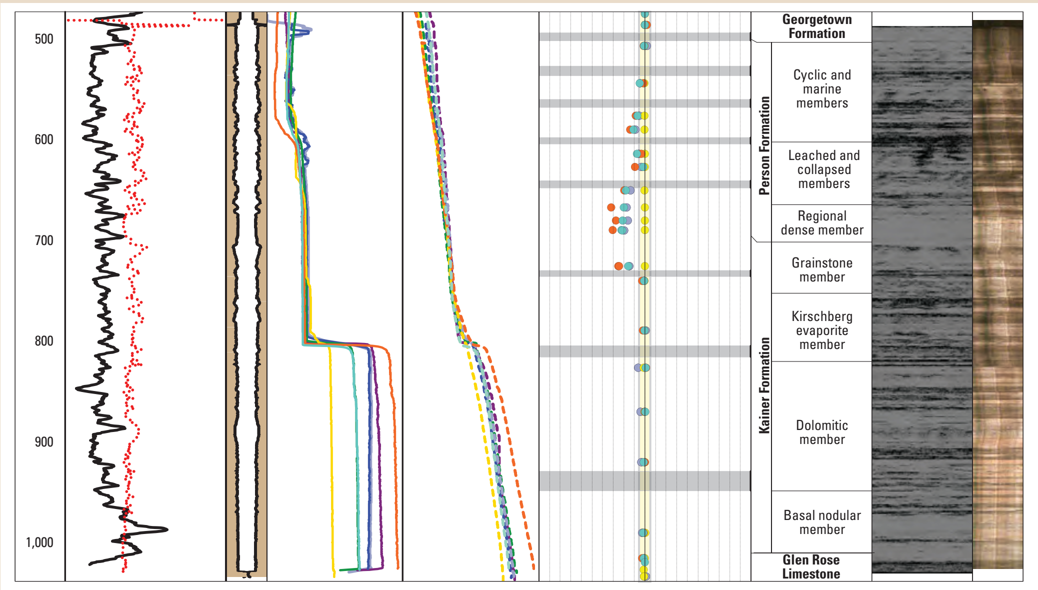
In cooperation with the San Antonio Water System

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



Scientific Investigations Report 2010–5122

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

Front cover:

Top, Graph showing daily mean equivalent freshwater head and borehole geophysical data in Tri-County 2 well (KX–68–21–403), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–07.

Bottom, San Antonio Water System drilling equipment used to drill Pitluk well, Bexar County, Texas (photograph by David Mahula, San Antonio Water System).

Back cover:

Top, U.S. Geological Survey pump hoist rig and logging truck collecting pumped and ambient flowmeter data from Kyle 2 well (LR–67–02–104), July 14, 2010 (photograph by R.B. Lambert, U.S. Geological Survey).

Middle, Monitor well C1 (AY–68–37–524) near the freshwater/saline-water transition zone in central Bexar County, Texas, being purged prior to sample collection, July 12, 2002 (photograph by R.B. Lambert, U.S. Geological Survey).

Bottom, Closeup of U.S. Geological Survey pump hoist rig and Kyle 2 well (LR–67–02–104) during pumped flowmeter test, July 14, 2010 (photograph by R.B. Lambert, U.S. Geological Survey).

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The authors gratefully acknowledge John Waugh, San Antonio Water System, who for many years has provided leadership, vision, and opportunities that have resulted in a better understanding of the Edwards aquifer and particularly the transition zone. The authors also acknowledge Denise Renaghan, formerly San Antonio Water System, for providing drilling information and water-level data, and David Mahula, San Antonio Water System, for providing water-level data and for helping with logistics to ensure that the monitoring wells were accessible for borehole geophysical logging. Alvin Schultz is acknowledged for his geologic insight and assistance in providing useful geologic information for constructing the hydrogeologic sections of the transects. Finally, the authors thank the property owners and ranchers who graciously provided access to their property and assistance in data collection during nearly a decade.

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Appendixes (available online at http://pubs.usgs.gov/sir/2010/5122/)

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Tables

Conversion Factors, Datums, and Water-Quality Units

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

SI to Inch/Pound

Multiply	By	To obtain
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

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

$$°F=(1.8×°C)+32$$

Datums

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

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) and North American Datum of 1983 (NAD 83).

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

Water-Quality Units

Concentrations are reported in metric units. Chemical concentrations are reported in milligrams per liter (mg/L), units expressing the concentration of chemical constituents in solution as weight of solute (milligrams) per unit volume (liter) of water.

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

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

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Abstract

The freshwater zone of the San Antonio segment of the Edwards aquifer in south-central Texas (hereinafter, the Edwards aquifer) is bounded to the south and southeast by a zone of transition from freshwater to saline water (hereinafter, the transition zone). The boundary between the two zones is the freshwater/saline-water interface (hereinafter, the interface), defined as the 1,000-milligrams per liter dissolved solids concentration threshold. This report presents the findings of a study, done by the U.S. Geological Survey in cooperation with the San Antonio Water System, to obtain lithologic properties (rock properties associated with known stratigraphic units) and physicochemical properties (fluid conductivity and temperature) and to analyze the hydraulics of flow in and near 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. No identifiable relation between conductivity values from geophysical logs in monitoring wells in all transects and equivalent freshwater heads in the wells at the times the logs were run is evident; and no identifiable relation between conductivity values and vertical flow in the boreholes concurrent with the times the logs were run is evident. The direction of the lateral equivalent freshwater head gradient and thus the potential lateral flow at the interface in the vicinity of the East Uvalde transect fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals. Whether the prevailing direction on average is into or out of the freshwater zone is not clearly indicated. Equivalent freshwater head data do not indicate a prevailing direction of the lateral gradient at the interface in the vicinity of the Tri-County transect. The prevailing direction on average of the lateral gradient and thus potential lateral flow at the interface in the vicinity of the Kyle transect likely is from the transition zone into the freshwater zone. The hypothesis regarding the vertical gradient at the East Uvalde transect, and thus the potential for vertical flow near an interface conceptualized as a surface sloping upward in the direction of the dip of the stratigraphic units, is that the potential for vertical flow fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals. At the Tri-County transect, a downward gradient on the freshwater side of the interface and an upward gradient on the saline-water side are evidence of opposing potentials that appear to have stabilized the position of the interface over the range of hydrologic conditions that occurred at the times the logs were run. At the Fish Hatchery transect, an upward gradient on the saline-water side of the interface, coupled with the assumption of a sloping interface, implies a vertical gradient from the transition zone into the freshwater zone. This potential for vertical movement of the interface apparently was opposed by the potential (head) on the freshwater side of the interface that kept the interface relatively stable over the range of hydrologic conditions during which the logs were run. The five flow logs for Kyle transect freshwater well KY1 all indicate upward flow that originates from the Glen Rose Limestone, the uppermost unit of the Trinity aquifer; and one log for well KY2 shows upward flow entering the borehole from the Trinity aquifer. These flow data constitute evidence of the potential for flow from the Trinity aquifer into the Edwards aquifer in the vicinity of the Kyle transect. Subsurface temperature data indicate that flow on average is more active, or vigorous, on the freshwater side of the interface than on the saline-water side. A hydraulic connection between the transition zone and the freshwater zone is indicated by similar patterns in the hydrographs of the 15 transect monitoring wells in and near the transition zone and three county index wells in the freshwater zone during 1999–2007. The data for this report in part support a conceptualization of regional flow in and near the transition zone in which water enters the transition zone from the freshwater zone in the western part of the Edwards aquifer, flows toward the northeast, and discharges to the freshwater zone in the eastern part of the aquifer. The data for this report support the hypothesis that the interface is likely to remain stable laterally and vertically over time. The most direct evidence in support of that hypothesis is the conductivity data from Tri-County transect well TC2

