle transect consists of wells within each of the three zones, freshwater, transition, and saline (fig. 26). Within the Kyle transect, the total transmissivities varied considerably from 297 ft^2/day at well KY1, in the freshwater zone, to 3,440 ft^2/day at well KY4, in the saline zone (table 2). Zones of high transmissivity were observed to not be continuous across the site and are likely caused by localized secondary porosity resulting from intersecting faults or karst features. Although the transmissivity varied within the transect, the two wells adjacent to the freshwater/saline-water interface, KY2 and KY3, had similar total transmissivities at 472 and 451 ft^2/day, respectively (table 2).

Similar to measurements at the other transects, ambient vertical flow measurements within the boreholes of the Kyle transect varied both in magnitude and direction of flow throughout the transect. The magnitude of all observed vertical flow was small and near or within the noise range of the EM flowmeter probe.

Pumping data indicated that four common stratigraphic units—the leached and collapsed members, Kirschberg Evaporite member, cyclic and marine members, and grainstone member—contributed the majority of the flow throughout the transect. These results are similar to the flow zones observed within the Tri-County transect; however, no flow zones were observed within the Georgetown Formation in the Kyle transect. Also similar to findings for the Tri-County transect, analyses of the flow data indicated that the Kirschberg Evaporite member is one of the main contributors of flow and displayed the highest transmissive zones throughout the Kyle transect. The two wells adjacent to the freshwater/saline-water interface (KY2 and KY3) indicated very similar flow zones within the cyclic and marine members, leached and collapsed members, and Kirschberg Evaporite member with the highest transmissive zone in the cyclic and marine members. To the southeast in the saline zone, deviating from the transition zone a moderate flow zone was observed within the grainstone member, and no flows were seen within the leached and collapsed members. These results in the saline zone at well KY4 are very similar to observations from the transition wells in the Tri-County transect. Moderate differences in head values were observed in wells KY1 and KY2, indicating some amount of vertical disconnect between the flow zones; however, differences in heads observed in wells KY3 and KY4 indicated that the flow zones were relatively well connected in those zones, compared to the freshwater and interface wells KY1 and KY2 .

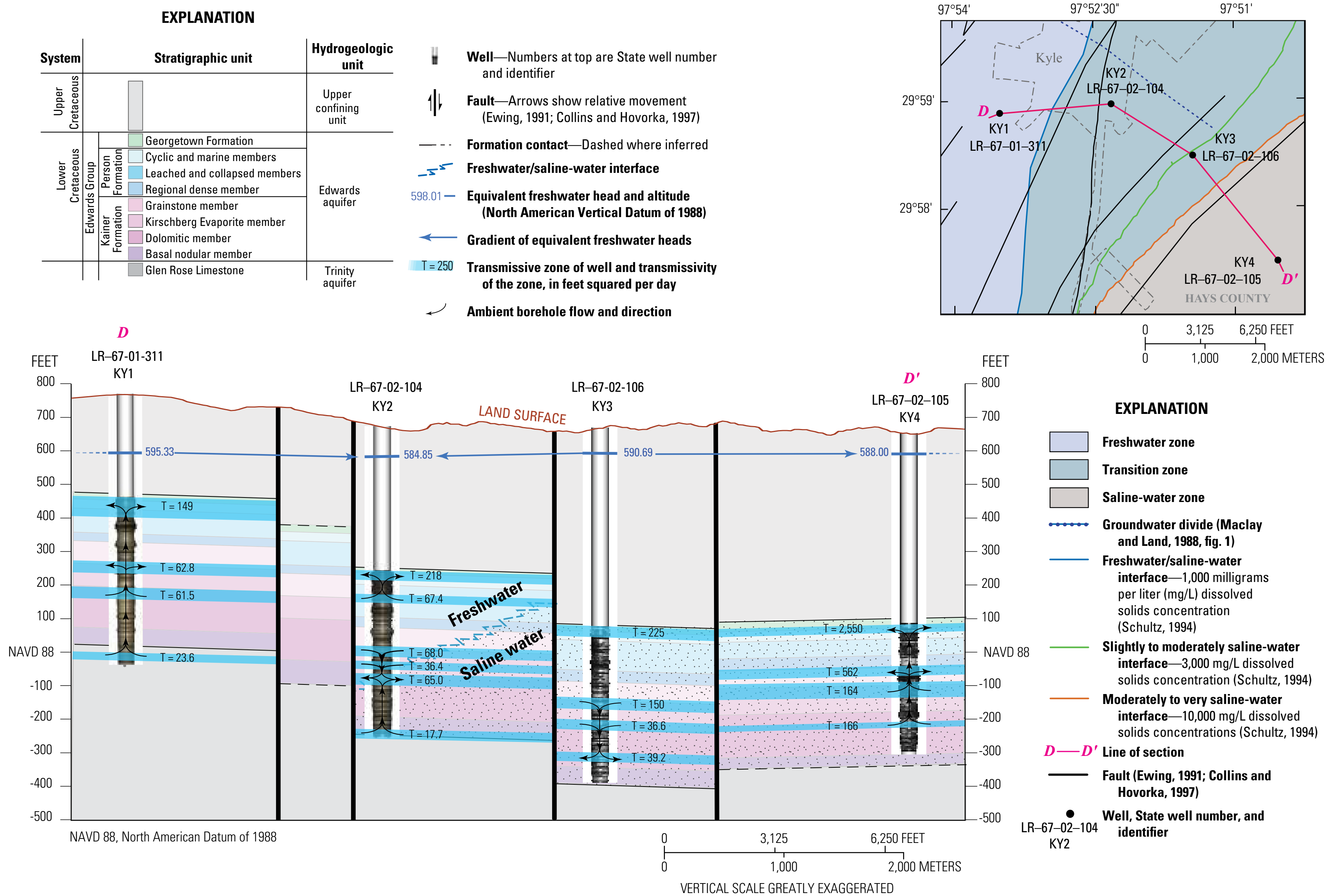


Figure 26. Conceptual diagram showing ambient flow, transmissive zones, and equivalent freshwater head in monitoring wells in the Kyle transect, San Antonio segment of the Edwards aquifer, south-central Texas, 2010.

Unlike the other transects, wells KY1, KY2, and KY3 of the Kyle transect are also open to the Trinity aquifer (fig. 26). Similar to that observed in the East Uvalde transect at well EU2, a deep flow zone was observed in the Kyle transect at well KY1. This deep flow zone in well KY1 enters near the bottom of the borehole from the Glen Rose Limestone (Trinity aquifer) (fig. 26) and corresponds to a large negative deflection of the specific-conductance curve, indicating the inflow of freshwater (fig. 19). Also similar to findings at the East Uvalde transect a flow zone was indicated at the interface well KY2 from the Glen Rose Limestone, but with a reduction in transmissivity. Unlike the flow zone from the Glen Rose Limestone at well KY1, this flow from the Trinity aquifer at well KY2 does not appear to be freshwater (fig. 20), possibly because only the upper interval of the Glen Rose Limestone was open to the borehole or of a disconnect between zones. At well KY3, only a minimal interval of the Glen Rose Limestone was open to the borehole and no flow zone was indicated from the Trinity aquifer.

Hydraulics of Lateral Flow

Changes in hydraulic heads were used to evaluate lateral-head gradients and thus the potential for movement of water from the saline zone into the freshwater zone. Hydraulic heads primarily change in response to changes in recharge from rainfall (fig. 27) and changes in nearby groundwater pumping. In karst systems such as the Edwards aquifer, changes in hydraulic heads can be abrupt, prolonged, or both (Wong and others, 2012); such changes are hereinafter referred to as hydraulic events. The interface of the saline and freshwater zones is conceptualized as a surface sloping upward toward the direction of dip of the stratigraphic units as indicated in the hydrogeologic sections in figures 5–8, which imply horizontal and vertical components of head gradient across the interface.

Lateral-head gradients (change in head divided by the distances between two points) were computed from daily mean equivalent freshwater heads. The direction of lateral-head gradients across the freshwater/saline-water interface relative to the freshwater zone was used to evaluate the potential for lateral flow across the freshwater/saline-water interface relative to freshwater zone in the East Uvalde, Tri-County, and Kyle transects; lateral-head gradients indicated whether potential lateral flow was into the freshwater zone, out of the freshwater zone, or mixed with regard to direction (head higher or lower at the freshwater/saline-water interface than on either side). Lateral-head gradients were not computed for the Fish Hatchery transect because of the relatively large difference in altitude between the open-hole sections of wells FH1 and FH2, caused by fault offset (fig. 7), and the relative shallowness of well FH1. The assumption of a horizontal aquifer, necessary for computation of accurate equivalent heads, was judged not applicable for the Fish Hatchery transect. The equivalent freshwater head data are summarized in tables 5–7.

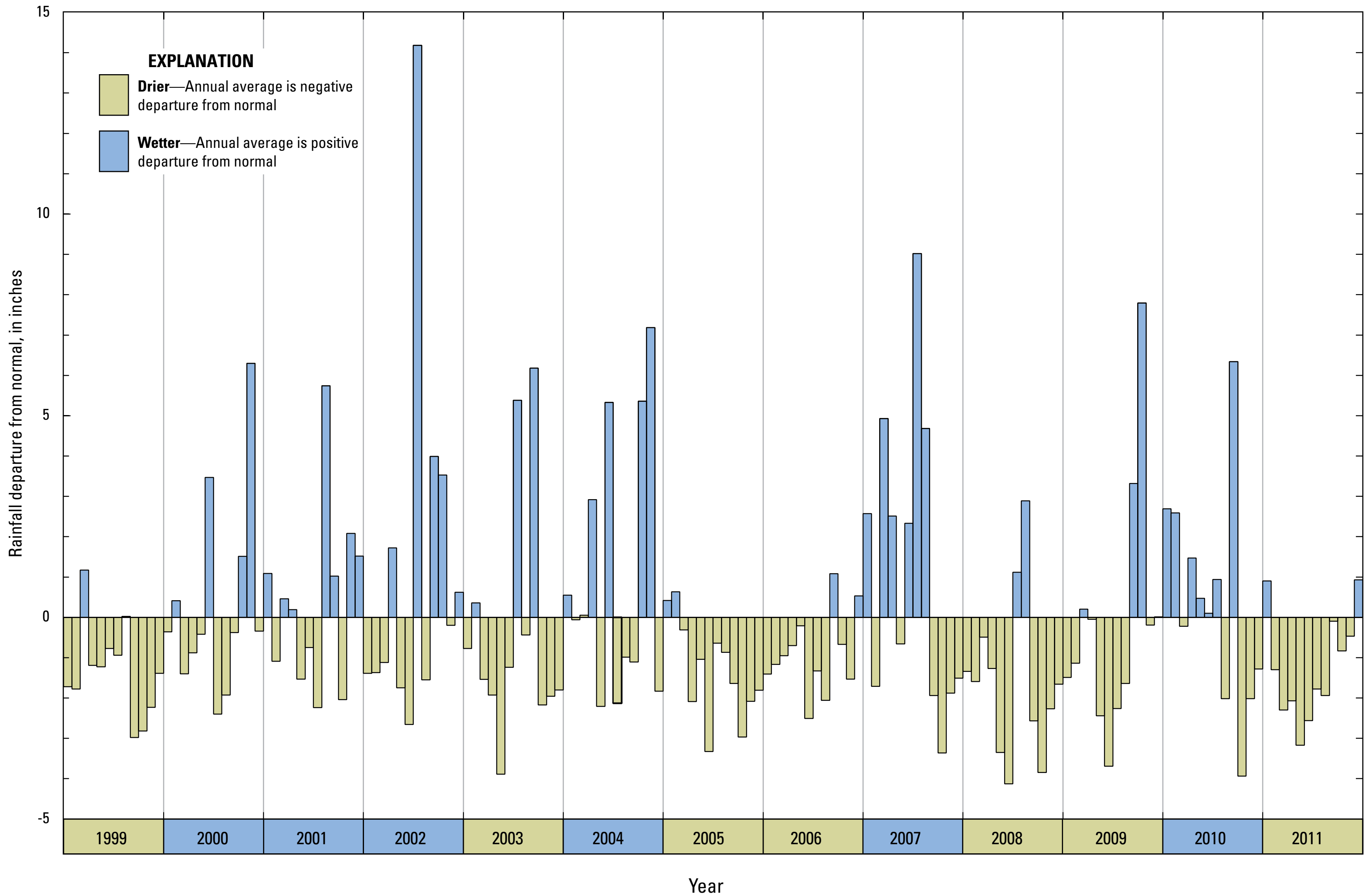


Figure 27. Monthly departure from normal (1981–2010) rainfall, National Weather Service station 417945/12921, San Antonio International Airport, Texas, 1999–2011.

Table 5. Summary mean daily equivalent freshwater heads and directions of lateral-head gradients for coincident periods of record for East Uvalde transect wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–11.

[NAVD 88, North American Vertical Datum of 1988; gray shading represents interface location; --, no data]

Period number	Period start date	Period end date	Length of period (days)	Mean daily equivalent freshwater head computed as the average of daily mean freshwater head values for the period of record shown for each period (feet above NAVD 88) — East Uvalde transect monitoring wells[1]				Direction of lateral-head gradient across freshwater/saline-water interface relative to freshwater zone
				EU2	EU1	EU4	EU3	
1	1/20/2000	4/19/2000	91	761.68	760.35	775.11	775.18	Into
2	6/13/2000	7/3/2000	21	745.96	745.12	745.34	746.82	Into
3	7/20/2000	8/25/2000	37	737.73	735.92	637.91	657.65	Out of
4	10/25/2000	11/30/2000	37	753.57	753.05	--	734.88	Out of
5	12/1/2000	2/6/2001	68	771.51	771.23	772.68	773.41	Into
6	9/11/2001	11/27/2001	78	773.31	772.49	757.96	760.76	Out of
7	1/11/2002	3/20/2002	69	780.75	779.35	763.22	766.93	Out of
8	3/23/2002	6/9/2002	79	770.40	769.11	--	749.94	Out of
9	7/24/2002	10/14/2002	83	791.59	790.51	--	740.14	Out of
10	1/8/2003	4/12/2003	95	811.05	809.92	--	808.79	Out of
11	7/20/2003	4/26/2004	282	794.97	794.03	--	787.46	Out of
12	9/15/2004	1/18/2005	126	828.25	826.74	--	826.57	Out of
13	5/20/2005	11/14/2005	179	809.19	807.50	--	804.47	Out of
14	12/2/2005	2/7/2006	68	799.05	797.54	--	807.71	Into
15	2/22/2006	3/14/2006	21	786.84	785.11	--	800.60	Into
16	8/10/2006	9/24/2006	46	751.20	750.39	--	761.95	Into
17	10/4/2006	1/31/2007	120	755.52	754.99	--	769.48	Into
18	3/20/2007	5/9/2007	51	762.86	762.69	--	775.32	Into
19	10/24/2007	12/31/2007	69	825.72	824.60	--	830.14	Into
20	4/25/2008	5/31/2008	37	792.75	790.75	--	789.66	Out of
21	9/3/2008	4/23/2009	233	769.73	768.81	--	784.83	Into
22	5/9/2009	6/5/2009	28	742.83	741.60	--	761.36	Into
23	6/20/2009	7/25/2009	36	730.08	728.68	--	718.71	Out of
24	7/31/2009	8/22/2009	23	731.11	730.43	--	738.95	Into
25	10/22/2009	12/14/2009	54	743.70	743.80	--	758.04	Into
26	12/25/2009	5/8/2010	135	753.64	753.57	--	766.81	Into
27	5/14/2010	6/6/2010	24	762.75	762.51	--	763.08	Into
28	8/6/2010	8/8/2010	3	758.35	757.85	753.29	750.82	Out of
29	8/19/2010	10/22/2010	65	762.30	762.13	758.87	757.46	Out of
30	11/11/2010	11/17/2010	7	762.94	762.65	775.72	774.89	Out of
31	11/19/2010	1/19/2011	62	759.98	759.51	774.21	773.70	Out of
32	1/24/2011	1/29/2011	6	759.55	759.22	768.21	767.38	Into
33	2/16/2011	4/12/2011	56	747.82	747.28	766.68	765.85	Into
34	5/24/2011	6/14/2011	22	718.69	718.19	749.58	749.23	Into
35	6/23/2011	8/26/2011	65	714.56	713.35	736.38	735.94	Into

[1]Listed in order of relative position in transect, from freshwater zone to transition zone.

Table 6. Summary of mean daily equivalent freshwater heads and directions of lateral-head gradients for coincident periods of record for Tri-County transect wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–11.

[NAVD 88, North American Vertical Datum of 1988; gray shading represents interface location; --, no data]

Period number	Period start date	Period end date	Length of period (days)	Mean daily equivalent freshwater head computed as the average of daily mean freshwater head values for the period of record shown for each period (feet above NAVD 88)					Direction of lateral-head gradient across freshwater/saline-water interface relative to freshwater zone
				Tri-County transect monitoring wells[1]					
				TC5	TC1	TC2	TC3	TC4	
1	4/22/2000	12/11/2000	234	--	643.38	649.42	648.35	--	Mixed
2	12/14/2000	1/23/2001	41	--	660.71	670.37	664.62	--	Mixed
3	2/10/2001	4/3/2001	53	--	665.88	675.00	669.51	--	Mixed
4	5/12/2001	6/5/2001	25	665.67	666.06	674.65	670.70	--	Mixed
5	6/13/2001	8/29/2001	78	--	654.28	659.83	659.76	--	Mixed
6	10/12/2001	11/17/2001	37	663.16	661.77	670.94	666.24	--	Mixed
7	1/9/2002	3/5/2002	56	668.04	668.62	676.82	672.48	--	Mixed
8	4/19/2002	5/21/2002	33	660.95	663.36	670.08	667.91	--	Mixed
9	5/22/2002	9/6/2002	108	662.64	660.85	670.00	666.42	656.05	Mixed
10	9/7/2002	9/29/2002	23	671.58	668.01	679.50	673.94	--	Mixed
12	11/16/2002	2/23/2003	100	678.70	678.54	688.73	--	663.55	Mixed
13	2/27/2003	3/27/2003	29	677.67	678.28	687.92	--	664.40	Mixed
14	4/2/2003	7/2/2003	92	669.26	670.70	678.64	--	662.64	Mixed
15	8/20/2003	1/27/2004	161	667.43	667.62	675.65	--	660.65	Mixed
16	3/1/2004	6/8/2004	100	668.93	668.87	677.59	--	661.53	Mixed
17	7/19/2004	10/6/2004	80	671.08	671.32	679.84	--	664.16	Mixed
18	10/22/2004	11/24/2004	34	677.71	674.21	683.44	--	663.93	Mixed
20	4/22/2005	8/22/2005	123	672.57	673.70	680.97	--	667.57	Mixed
21	9/1/2005	10/18/2005	48	666.43	666.75	673.96	--	663.06	Mixed
23	12/10/2005	4/16/2006	128	662.36	663.97	670.49	--	661.17	Mixed
24	8/2/2006	8/28/2006	27	642.61	--	648.34	--	649.26	Into
25	11/23/2006	1/3/2007	42	652.26	--	659.66	--	651.61	Mixed
27	3/22/2007	4/15/2007	25	661.64	658.98	667.94	--	654.50	Mixed
28	4/20/2007	5/24/2007	35	664.60	663.28	672.19	--	657.06	Mixed
29	6/13/2007	7/2/2007	20	665.58	664.36	672.81	--	658.96	Mixed
30	11/7/2007	12/31/2007	55	676.80	677.43	685.45	--	667.32	Mixed
31	4/15/2008	6/4/2008	51	--	667.3137113	--	670.3558889	663.8086859	Mixed
32	6/12/2008	7/7/2008	26	--	656.5698832	--	659.9560423	658.7981075	Mixed
33	6/12/2008	11/14/2008	156	--	658.6983694	--	662.501636	656.9641381	Mixed
34	11/15/2008	1/5/2009	52	--	657.4409679	664.08624	661.4707312	656.3280015	Mixed
35	1/7/2009	3/11/2009	64	--	657.2783631	663.1604296	661.1292907	656.4673434	Mixed
36	3/30/2009	4/7/2009	9	--	655.454589	661.171762	659.0145083	654.7875903	Mixed
37	4/11/2009	6/27/2009	78	--	649.4458904	653.4162061	653.3570321	652.1108845	Mixed
38	7/1/2009	8/22/2009	53	--	640.8357979	642.7075067	643.7468551	645.74003	Into
39	8/24/2009	9/16/2009	24	--	639.531833	643.3532667	642.554415	643.4008171	Mixed
40	9/19/2009	10/28/2009	40	--	645.6063029	652.4957394	648.5761003	644.4275737	Mixed
41	12/18/2009	3/9/2010	82	--	657.767592	664.577416	659.95218	652.292926	Mixed