and Kyle transect well KY2 that show an essentially stable vertical interface position (depth in the borehole) over a range of hydrologic conditions. No single line of evidence confirms the hypothesis that the interface in the San Antonio segment of the Edwards aquifer is relatively stable over time, and thus the potential for irreversible movement of saline water into the freshwater zone is small; but the cumulative evidence from the water-level (head) and borehole geophysical log data supports that hypothesis.

Introduction

The San Antonio segment of the Edwards aquifer (hereinafter, the Edwards aquifer), is the primary source of water supply in south-central Texas. In addition to withdrawals for public supply, the Edwards aquifer provides water for irrigation, military, industrial, commercial, and domestic uses in San Antonio, Tex., and other communities in the region. The freshwater zone of the aquifer is bounded to the south and southeast by a zone of transition from freshwater to saline water (fig. 1). For this report, freshwater is defined as that containing less than 1,000 milligrams per liter (mg/L) dissolved solids concentration; slightly saline water, that containing 1,000 to 3,000 mg/L dissolved solids concentration; moderately saline water, that containing 3,000 to 10,000 mg/L dissolved solids concentration; and very saline water, that containing 10,000 to 35,000 mg/L dissolved solids concentration (Winslow and Kister, 1956). The freshwater/saline-water interface (hereinafter, the interface) is the 1,000-mg/L dissolved solids concentration threshold. The freshwater/saline-water transition zone of the Edwards aquifer (hereinafter, the transition zone) is defined as the region of the aquifer with dissolved solids concentrations ranging from 1,000 to 10,000 mg/L (Schultz, 1994). The transition zone primarily contains slightly and moderately saline water, although very saline water is present in a few locations.

In 1985, the U.S. Geological Survey (USGS), the San Antonio Water System (SAWS), and other Federal, State, and local agencies began a series of studies to learn more about the interaction between the freshwater and transition zones of the Edwards aquifer, and in particular, the potential for irreversible movement of saline water into the freshwater zone of the aquifer. The primary objective of the study reported here, done by the USGS in cooperation with SAWS, was to obtain lithologic properties (rock properties associated with known stratigraphic units) and physicochemical properties (fluid conductivity and temperature in this report) of the aquifer and to analyze the hydraulics of flow in and near the transition zone using water-level and borehole geophysical log data collected during 1999–2007 and, on the basis of findings, to assess the potential for irreversible movement of saline water into the freshwater zone of the aquifer. The study included drilling of additional monitoring wells by SAWS in transects across the interface. Monitoring wells from which data were collected for this report are in and near the transition zone in Uvalde County (East Uvalde transect, four wells), in Comal and Guadalupe Counties (Tri-County transect, five wells), and in Hays County (Fish Hatchery transect [two wells] and Kyle transect [four wells]) (fig. 1). Water-level, borehole geophysical log, and water-quality data were collected from selected monitoring wells in the four transects during various periods from October 1999 through December 2007 (table 1).

Purpose and Scope

This report presents the findings of a study to obtain lithologic properties (rock properties associated with known stratigraphic units) and physicochemical properties (fluid conductivity and temperature) and to analyze the hydraulics of flow in and near 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; and on the basis of findings, assesses the potential for irreversible movement of saline water into the freshwater zone of the Edwards aquifer. Water-level data were collected to obtain head distribution over time as an indicator of hydrologic conditions. Daily mean water levels from continuously measured hydraulic heads in monitoring wells of the East Uvalde transect, Tri-County transect, Fish Hatchery transect, and Kyle transect were converted to equivalent freshwater heads to account for differences in salinity of water in some wells. Conversion to equivalent freshwater heads was done so that accurate lateral head gradients between the transition zone and the freshwater zone could be computed.

Geophysical log data were collected using conventional methods that include caliper, gamma, resistivity, induction, fluid conductivity, and fluid temperature, and using advanced methods that include borehole televiewer imaging tools and electromagnetic and heat-pulse vertical flowmeters. These tools were used to obtain lithologic properties from which stratigraphic units of the aquifer could be identified (the tops of the stratigraphic units penetrated were picked from drillers' logs but were refined by the geophysical logs) and to obtain vertical flow (magnitude and direction under ambient conditions) relative to the stratigraphic units in each well. The directions of vertical flow indicated the directions of vertical gradients at each well. Spatial and temporal variation in fluid conductivity and temperature as measured from borehole geophysical logs is described with regard to hydrologic conditions where applicable.

Water-quality data (discrete samples and field-measured properties) were collected from monitoring wells in the transition zone to characterize selected chemical properties and constituents of the water and changes in some of those properties and constituents over time. All the data for this report (except some data for computation of equivalent freshwater heads, which are contained in appendixes of this report) are in Lambert and others (2009), which also summarizes data-collection techniques, water-quality sampling methods, analytical methods, and quality assurance.