Table 6. Summary of mean daily equivalent freshwater heads and directions of lateral-head gradients for coincident periods of record for Tri-County transect wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–11.—Continued

[NAVD 88, North American Vertical Datum of 1988; gray shading represents interface location; --, no data]

Period number	Period start date	Period end date	Length of period (days)	Mean daily equivalent freshwater head computed as the average of daily mean freshwater head values for the period of record shown for each period (feet above NAVD 88)					Direction of lateral-head gradient across freshwater/saline-water interface relative to freshwater zone
				Tri-County transect monitoring wells[1]					
				TC5	TC1	TC2	TC3	TC4	
42	3/15/2010	4/12/2010	29	--	666.6694943	673.9864954	668.8390037	658.4411814	Mixed
43	4/14/2010	6/13/2010	61	--	666.830506	674.0137795	669.1267817	658.6974338	Mixed
44	6/17/2010	6/22/2010	6	--	667.1264093	672.4997173	668.9280543	659.2485088	Mixed
45	6/29/2010	10/18/2010	112	--	663.9066338	669.8495925	666.1424454	658.2714529	Mixed
46	10/21/2010	11/1/2010	12	--	665.1280573	670.8898022	667.1979395	658.9691162	Mixed
47	11/3/2010	1/13/2011	72	--	663.0654562	668.6786438	665.4119164	658.2927451	Mixed
48	1/22/2011	3/10/2011	48	--	661.4342674	667.3999185	664.2042192	657.477141	Mixed
49	3/16/2011	4/7/2011	23	--	657.606078	661.0777325	659.9334058	655.7611417	Mixed
50	4/13/2011	5/1/2011	19	--	653.8597406	656.3265502	656.3292496	653.8784349	Mixed
51	5/7/2011	5/29/2011	23	--	649.8891024	652.2217464	652.5176071	651.2718602	Mixed
52	6/2/2011	6/8/2011	7	--	646.6688967	647.18864	649.2144129	649.5868739	Into
53	6/11/2011	9/26/2011	108	--	640.1581554	642.3439984	642.9995174	644.2373499	Into
54	9/29/2011	11/16/2011	49	--	639.9836696	645.4269817	643.5228404	641.7661798	Mixed
55	11/23/2011	12/26/2011	34	--	641.917013	647.4900339	645.2314941	643.0073544	Mixed

[1]Listed in order of relative position in transect, from freshwater zone to transition zone.

Table 7. Summary of mean daily equivalent freshwater heads and directions of lateral-head gradients for coincident periods of record for Kyle transect wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–11.

[NAVD 88, North American Vertical Datum of 1988; gray shading represents interface location; --, no data]

Period number	Period start date	Period end date	Length of period (days)	Mean daily equivalent freshwater head computed as the average of daily mean freshwater head values for the period of record shown for each period (feet above NAVD 88)				Direction of lateral-head gradient across freshwater/saline-water interface relative to freshwater zone
				Kyle transect wells[1]				
				KY1	KY2	KY3	KY4	
1	1/11/2000	4/11/2000	92	561.22	563.67	581.26	583.91	Into
2	4/14/2000	5/31/2000	48	555.63	559.43	579.62	583.24	Into
3	6/2/2000	9/10/2000	101	551.63	556.01	577.87	582.37	Into
4	10/1/2000	12/7/2000	68	557.86	558.32	576.23	--	Into
5	12/8/2000	5/4/2001	148	577.64	572.23	584.62	583.46	Mixed
6	5/9/2001	7/18/2001	71	573.36	572.35	588.68	586.69	Mixed
7	7/29/2001	8/28/2001	31	566.36	567.35	586.54	586.66	Into
8	10/18/2001	10/31/2001	14	565.89	565.78	584.99	586.17	Into
9	12/8/2001	1/22/2002	46	577.46	--	589.11	586.69	Into (probably)
10	2/7/2002	3/2/2002	24	573.52	--	582.12	585.25	Into (probably)
11	3/22/2002	7/25/2002	126	575.06	--	588.24	587.65	Into (probably)
13	1/27/2003	2/10/2003	15	603.40	598.44	598.67	590.69	Out of (probably)
14	3/13/2003	4/2/2003	21	597.22	596.75	599.71	591.81	Mixed
15	5/28/2003	6/23/2003	27	566.33	568.88	591.63	590.91	Into
16	7/2/2003	9/14/2003	75	564.44	567.25	588.72	589.23	Into
17	10/7/2003	12/3/2003	58	568.44	570.61	579.47	587.22	Into
18	12/9/2003	3/8/2004	91	572.61	570.88	578.66	586.02	Mixed
19	3/30/2004	6/30/2004	93	589.49	585.78	581.93	585.86	Out of
20	7/15/2004	9/6/2004	54	577.41	576.91	582.77	585.36	Mixed
21	9/8/2004	9/21/2004	14	561.97	564.91	580.69	585.49	Into
22	10/27/2004	11/23/2004	28	567.98	566.47	579.00	584.74	Mixed
23	12/9/2004	1/9/2005	32	578.31	574.16	583.04	586.17	Mixed
24	1/20/2005	3/7/2005	47	584.25	580.65	585.59	587.57	Mixed
25	3/11/2005	3/30/2005	20	589.30	584.26	587.96	588.55	Mixed
26	4/2/2005	4/19/2005	18	584.25	583.46	588.01	588.17	Mixed
27	4/27/2005	5/16/2005	20	583.05	581.32	587.24	588.40	Mixed
28	5/21/2005	6/21/2005	32	576.46	576.73	586.47	588.48	Into
29	6/23/2005	7/25/2005	33	572.46	573.61	584.91	588.05	Into
30	8/11/2005	9/19/2005	40	565.91	569.19	581.96	587.08	Into
31	4/8/2006	5/2/2006	25	543.87	--	570.14	580.96	Into
32	5/10/2006	6/12/2006	34	543.77	548.92	568.43	580.20	Into
33	7/7/2006	9/5/2006	61	542.28	549.76	567.22	578.75	Into
34	9/16/2006	10/14/2006	29	541.48	546.65	563.96	577.30	Into
35	11/10/2006	12/12/2006	33	560.95	563.76	567.88	576.74	Into
36	1/9/2007	4/7/2007	89	567.20	562.93	569.53	577.74	Mixed
38	6/18/2007	9/9/2007	84	--	588.27	584.76	583.77	Out of (probably)
39	9/10/2007	9/30/2007	21	583.89	582.60	587.37	586.35	Mixed
40	10/1/2007	10/28/2007	28	574.35	574.49	585.41	--	Into

Table 7. Summary of mean daily equivalent freshwater heads and directions of lateral-head gradients for coincident periods of record for Kyle transect wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–11.—Continued

[NAVD 88, North American Vertical Datum of 1988; gray shading represents interface location; --, no data]