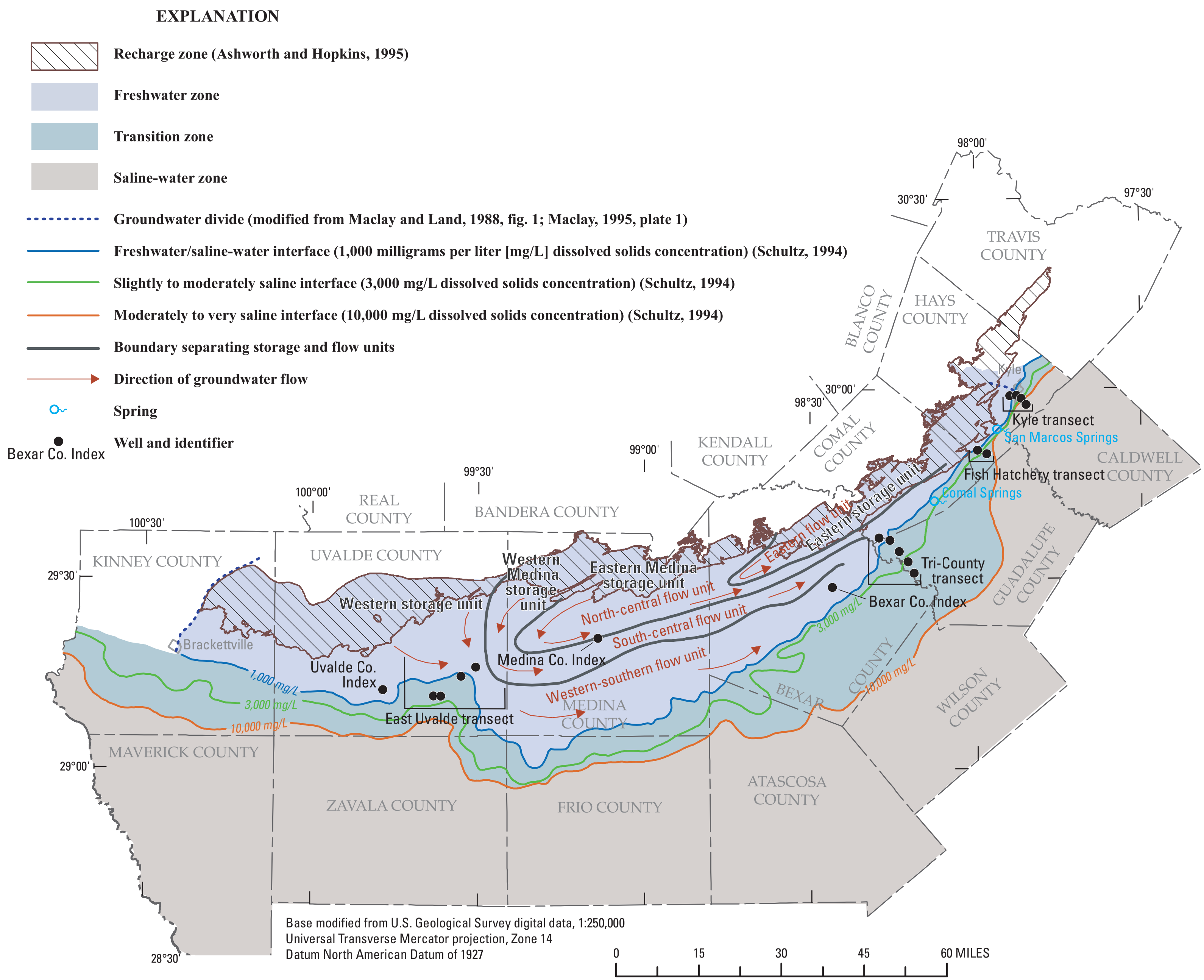


Figure 1. Areal extent of the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, and location of monitoring wells in and near the transition zone from which data were collected for this report (modified from Lambert and others, 2009, fig. 1).

Table 1. Descriptive information for monitoring wells in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, from which data were collected for this report, 1999–2007.

[LSD, land-surface datum; NAVD 88, North American Vertical Datum of 1988; Well descriptor: 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]

U.S. Geological Survey site 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 to 1,500	Freshwater
291612099302001	East Uvalde 2	EU2	YP–69–44–902	1999	1,560	899.91	1,072 to 1,560	Freshwater
291136099375801	East Uvalde 3	EU3	YP–69–51–606	1999	1,400	877.55	768 to 1,400	Saline water
291133099363801	East Uvalde 4	EU4	YP–69–52–404	1999	1,463	867.02	950 to 1,463	Saline water
293610098152701	Tri-County 1	TC1	KX–68–30–314	1999	920	871.01	385 to 920	Freshwater
293424098134701	Tri-County 2	TC2	KX–68–31–403	1999	1,050	709.08	486 to 1,050	Interface
293245098121001	Tri-County 3	TC3	KX–68–31–511	1999	1,222	674.00	656 to 1,222	Saline water
293058098110501	Tri-County 4	TC4	KX–68–31–808	2000	1,562	648.92	1,000 to 1,562	Saline water
293632098172401	Tri-County 5	TC5	DX–68–30–315	2000	975	782.22	553 to 975	Freshwater
295019097592701	Fish Hatchery 1	FH1	LR–67–09–113	2000	280	714.73	216 to 280	Freshwater
294946097574501	Fish Hatchery 2	FH2	LR–67–09–401	2001	1,030	642.51	510 to 1,030	Saline water
295853097532901	Kyle 1	KY1	LR–67–01–311	1997	810	770.52	307 to 810	Freshwater
295858097521801	Kyle 2	KY2	LR–67–02–104	1998	975	674.32	427 to 975	Interface
295829097512601	Kyle 3	KY3	LR–67–02–106	1998	1,100	678.28	600 to 1,100	Saline water
295730097503201	Kyle 4	KY4	LR–67–02–105	1998	970	646.70	562 to 970	Saline water

Hydrogeologic sections along transects are used to illustrate vertical flow in the boreholes relative to stratigraphic units at each well and to hydrologic conditions in the aquifer at the times the flow logs were run during 2005–07. Hydrographs of equivalent freshwater heads for 2005–07 were superimposed on the sections to indicate hydrologic conditions at the times the flow logs were run. Temperature data were used to interpret relative rates of groundwater flow in the transition zone and in the freshwater zone near the transition zone.

Finally, the relation between the transition zone and the freshwater zone is discussed in light of the findings presented, with a focus on the potential for irreversible movement of saline water into the freshwater zone of the aquifer. Average lateral head gradients computed for periods during 1999–2007 indicate whether potential lateral flow at the interface along each transect was into, out of, or of mixed direction with regard to the freshwater zone. Vertical head gradients indicated by measured vertical flow in boreholes offer insight into the potential for upward flow from deeper, generally more-saline parts of the flow system toward shallower, generally fresher parts of the flow system.

Previous Studies

Previous studies were done that characterized the transition zone and contributed insight into the potential for movement of saline water into the freshwater zone of the aquifer. Published results of a series of studies begun in 1985 by the USGS and other agencies are in Pavlicek and others (1987), William F. Guyton and Associates, Inc. (1986, 1988), Poteet and others (1992), Groschen (1994), and Groschen and Buszka (1997). William F. Guyton and Associates, Inc. (1988) described an aquifer test conducted near another monitoring-well transect, the San Antonio transect (Lambert and others, 2009, fig. 1), and reports 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 Buzka (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.

Other previous studies addressed 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 saline-water zone.

Schultz (1992–94) 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 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 previous studies have focused on water chemistry and the possible origin of salinity in the transition zone. An early 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 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 (Lambert and others, 2009, fig. 1) was done by Mahler (2008). The statistical analyses indicate, among other things, that although the transition-zone wells are less well connected to surficial hydrologic conditions than the freshwater-zone wells, there is some connection but the response time is longer.

Hydrogeologic Setting

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 to 400 feet per mile and becomes buried and confined toward the present Gulf of Mexico coast (Maclay, 1995). 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 in the northeastern part of the study area in Hays County to more than 2,600 feet in southern Medina County. The average thickness of the Edwards aquifer in the transition zone is about 500 feet; 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 (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. To the east in eastern Uvalde and Medina Counties, the Edwards aquifer 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 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). 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. 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.

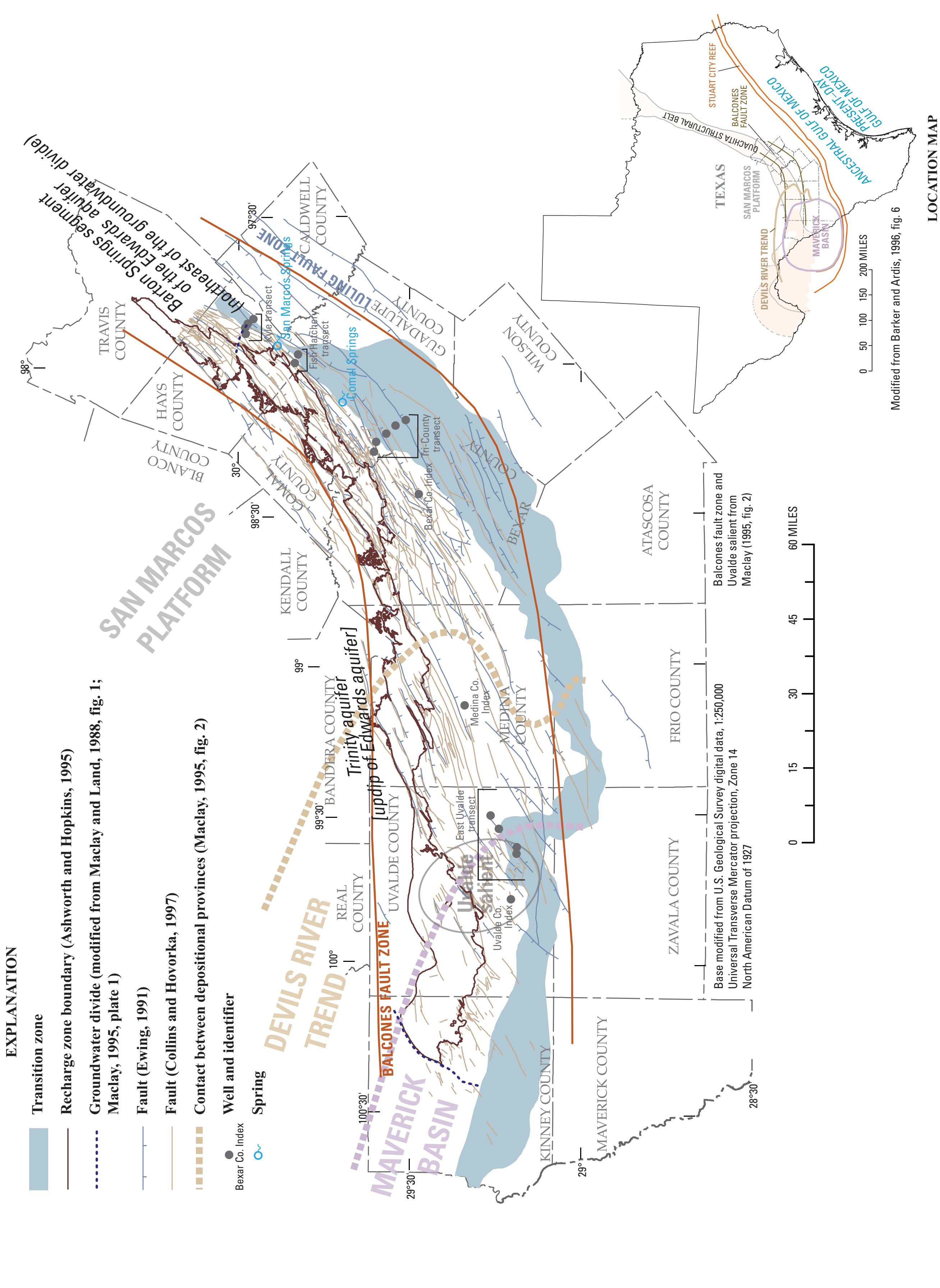
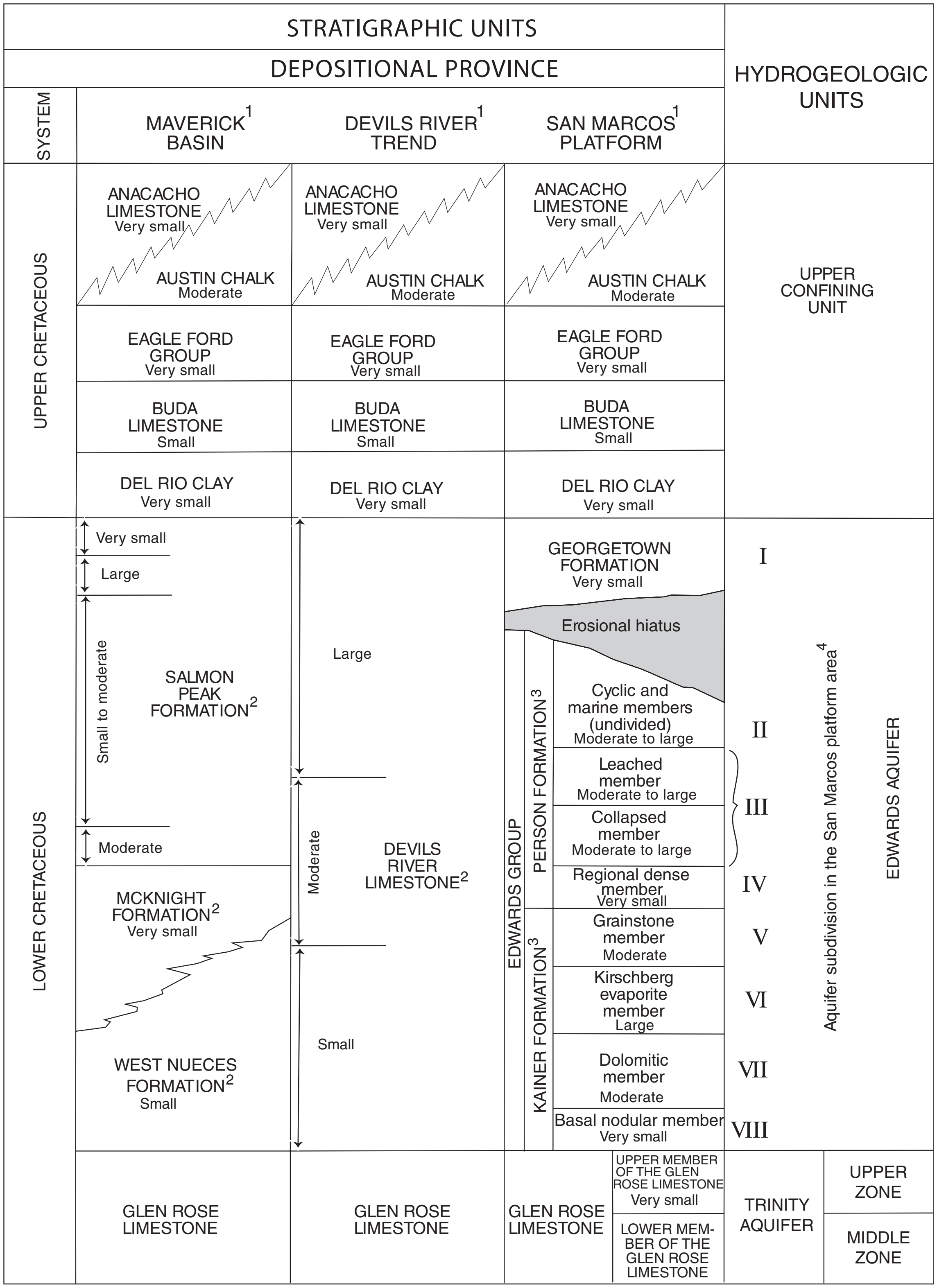