Period number	Period start date	Period end date	Length of period (days)	Mean daily equivalent freshwater head computed as the average of daily mean freshwater head values for the period of record shown for each period (feet above NAVD 88)				Direction of lateral-head gradient across freshwater/saline-water interface relative to freshwater zone
				Kyle transect wells[1]				
				KY1	KY2	KY3	KY4	
41	11/8/2007	11/22/2007	15	581.11	579.06	584.88	586.67	Mixed
42	11/26/2007	12/5/2007	10	575.73	576.50	584.32	586.56	Into
43	12/26/2007	2/22/2008	59	569.26	573.82	582.97	586.24	Into
44	6/10/2008	8/6/2008	58	543.04	551.17	571.58	582.45	Into
45	8/14/2008	8/28/2008	15	559.69	560.02	569.73	580.58	Into
46	9/5/2008	9/13/2008	9	562.99	564.57	571.17	580.22	Into
47	9/21/2008	10/8/2008	18	563.32	566.26	571.88	579.91	Into
48	10/14/2008	12/3/2008	51	554.44	558.08	570.79	579.49	Into
49	12/9/2008	2/16/2009	70	555.91	556.85	568.62	578.42	Into
50	3/19/2009	4/8/2009	21	561.04	562.23	571.67	578.68	Into
51	4/23/2009	4/28/2009	6	570.97	570.31	571.34	578.37	Mixed
52	5/5/2009	6/24/2009	51	566.07	566.72	571.41	578.46	Into
53	8/1/2009	8/19/2009	19	561.19	562.67	568.50	577.61	Into
54	8/23/2009	9/10/2009	19	565.71	565.65	568.76	577.29	Mixed
55	9/30/2009	10/5/2009	6	573.18	571.29	569.39	577.31	Into
56	10/8/2009	11/24/2009	48	576.13	570.71	570.94	577.32	Mixed
57	5/8/2010	6/7/2010	31	598.63	590.38	585.82	583.94	Out of
58	6/15/2010	6/29/2010	15	593.96	586.56	585.11	584.41	Out of
59	7/1/2010	7/11/2010	11	592.95	585.64	585.00	584.68	Out of
60	8/4/2010	9/13/2010	41	579.25	578.12	--	584.73	Mixed
61	1/7/2011	2/5/2011	30	587.89	584.47	581.66	583.89	Mixed
62	2/17/2011	3/28/2011	40	585.17	584.06	581.78	583.93	Mixed
63	4/6/2011	8/31/2011	148	564.34	568.95	575.65	582.13	Into
64	10/14/2011	12/11/2011	59	570.38	570.99	571.36	578.44	Into

[1]Listed in order of relative position in transect, from freshwater zone to transition zone.

East Uvalde Transect

Borehole data were collected from wells in the East Uvalde transect during August 4–17, 2010. Daily mean equivalent freshwater heads coincident with the collection of the borehole data in August 2010 were generally lower compared to the mean computed from all daily mean equivalent freshwater heads for each well during 1999–2011 (mean daily equivalent freshwater head was computed as the average of daily mean freshwater head values for the period of record shown for each well) (fig. 28). Daily mean equivalent freshwater heads measured during August 4–17, 2010, ranged from about 22 ft below the mean daily equivalent freshwater head to about 4 ft above the mean daily equivalent freshwater head for a particular well. Because of a large period of missing data for well EU4 during wetter hydraulic conditions, the mean daily equivalent freshwater head at well EU4 is markedly different compared to the mean daily equivalent freshwater heads measured at the other wells in the East Uvalde transect and does not reflect the "true" mean daily equivalent freshwater head (mean daily equivalent freshwater head if no measurements were missing) for this well. Analyses of daily mean equivalent freshwater heads for the East Uvalde transect (fig. 28) indicated that the two freshwater wells, EU1 and EU2, had similar responses to hydraulic events, indicating a strong hydraulic connection between these wells. Likewise, hydraulic heads measured in the two transition zone wells, EU3 and EU4, responded in the same way to hydrologic events, indicating a strong hydraulic connection between the two saline zone wells. The relation between daily mean equivalent freshwater head measured in the freshwater and transition zone wells was weaker, indicating only a slight hydraulic connection between the two zones. As hydrologic conditions became drier (as indicated by departure from normal [1981–2010] rainfall at the National Weather Service Station at the San Antonio International Airport [fig. 27]) and hydraulic heads in all four wells decreased to values well below mean daily equivalent freshwater heads, the tendency for daily mean equivalent freshwater heads measured in the freshwater and transition zones to react somewhat similarly decreased further, and the weak hydraulic connection between the freshwater and saline zones observed during wetter periods when hydraulic heads were above average became even more difficult to discern.

Hydrologic conditions varied substantially during the study period, which is typical for the study area (National Climatic Data Center, 2012). On an overall basis, hydrologic conditions can be characterized as near normal, with 6 years drier than normal and 7 years wetter than normal during the period analyzed for this report (January 1999 through September 2011). Average annual rainfall from January 1999 through December 2010 was 31.33 inches per year, slightly less than the 1981–2010 average of 32.27 inches per year (National Weather Service, 2012). Rainfall for the first 9 months of 2011 was much lower than the average normal rainfall for January through September (fig. 27). The years 1999 (16.41 inches), 2003 (28.45 inches), 2005 (16.54 inches), 2006 (21.34 inches), 2008 (13.76 inches), 2009 (30.69 inches), and 2011 (17.58 inches) were drier than normal, and the years 2000 (35.85 inches), 2001 (36.72 inches), 2002 (46.27 inches), 2004 (45.32 inches), 2007 (47.25 inches), and 2010 (37.39 inches) were wetter than normal.

Drier than normal hydrologic conditions persisted during August 2010 when several transect wells were logged. In contrast to generally drier than normal hydrologic conditions during August 2010 (fig. 27), hydrologic conditions during the previous study by Lambert and others (2009) were generally wetter than normal. Annual rainfall at San Antonio was above normal during 4 of the 6 years between 2000 and 2005 evaluated by Lambert and others (2010), and the lateral-head gradients computed by these investigators for January 2000–November 2005 likely reflect the relatively wet conditions compared to normal, implying above normal recharge (Lambert and others, 2010).

The daily mean equivalent freshwater head values at well EU4 (near the freshwater/saline-water interface) were on average smaller compared to daily mean equivalent freshwater head values measured at the other wells in the East Uvalde transect, indicating small lateral-head gradients toward that location. Lateral-head gradients computed from daily mean equivalent freshwater heads indicate that the gradient across the interface varied (periods when the flow was into or out of the freshwater zone were found); the gradient was out of the freshwater zone more often (number of days) compared to into the freshwater zone (table 5). These results are consistent with results from previous studies. For example, the direction of the lateral-head gradient along the East Uvalde transect was out of the freshwater zone and into the transition zone during a majority of coincident periods of record during January 2000–November 2005 (Lambert and others, 2010). Previously, Maclay (1995, p. 37) reported on the basis of scant data that the prevailing hydraulic gradient in Uvalde County (and Bexar County) was out of the freshwater zone and that "most of the flow from the freshwater zone of the aquifer to the saline-water [transition] zone is in southeastern Uvalde and southwestern Medina Counties."

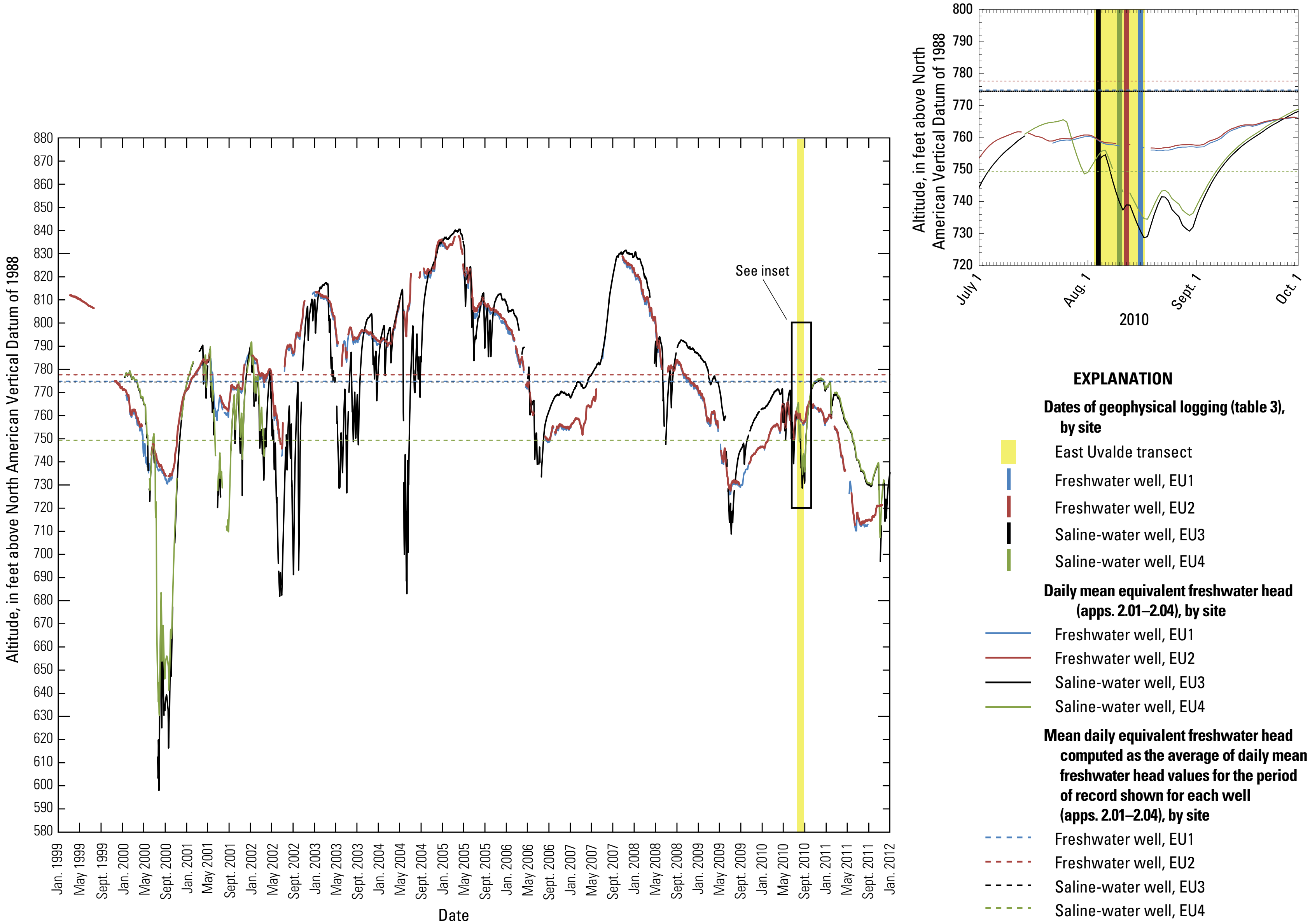


Figure 28. Daily mean equivalent freshwater head and geophysical logging dates in monitoring wells of the East Uvalde transect (EU1 through EU4), San Antonio segment of the Edwards aquifer, south-central Texas, 1999–2011.