Figure 2. Structural elements and depositional provinces associated with the San Antonio segment of the Edwards aquifer, south-central Texas.



[1] Location shown in figure 2.
[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 stratigraphic units.

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

Maclay and Land (1988, fig. 2) delineated four major storage and flow units in the freshwater zone of the Edwards aquifer (fig. 4). 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. The transition zone is adjacent to the southernmost storage units and 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

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 feet 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, but some wells did not penetrate the entire thickness because of a depth limitation of the drill rig. 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 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. 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 (fig. 2). 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. Schulz (1994) placed EU1 in the transition zone (fig. 5, inset map). However, EU1 was drilled in 1998, and water-quality samples collected from EU1 (Lambert and others, 2009) indicate that the well is completed in the freshwater zone of the Edwards aquifer. Thus the interface based on data for this report 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 the 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) are freshwater wells based on water-quality samples collected from these wells (Lambert and others, 2009). Tri-County 2 (TC2), designated an interface well because it intersects the interface, contains freshwater in the upper part of the well and saline water in the bottom part of the well. Thus the interface based on data for this report occurs at about the location of well TC2. Shultz (1994) located TC1 in the transition zone, before TC1 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, data collection in TC5 was restricted to only water levels and a partial log of the upper section of the borehole for fluid conductivity and temperature collected in 2002. No flowmeter data were collected from TC5.

The Fish Hatchery transect comprises two wells and is in the northeastern part of the Edwards aquifer in Hays County (fig. 1). Both wells are completed in rocks of the Edwards Group and the Georgetown Formation in the San Marcos Platform depositional province (fig. 2). Fish Hatchery 1 (FH1) is a freshwater well and Fish Hatchery 2 (FH2) is a saline-water well on the basis of water-quality samples (Lambert and others, 2009) (fig. 7). Thus the interface based on data for this report occurs between wells FH1 and FH2, but both were located in the transition zone by Schulz (1994) (fig. 7, inset map). The Fish Hatchery transect is about midway between Comal Springs and San Marcos Springs (fig. 1).

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. Thus the interface based on data for this report occurs about at the location of well KY2. Kyle 3 (KY3) and Kyle 4 (KY4) are saline-water wells on the basis of water samples (Lambert and others, 2009). Schultz (1994) located KY3 in the transition zone (fig. 8, inset map).

Methods of Analysis

Water-level data and borehole geophysical data were analyzed for this report. Equivalent freshwater heads were computed from measured water-level data (daily mean depth to water, termed environmental-water head) collected by the USGS and SAWS from February 1999 through December 2007 for 15 wells in the East Uvalde, Tri-County, Fish Hatchery, and Kyle transects to define hydraulic gradients in the horizontal direction. Because the boreholes in the wells were open to the entire length of the aquifer, the computed equivalent freshwater heads are composite heads that are the

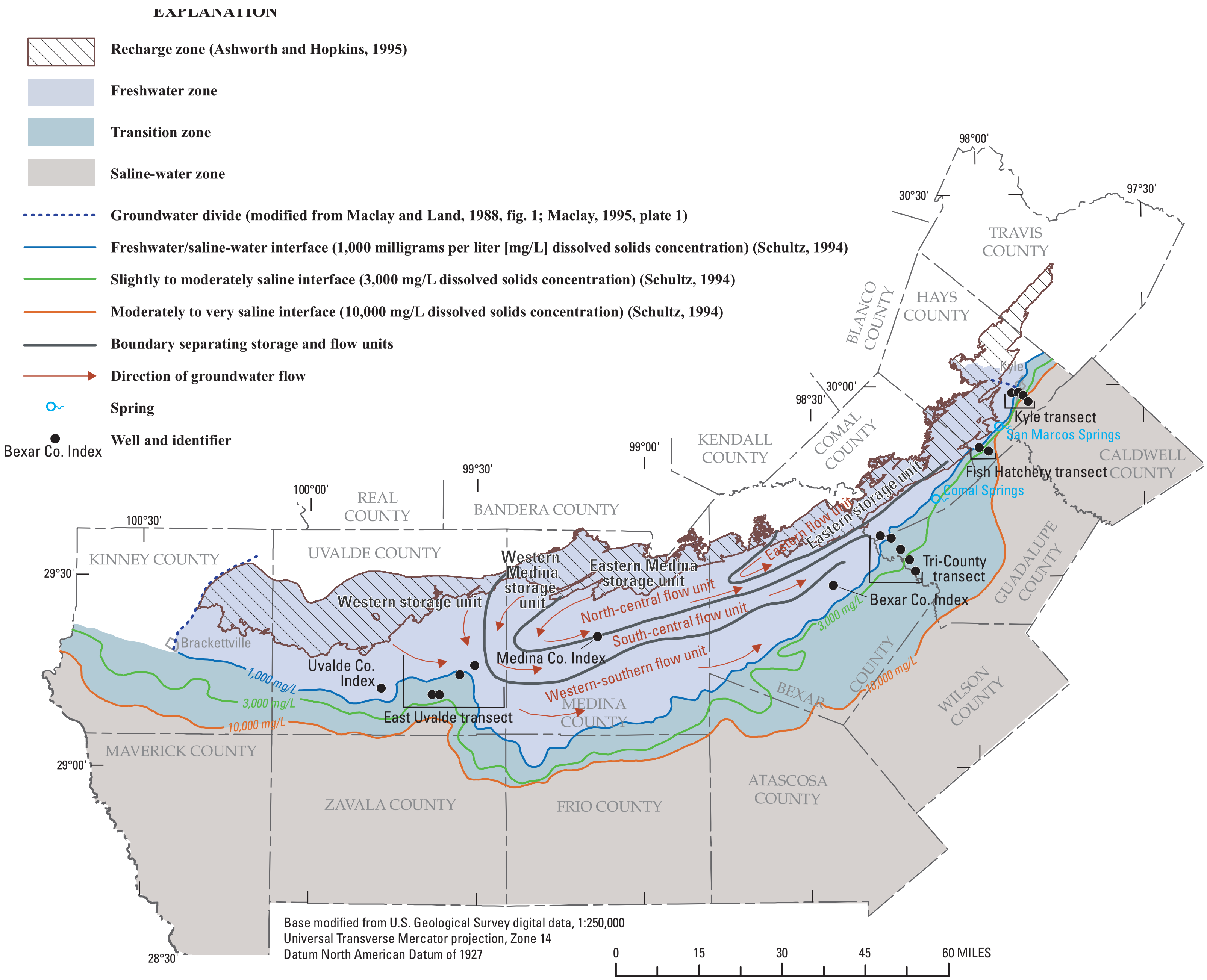


Figure 4. Major storage and flow units and regional flow patterns in the San Antonio segment of the Edwards aquifer, south-central Texas (modified from Maclay and Land, 1988, fig. 22).

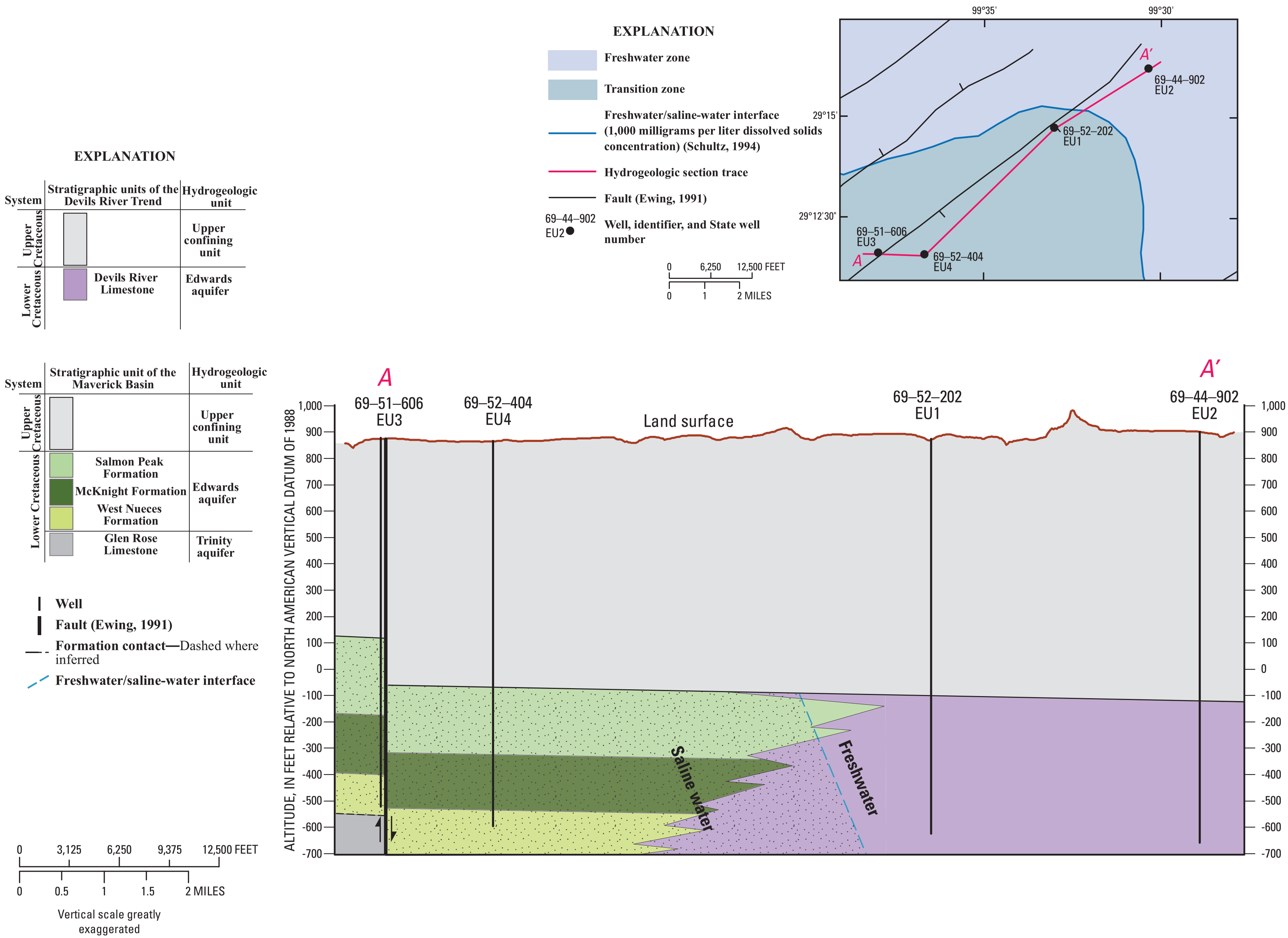


Figure 5. Hydrogeologic section of the East Uvalde transect (*A–A′*), San Antonio segment of the Edwards aquifer, south-central Texas.