Tri-County Transect

Borehole data were collected from the Tri-County transect during June 14–25, 2010. Daily mean equivalent freshwater heads measured at the Tri-County wells during June 2010 were higher than the mean daily equivalent freshwater heads during 2000–11 (fig. 29). Daily mean equivalent freshwater heads for the Tri-County transect ranged from slightly more than 4 ft to approximately 9 ft above observed mean daily equivalent freshwater heads. Analyses of all collected and complied daily mean equivalent freshwater heads indicate that the lateral-head gradients across the interface were typically mixed (not indicating into or out of freshwater zone) (table 6). Assessment of the daily mean equivalent freshwater heads also indicated that the lateral-head gradients were not greatly affected by changes in hydrologic conditions (fig. 27) and were generally similar (table 6) regardless of whether hydraulic heads were higher or lower compared to mean daily equivalent freshwater heads (fig. 29).

Changes in daily mean equivalent freshwater heads were assessed to determine to what extent the Tri-County wells were hydraulically connected. Similar changes in daily mean equivalent freshwater heads were observed in wells TC1, TC2, and TC3 and indicated a strong hydraulic connection between the three wells (fig. 29). Data also indicated that a connection between well TC4 and wells TC1, TC2, and TC3 was present; however, the hydraulic connection appeared to be weaker than the connections among the other three wells. Daily mean equivalent freshwater head data appeared to indicate that these connections among wells in the Tri-County transect increased as equivalent freshwater heads decreased to values less than the mean daily equivalent freshwater heads, indicating a negative correlation (hydraulic condition increased as daily mean equivalent freshwater heads decreased) between the hydraulic connection and hydraulic heads.

Daily mean equivalent freshwater head analyses for the Tri-County wells indicated slight lateral-head gradients away from the interface, toward the saline zone and freshwater zone, with the highest daily equivalent freshwater head observed at the transition well, TC2. Although these findings correspond with results from previous studies, it is now known why the highest daily mean equivalent freshwater heads were observed at the interface well, in contrast with the results from the other transects. A prevailing direction of the lateral-head gradient did not appear to be evident at the Tri-County transect (table 6). Variations in the equivalent freshwater heads of the multiple flow zones in each well observed at the Tri-County transect also appeared to indicate that the flow zones are horizontally not well connected (fig. 24).

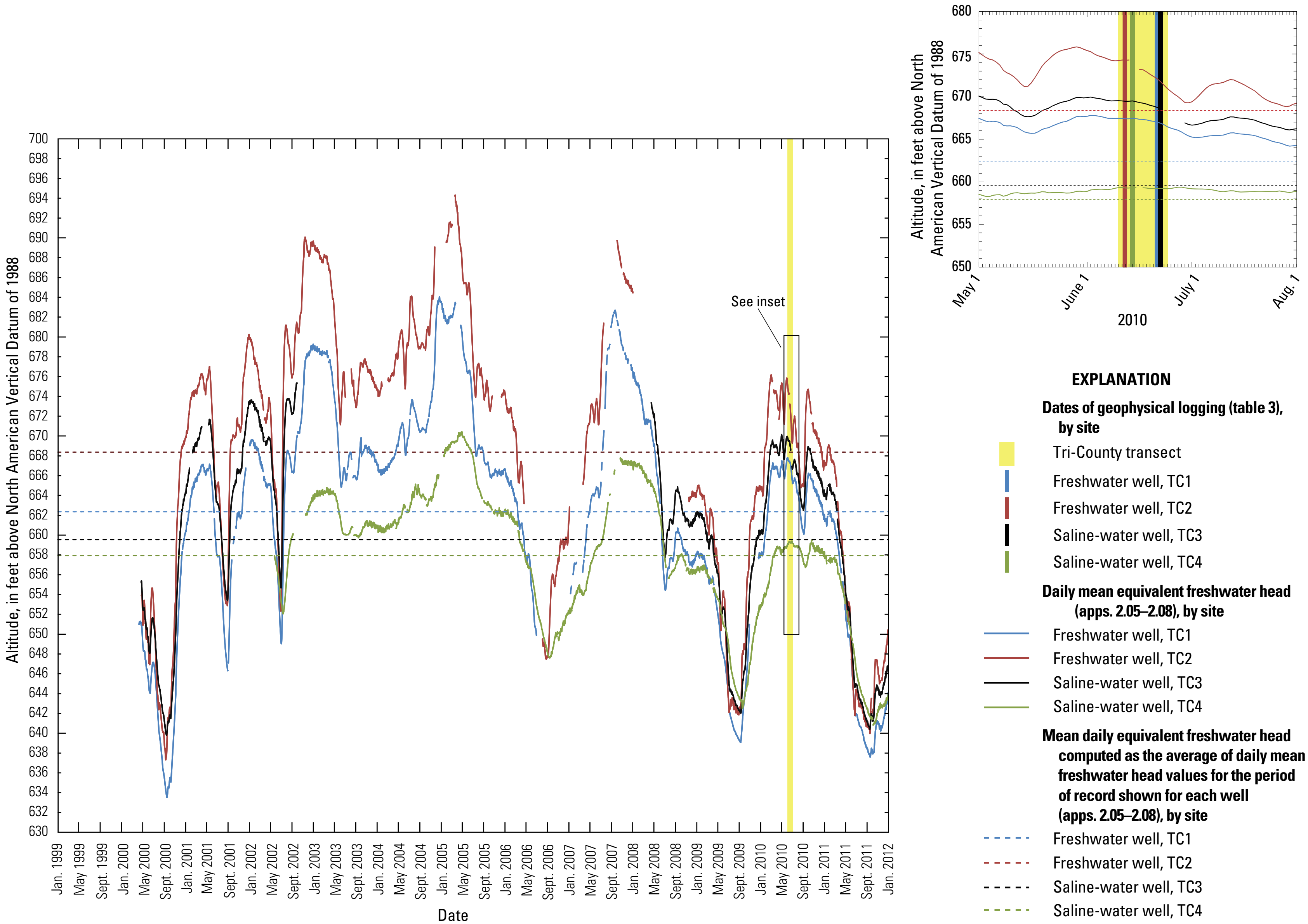


Figure 29. Daily mean equivalent freshwater head and geophysical logging dates in monitoring wells of the Tri-County transect (TC1 through TC4), San Antonio segment of the Edwards aquifer, south-central Texas, 2000–2011.

Fish Hatchery Transect

Borehole data were collected at the Fish Hatchery transect during August 2–3, 2010. Based on normal rainfall (1981–2010) hydraulic conditions at the time of geophysical logging were drier than normal (fig. 27). Daily mean equivalent freshwater heads at well FH2 during this time were slightly elevated compared to the mean daily equivalent freshwater head from January 2001 through September 2011 at this well (about 0.25 ft higher compared to the mean daily equivalent freshwater head) (fig. 30).