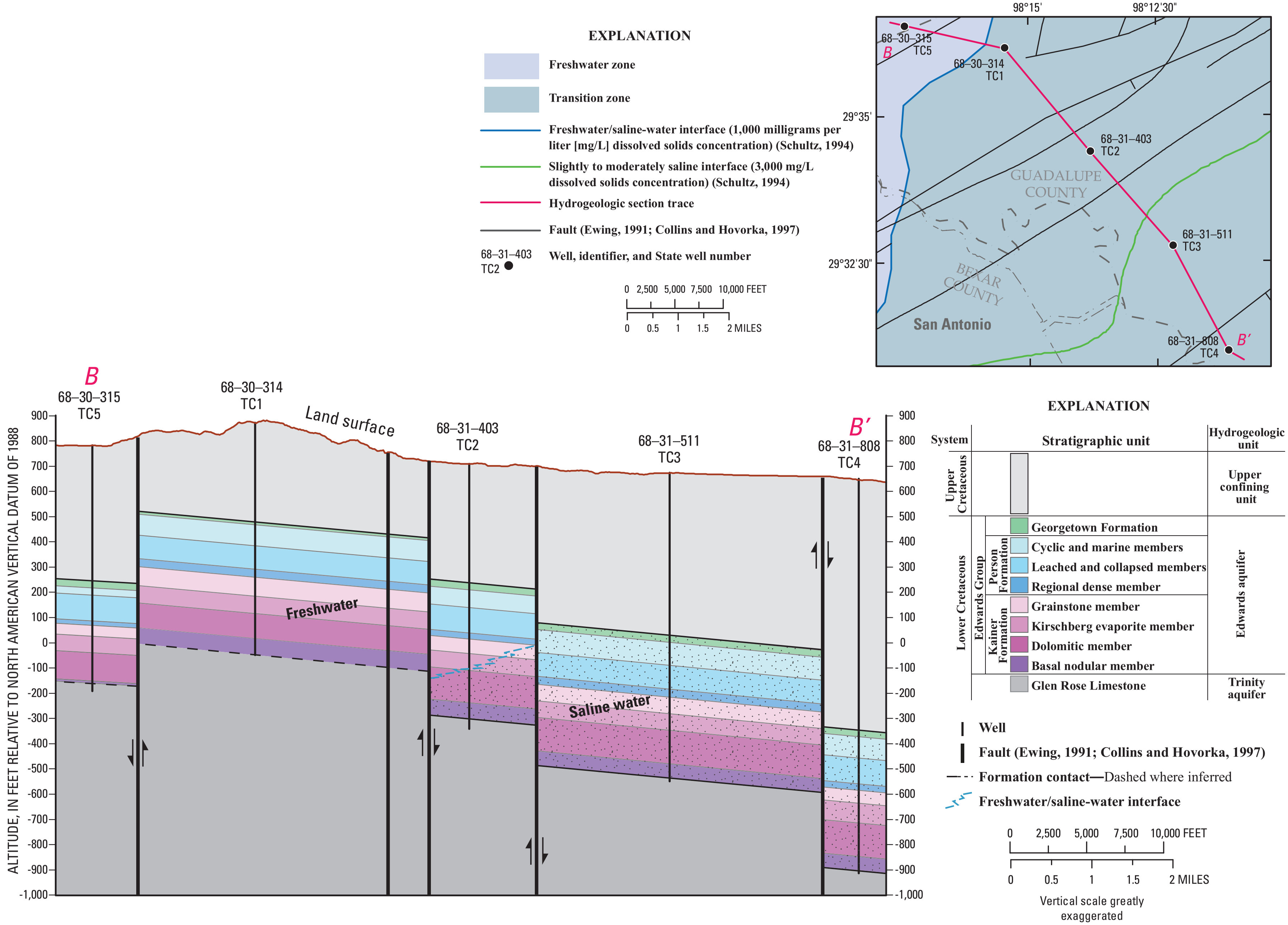


Figure 6. Hydrogeologic section of the Tri-County transect (*B–B′*), San Antonio segment of the Edwards aquifer, south-central Texas.

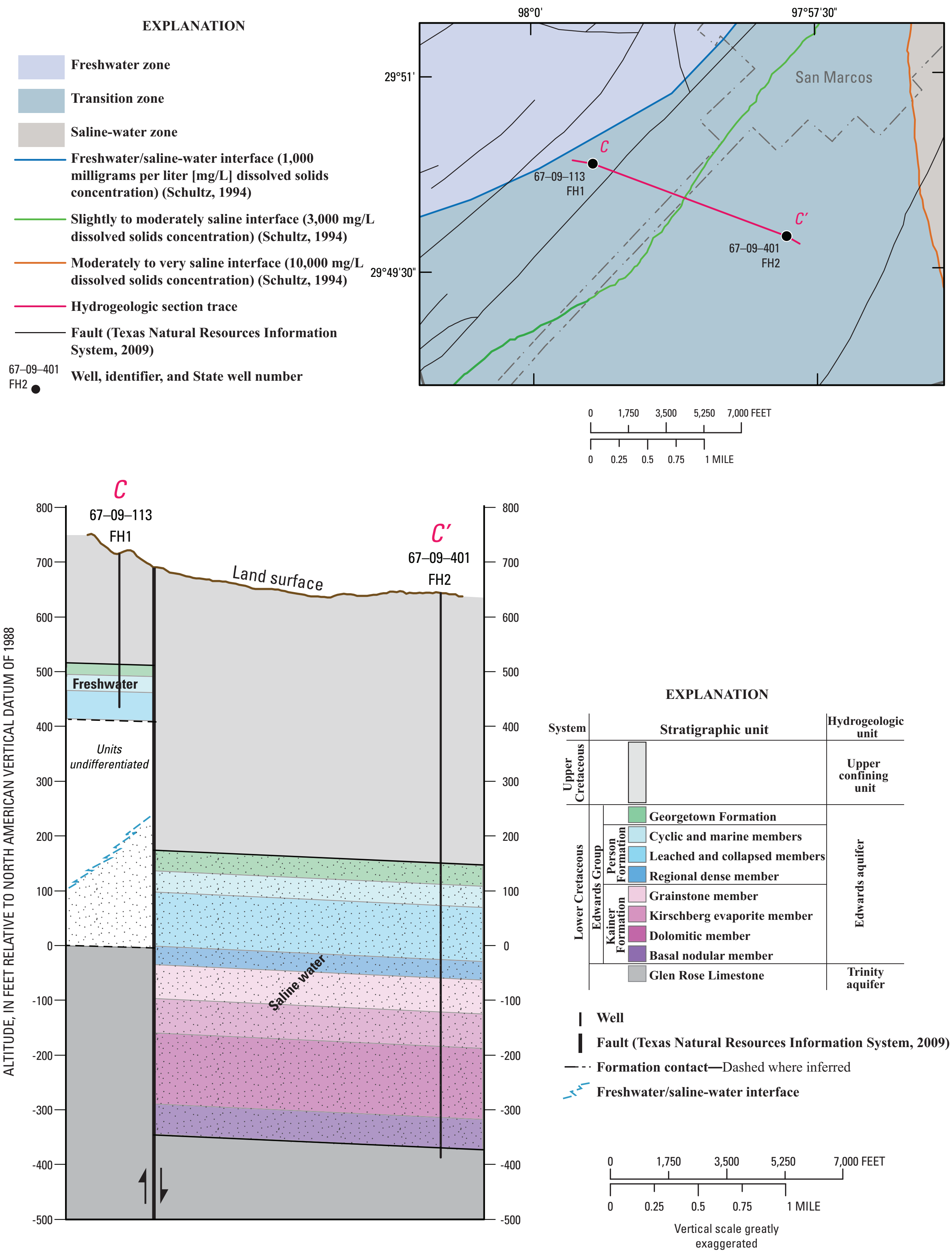


Figure 7. Hydrogeologic section of the San Marcos Fish Hatchery transect (*C*–*C′*), San Antonio segment of the Edwards aquifer, south-central Texas.