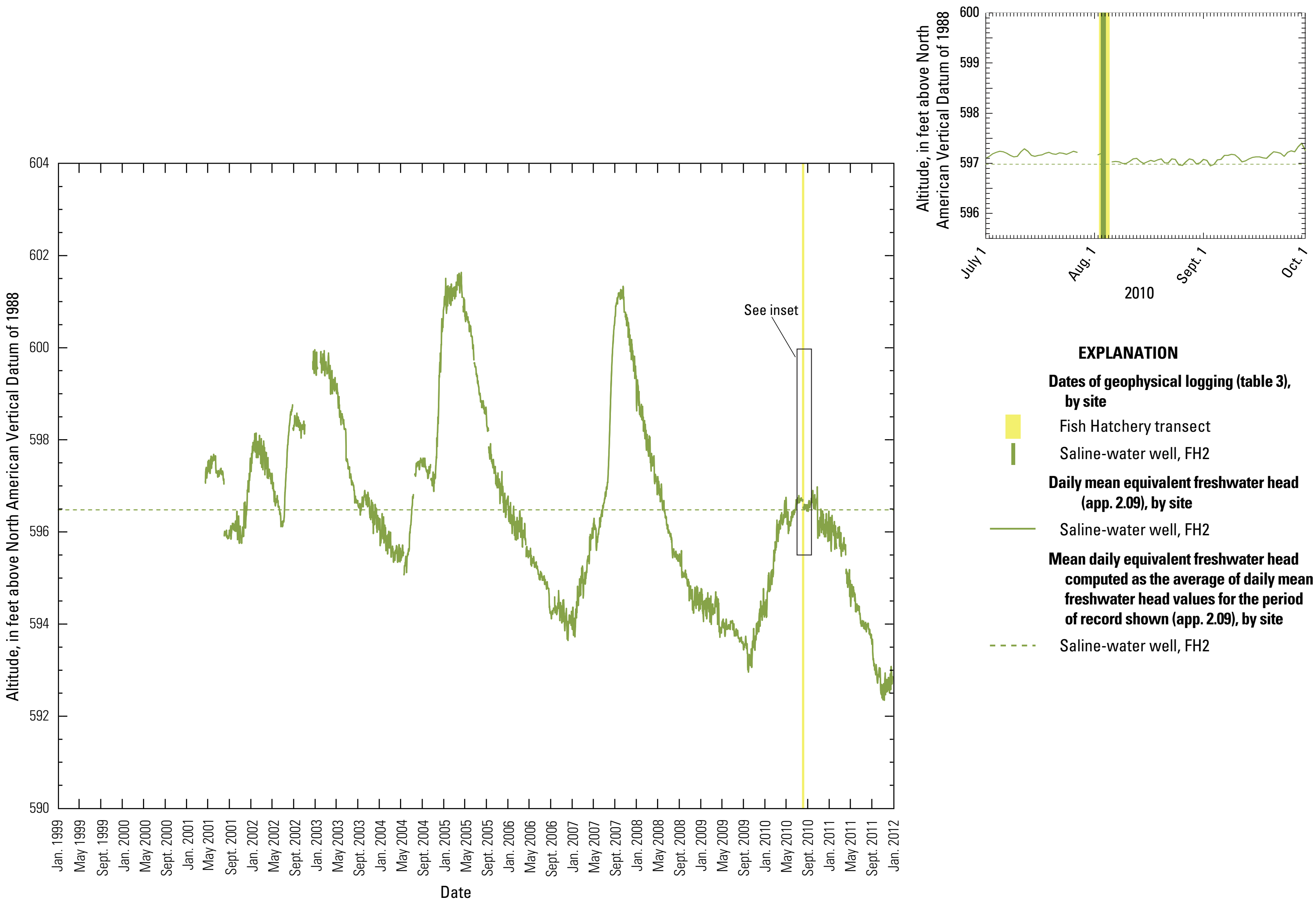


Figure 30. Daily mean equivalent freshwater head and geophysical logging dates in a monitoring well of the Fish Hatchery transect (FH2), San Antonio segment of the Edwards aquifer, south-central Texas, 2001–2011.

Kyle Transect

Borehole data were collected from the Kyle transect during July 12–28, 2010. Daily mean equivalent freshwater heads at the Kyle transect during July 2010 were higher compared to the mean daily equivalent freshwater heads during 1999–2011 (fig. 31).The freshwater and transition zone wells, KY1 and KY2, were well above average, with the daily mean equivalent freshwater heads ranging from about 14 to more than 25 ft above observed mean daily equivalent freshwater heads, while the transition and saline zone wells were only slightly above average with daily mean equivalent freshwater heads ranging from slightly more than 1 to about 4 ft above observed mean daily equivalent freshwater heads. In the freshwater well (KY1) and the transition zone well (KY2), similar hydraulic responses were observed, indicating a strong hydraulic connection between the two wells. Daily mean equivalent freshwater head responses in the two saline zone wells (KY3 and KY4) indicated only a very weak connection with any of the Kyle transect wells. Similar to the East Uvalde transect, this hydraulic connection appeared to have a positive correlation to daily mean equivalent freshwater heads in the aquifer, except for the saline zone well KY4, which never appeared to indicate a strong hydraulic connection with any of the other wells.

Analyses of daily mean equivalent freshwater heads indicated results similar to those of the East Uvalde transect, with slight lateral-head gradients towards the interface, and on average a minimum daily mean equivalent freshwater head was observed at the interface well, KY2 (fig 31). Assessment of the daily mean equivalent freshwater heads indicated that, although the lateral-head gradient varied between into and out of the freshwater zone, the lateral-head gradient was typically from the transition zone into the freshwater zone (table 7). Similar to the heads observed at the Tri-County transect wells, observed calculated heads for the multiple flow zones within each well at the Kyle transect appeared to indicate that the flow zones were horizontally not well connected to each other (fig. 26).

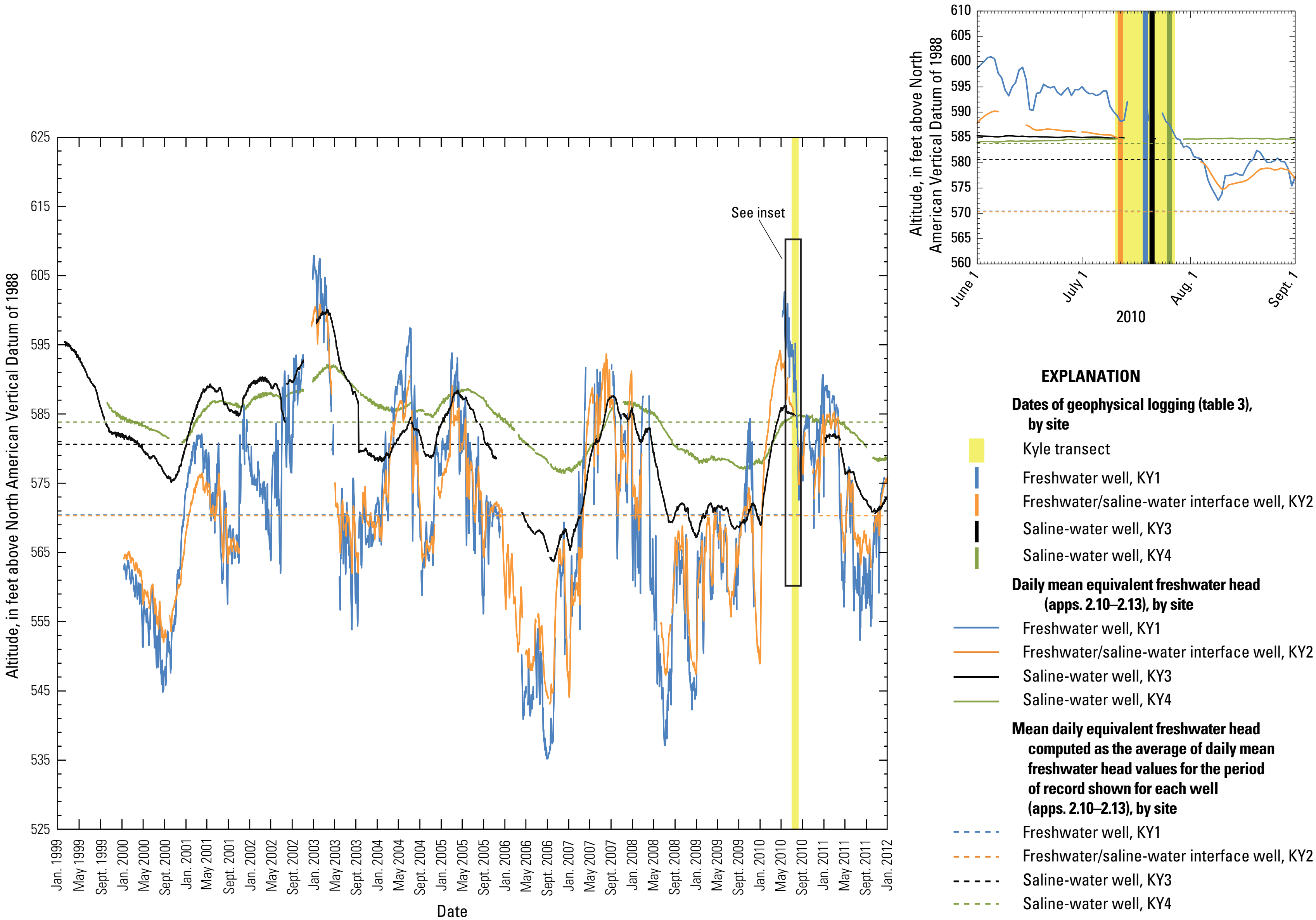


Figure 31. Daily mean equivalent freshwater head and geophysical logging dates in monitoring wells of the Kyle transect (KY1 through KY4), San Antonio segment of the Edwards aquifer, south-central Texas, 1999–2011.

Summary

The freshwater zone of the San Antonio segment of the Edwards aquifer is used by residents of San Antonio and numerous other rapidly growing communities in south-central Texas as their primary water supply source. This freshwater zone is bounded to the south and southeast by a saline-water zone with an intermediate zone transitioning from freshwater to saline water, the transition zone. As demands on this water supply increase, there is concern that the transition zone could potentially move, resulting in more saline water in current supply wells. Since 1985, the U.S. Geological Survey (USGS), San Antonio Water System (SAWS), and other Federal and State agencies have conducted studies to better understand the transition zone.

During 2010 and 2011, the USGS, in cooperation with SAWS, conducted a study to further assess the potential for movement of the transition zone in part of the San Antonio segment of the Edwards aquifer. Equivalent freshwater heads were computed to further investigate the transition from saline to freshwater zones in the San Antonio segment and evaluate the potential for lateral flow at the freshwater/saline-water interface. Data were collected within and surrounding the transition zone from 13 wells in four transects (East Uvalde, Tri-County, Fish Hatchery, and Kyle).

Hydraulic head and geophysical log data were used to calculate equivalent freshwater heads and then analyzed to identify possible horizontal gradients across the transition zone and thus flow. Continuous water-level measurement data from the 13 wells were assessed to identify the hydraulic condition at the time of logging. Unlike previous studies that used indirect methods to calculate fluid conductivity from fluid resistivity, in this study geophysical tools that directly measured fluid conductivity were used. Electromagnetic (EM) flowmeter logs were collected under both ambient and stressed (pumping) conditions and were processed to identify vertical flow zones within the borehole. For this report, previously identified standards are used to define freshwater as that containing less than 1,000 milligrams per liter (mg/L) dissolved solids concentration; slightly saline water as that containing 1,000–3,000 mg/L dissolved solids concentration; moderately saline water as that containing 3,000–10,000 mg/L dissolved solids concentration; and very saline water as that containing 10,000–35,000 mg/L dissolved solids concentration.

The San Antonio segment of the Edwards aquifer (the study area) is about 175 miles long and extends from the western groundwater divide near Brackettville in Kinney County to the eastern groundwater divide near Kyle in Hays County. Depth below land surface to the top of the Edwards aquifer in the transition zone ranges from about 200 feet (ft) in the northeastern part of the study area in Hays County to more than 2,600 ft in southern Medina County. The average thickness of the Edwards aquifer in the transition zone is about 500 ft. The monitoring wells that provided data for this report were drilled during 1997–2001 by SAWS. The four transects consist of two to five wells per transect and were configured approximately perpendicular to and across the expected trace of the interface.

Curve deflections of fluid logs in ambient conditions can indicate horizontal or vertical flow, stratification of borehole fluid, or screen openings in cased wells. Fluid property logs were used as indicators of possible flow zones, as equivalent freshwater head calculations, and as a characterization of the borehole fluid. Fluid properties, EM flowmeter data and well-completion data were used to assess vertical flow within the borehole. A numerical model, Flow-Log Analysis of Single Holes (FLASH), was used to process the EM flowmeter data and calculate different zones of transmissivity and hydraulic heads for the open interval of each borehole.

Similar total transmissivities of 418 and 437 square feet per day (ft^2/d) were calculated at the two freshwater wells in the East Uvalde transect (wells EU1 and EU2, respectively) in August 2010. Compared to the upper zones, the lower zones displayed greater magnitudes of hydraulic head changes, indicating that the lower flow zones were not as well connected vertically. Pumping data from the freshwater zone (wells EU1 and EU2) indicated there are three main zones that contribute vertical flow to each well (a fourth flow zone with markedly lower transmissivities values was identified). All of the flow zones are in the Devils River Limestone formation: the two main flow zones are near the top of the formation, and a third zone that also contributes appreciable flow is near the bottom of each well. The deep flow zone indicated by the EM flowmeter data for well EU2 corresponds directly with a large, negative deflection of the fluid logs, indicating an inflow of fresher water from the Devils River Limestone. To the southwest, towards the interface, this same flow zone was observed in well EU1, but with a reduction of flow, and displayed no apparent fluid curve deflections. Transmissivity of this zone decreased from 115 ft^2/d at well EU2 to 42.6 ft^2/d at well EU1. These results appear to indicate that this flow zone is spatially connected but decreases toward the interface.

Total transmissivity values varied widely throughout the Tri-County transect. The largest observed transmissivity of the study area was observed in the saline zone of the Tri-County transect, at well TC3, which had a total transmissivity of 24,900 ft^2/d. Zones of high transmissivity were observed to not be continuous across the site and are likely caused by localized secondary porosity such as intersecting faults or karst features.

Analyses of EM flowmeter data collected in three wells of the Tri-County transect indicated five common stratigraphic units—the Georgetown Formation, leached and collapsed members, Kirschberg Evaporite member, cyclic and marine members, and grainstone member—that contributed the majority of the flow. Processing the data with FLASH indicated that, for all three wells, one of the highest transmissive zones was within the Kirschberg Evaporite member. Calculated differences in head values for flow zones of the Tri-County transect were relatively small in all zones with the exception of the transition zone well (TC4) and indicated that well TC4 was less hydraulically connected vertically than were the other wells in the Tri-County transect.

The total transmissivity measured in Fish Hatchery transect well FH2 was 528 ft^2/d. During pumping of well FH2, several flow zones were identified within the Georgetown formation, leached and collapsed members, grainstone member, Kirschberg Evaporite member, and dolomitic member. Differences in head values for the different flow zones were estimated to be minimal and indicated that the flow zones were vertically well connected at well FH2. Because of the relatively large difference in altitude between the open-hole sections of wells FH1 and FH2, caused by fault offset and the relative shallowness of well FH1, it was judged that additional data collection at well FH1 would not be advantageous for this project.

Within the Kyle transect, the total transmissivities varied considerably from 297 ft^2/d at well KY1, in the freshwater zone, to 3,440 ft^2/d at well KY4, in the saline zone. Zones of high transmissivity were observed to not be continuous across the site and are likely caused by secondary porosity resulting from intersecting faults or karst features. Although the transmissivity varied within the transect, the two wells adjacent to the interface, KY2 and KY3, had similar total transmissivities at 472 and 451 ft^2/d, respectively.

Pumping data indicated that four common stratigraphic units—the leached and collapsed members, Kirschberg Evaporite member, cyclic and marine members, and grainstone member—contributed the majority of the flow throughout the Kyle transect.

Moderate differences in head values were observed in wells KY1 and KY2, indicating some amount of disconnect between the flow zones; however, differences in heads observed in wells KY3 and KY4 indicated that the flow zones were relatively well connected in those zones.

Changes in daily mean equivalent freshwater heads were used to evaluate lateral-head gradients and thus the potential for movement of water from the saline zone into the freshwater zone. Borehole data were collected from wells in the East Uvalde transect during August 4–17, 2010. Daily mean equivalent freshwater heads coincident with the collection of the borehole data in August 2010 were generally lower compared to the mean computed from all daily mean equivalent freshwater heads for each well during 1999–2011 (mean daily equivalent freshwater head was computed as the average of daily mean freshwater head values for the period of record shown for each well). Although analyses of daily mean equivalent freshwater heads indicate that the gradient across the interface varied between into and out of the freshwater zone, the data indicate that there was a slightly longer period which the gradient was out of the freshwater zone.

Borehole data were collected from wells in the Tri-County transect during June 14–25, 2010. Daily mean equivalent freshwater heads measured at the Tri-County transect wells during June 2010 were higher than the long-term mean computed from daily mean equivalent freshwater heads during 2000–11. Analyses of all collected and complied daily mean equivalent freshwater heads indicate that the lateral-head gradients across the interface were typically mixed (not indicating into or out of freshwater zone).

Borehole data were collected from the Fish Hatchery transect during August 2–3, 2010. Based on normal rainfall (1981–2010) hydraulic conditions at the time of geophysical logging were drier than normal. Daily mean equivalent freshwater heads at well FH2 during borehole data collection were slightly higher compared to the long-term mean computed from all daily equivalent freshwater heads from January 2001 through September 2011 at this well (about 0.25 ft higher compared to the long-term mean).

Borehole data were collected from the Kyle transect during July 12–28, 2010. Daily mean equivalent freshwater heads at the Kyle transect wells during July 2010 were higher compared to the long-term mean computed from all daily mean equivalent freshwater heads during 1999–2011. Assessment of the daily mean equivalent freshwater heads indicated that, although the lateral-head gradient varied between into and out of the freshwater zone, the lateral-head gradient was typically from the transition zone into the freshwater zone.

References Cited

American Society of Testing and Materials, 2004, Standard guide for conducting borehole logging— Mechanical caliper: American Society of Testing and Materials (ASTM) D 6767–97, 6 p.

American Society of Testing and Materials, 2007, Standard guide for conducting borehole geophysical logging—electromagnetic induction: American Society of Testing and Materials (ASTM) D 6726–01, 8 p.

American Society of Testing and Materials, 2010, Standard guide for planning and conducting borehole geophysical logging: American Society of Testing and Materials (ASTM) D 5753–05, 9 p.

Anderson, J.A., Williams, J.H., Eckhardt, D.A., and Miller, T.S., 2003, Geophysical, stratigraphic, and flow-zone logs of selected test, monitor, and water-supply wells in Cayuga County, New York: U.S. Geological Survey Open-File Report 03–468, 169 p.

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

Barker, R.A., and Ardis, A.F., 1996, Hydrogeologic framework of the Edwards-Trinity aquifer system, west-central Texas: U.S. Geological Survey Professional Paper 1421–B, 61 p.

Canadian Well Logging Society, 2011, LAS information—Log ASCII Standard (LAS) software: accessed August 29, 2011, at http://www.cwls.org/las_info.php.

Century Geophysical Corporation, 2012, Logging Tools—9722 E-M flowmeter: accessed February 17, 2012, at http://www.century-geo.info/dnn/EquipmentSales/LoggingTools/9721LoggingTool.aspx.

Clement, T.J., 1989, Hydrochemical facies in the bad water zone of the Edwards aquifer, central Texas: Austin, The University of Texas, M.A. thesis, 168 p.

Collins, E.W., and Hovorka, S.D., 1997, Structure map of the San Antonio segment of the Edwards aquifer and Balcones fault zone, south-central Texas—Structural framework of a major limestone aquifer, Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties: Austin, The University of Texas, Bureau of Economic Geology Miscellaneous Map 38, scale 1:250,000.

Cooper, H.H., Jr., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: American Geophysical Union Transactions, v. 27, no. 4, p. 526–534.

Cooper, H.H., Jr., Kohout, F.A., Henry, H.R., and Glover, R.E., 1964, Sea water in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613–C, 84 p.

Davies, P.B., 1987, Modeling areal, variable-density, groundwater flow using equivalent freshwater head—Analysis of potentially significant errors, *in* Solving Ground Water Problems with Models Conference, Denver, Colo., February 10–12, 1987, Proceedings: National Water Well Association, v. 2, p. 888–903.

Day-Lewis, F.D., Johnson, C.D., Paillet, F.L., and Halford, K.J., 2011: A computer program for flow-log analysis of single holes (FLASH): Ground Water, v. 49, no. 6, p. 926–931, accessed December 8, 2012, at http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.2011.00798.x/pdf.

Driscoll, F.G., 1986, Groundwater and wells (2nd ed.): St. Paul, Minn., Johnson Filtration Systems, Inc., 1,089 p.

Ewing, T.E., 1991, The tectonic framework of Texas—The tectonic map of Texas: Austin, The University of Texas, Bureau of Economic Geology, 36 p.

Frostburg State University Chemistry Department, 2011—Freshwater density calculator: accessed December 15, 2011, at http://antoine.frostburg.edu/chem/senese/javascript/water-density.html.

Groschen, G.E., 1994, Analysis of data from test-well sites along the downdip limit of freshwater in the Edwards aquifer, San Antonio, Texas, 1985–87: U.S. Geological Survey Water-Resources Investigations Report 93–4100, 92 p.

Groschen, G.E., and Buszka, P.M., 1997, Hydrogeologic framework and geochemistry of the Edwards aquifer saline-water zone, south-central Texas: U.S. Geological Survey Water-Resources Investigations Report 97–4133, 47 p.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water Resources Investigations, book 4, chapter A3, 522 p.

Hovorka, S.D., Mace, R.E., and Collins, E.W., 1998, Permeability structure of the Edwards aquifer, south Texas—Implications for aquifer management: Austin, The University of Texas, Bureau of Economic Geology Report of Investigations 250, 55 p.

Integrated Ocean Drilling Program, 2007, Downhole logging: accessed April 4, 2012, at http://publications.iodp.org/proceedings/310/103/103_4.htm.

Johns-Hopkins University Applied Physics Laboratory, 2005, APL ocean remote sensing—A sea water equation of state calculator: accessed April 4, 2012, at http://fermi.jhuapl.edu/denscalc.html.

Keys, W.S., 1997, A practical guide to borehole geophysics in environmental investigations: Boca Raton, Fla., CRC/Lewis Publishers, 176 p.

Lambert, R.B., Hunt, A.G., Stanton, G.P., and Nyman, M.B., 2009, Water-level, borehole geophysical log, and water-quality data from wells transecting the freshwater/saline-water interface of the San Antonio segment of the Edwards aquifer, south-central Texas, 1999–2007: U.S. Geological Survey Data Series 403 [variously paged].

Lambert, R.B., Hunt, A.G., Stanton, G.P., and Nyman, M.B., 2010, Lithologic and physicochemical properties and hydraulics of flow in and near the freshwater/saline-water transition zone, San Antonio segment of the Edwards aquifer, south-central Texas, based on water-level and borehole geophysical log data, 1999–2007: U.S. Geological Survey Scientific Investigations Report 2010–5122, 69 p.

Lindgren, R.J., Dutton, A.R., Hovorka, S.D., Worthington, S.R.H., and Painter, Scott, 2004, Conceptualization and simulation of the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Scientific Investigations Report 2004–5277, 143 p.

Lozo, F.E., Jr., and Smith, C.I., 1964, Revision of Comanche Cretaceous stratigraphic nomenclature, southern Edwards Plateau, southwest Texas: Gulf Coast Association of Geological Societies Transactions, v. 14, p. 285–306.

Lusczynski, N.J., 1961, Head and flow of groundwater of variable density: Journal of Geophysical Research, v. 66, no. 12, p. 4247–4256.

Maclay, R.W., 1995, Geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Water-Resources Investigations Report 95–4186, 64 p.

Maclay, R.W., and Land, L.F., 1988, Simulation of flow in the Edwards aquifer, San Antonio region, Texas, and refinement of storage and flow concepts: U.S. Geological Survey Water-Supply Paper 2336–A, 48 p.

Maclay, R.W., and Small, T.A., 1984, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Open-File Report 83–537, 72 p.

Mahler, B.J., 2008, Statistical analysis of major ion and trace element geochemistry of water, 1986–2006, at seven wells transecting the freshwater/saline-water interface of the Edwards aquifer, San Antonio, Texas: U.S. Geological Survey Scientific Investigations Report 2008–5224, 46 p.

Moredock, D.E., and Van Siclen, D.C., 1964, Regional variations of hydrocarbons in the Edwards Limestone (Cretaceous) of South Texas: Gulf Coast Association of Geological Societies Transactions, v. 14, p. 253–270.

Mount Sopris Instruments, 2012, 2IFA-1000 specifications: accessed April 4, 2012, at http://www.mountsopris.com/index.php/products/item/stand-alone-logging-toolsa/2ifa1000.

National Climatic Data Center, 2012, Annual climatological summary, 1999–2011, station 417945/12921, San Antonio International Airport, Texas: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, accessed November 25, 2012, at http://cdo.ncdc.noaa.gov/ancsum/ACS.

National Weather Service, 2012, Climate records for San Antonio—Monthly/annual average precipitation: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, accessed November 25, 2012, at http://www.srh.noaa.gov/ewx/?n=satclidata.htm.

Oetting, G.C., 1995, Evolution of fresh and saline groundwaters in the Edwards aquifer, central Texas—Geochemical and isotopic constraints on processes of fluid-rock interaction and fluid mixing: Austin, The University of Texas, M.A. thesis, 203 p.

Paillet, F.L., 1994, Application of borehole geophysics in the characterization of flow in fractured rocks: U.S. Geological Survey Water-Resources Investigations Report 93–4214, 39 p.

Pavlicek, Diane, Small, T.A., and Rettman, P.L., 1987, Hydrogeologic data from a study of the freshwater/saline-water zone interface in the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Open-File Report 87–389, 108 p.

Poteet, Diane, Collier, Hughbert, and Maclay, R.W., 1992, Investigation of the fresh/saline-water interface in the Edwards aquifer in New Braunfels and San Marcos, Texas: Edwards Underground Water District Report 92–02 [variously paged].

Rose, P.R., 1972, Edwards Group, surface and subsurface, central Texas: Austin, The University of Texas, Bureau of Economic Geology Report of Investigations 74, 198 p.

Schultz, A.L., 1992, Using geophysical logs in the Edwards aquifer to estimate water quality along the freshwater/saline-water interface (Uvalde to San Antonio, Texas): Edwards Underground Water District Report 92–03, 47 p.

Schultz, A.L., 1993, Defining the Edwards aquifer freshwater/saline-water interface with geophysical logs and measured data (San Antonio to Kyle, Texas): Edwards Underground Water District Report 93–06, 81 p.

Schultz, A.L., 1994, Review and update of the position of the Edwards aquifer freshwater/saline-water interface from Uvalde to Kyle, Texas: Edwards Underground Water District Report 94–05, 31 p.

Schultz, A.L., and Halty, S.R., 1997, Anhydrite—Source of high sulfate concentration near Edwards aquifer "bad-water" line: Bulletin of the South Texas Geological Society, v. 37, no. 9, p. 11–16.

Stanton, G.P., Kress, W.H., Teeple, A.P., Greenslate, M.L., and Clark, A.K., 2007, Geophysical analysis of the Salmon Peak Formation near Amistad Reservoir Dam, Val Verde County, Texas, and Coahuila, Mexico, March 2006, to aid in piezometer placement: U.S. Geological Survey Scientific Investigations Report 2007–5143, 72 p.

Stanton, G.P., Thomas, J.V., and Stovall, Jeffery, 2009, Analysis of vertical flow during ambient and pumped conditions in four monitoring wells at the Pantex Plant, Carson County, Texas, July–September 2008: U.S. Geological Survey Open-File Report 2009–1017, 26 p.

Texas Natural Resources Information System, 2009, Data search/download notes—GAT, Geologic Atlas of Texas: accessed April 27, 2010, at http://www.tnris.state.

U.S. Geological Survey, 2012, National Water Information System (NWISWeb) data: accessed December 4, 2012, at http://waterdata.usgs.gov/tx/nwis/nwis.

William F. Guyton and Associates, Inc., 1986, Drilling, construction, and testing of monitoring wells for the Edwards aquifer bad-water-line experiment: Report prepared for San Antonio City Water Board and Edwards Underground Water District, 56 p.

William F. Guyton and Associates, Inc., 1988, Bad water line transect pumping test at San Antonio City Water Board's Artesia Station, March 25, 1987: Report prepared for San Antonio City Water Board and Edwards Underground Water District, 19 p.

Winslow, A.G., and Kister, L.R., 1956, Saline-water resources of Texas: U.S. Geological Survey Water-Supply Paper 1365, 105 p.

Wong, C.I., Mahler, B.J., Musgrove, M., and Banner, J.L., 2012, Changes in sources and storage in a karst aquifer during a transition from drought to wet conditions: Journal of Hydrology, v. 468–469, 159–172 p.

Publishing support provided by
Lafayette Publishing Service Center

Information regarding water resources in Texas is available at
http://tx.usgs.gov/

USGS

Thomas and others—**Borehole Geophysical, Fluid, and Hydraulic Properties, Freshwater/Saline-Water Transition Zone**—SIR 2012–5285

ISBN 978-1-4113-3540-0

9 781411 335400

Printed on recycled paper