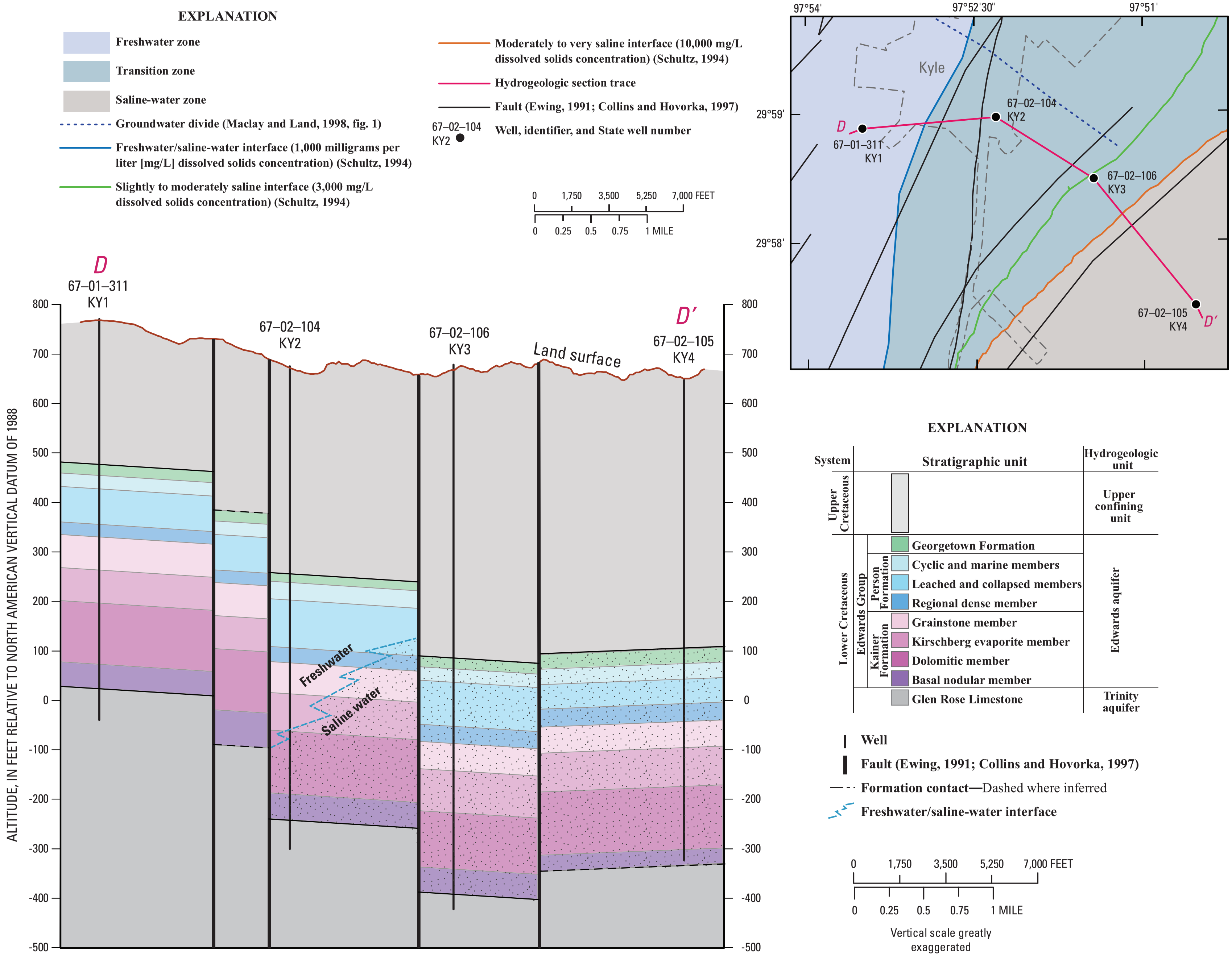


Figure 8. Hydrogeologic section of the Kyle transect (*D–D′*), San Antonio segment of the Edwards aquifer, south-central Texas.

transmissivity-weighted average of multiple flow zones in a single borehole. The measured water-level data used in the computation of equivalent freshwater heads are in appendixes 1.1–1.15 of this report and in Lambert and others (2009).

Borehole geophysical logging techniques can be useful for providing information on the heterogeneity in an aquifer as well as providing multiple, independent measurements that can be used to separate such formation properties as lithology, mineralogy, porosity, fracture distribution, and water salinity (Paillet, 1994). Borehole geophysical logs provide measurements that are collected from rocks saturated with water under natural stress conditions where measurements can be collected without missing or disturbing the samples (Paillet, 1994). For this report, borehole geophysical logs were used to identify stratigraphic units penetrated by the boreholes and graphically relate stratigraphic units, fluid conductivity, fluid temperature, and vertical flow over the lengths of the boreholes of each of the monitoring wells at several different times and hydrologic conditions. Here, "identify stratigraphic units penetrated" means that the tops of the stratigraphic units penetrated were picked from drillers' logs but were refined by the geophysical logs. The stratigraphic units penetrated and water in the boreholes were characterized using an integrated analysis of the natural gamma, caliper, acoustic-televiewer, fluid conductivity (recorded as fluid resistivity), temperature, and flowmeter logs. The individual logs are presented in the form of composite graphs showing the change in each of the logs with depth relative to the stratigraphic units penetrated.

Water-Level Data—Computation of Equivalent Freshwater Heads

Equivalent freshwater heads define hydraulic gradients in the horizontal direction, and environmental-water heads define hydraulic gradients in the vertical direction (Lusczynski, 1961). Thus, equivalent freshwater heads are needed 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 aquifer. A necessary assumption made in using lateral head gradients based on equivalent freshwater heads to infer flow direction is that the slope of the Edwards aquifer is small enough for the aquifer to be considered horizontal. Using 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 call into question the assumption of a horizontal aquifer; nevertheless, the judgment was made that equivalent freshwater heads provide the best data from which to compute lateral gradients for this report.

Hydrologic conditions, as indicated by departure from normal (1971–2000) rainfall at the National Weather Service Station at the San Antonio International Airport (fig. 9), varied substantially during the study period (National Climatic Data Center, 2008). On average, conditions for the 9-year period 1999–2007 were essentially normal, and similar variability relative to normal conditions likely characterized water levels in the aquifer during the period. Average annual rainfall for 1999–2007 was 32.68 inches per year, slightly less than the 1971–2000 average of 32.92 inches per year (National Weather Service, 2010). The years 1999 (16.41 inches), 2003 (28.45 inches), 2005 (16.54 inches), and 2006 (21.34) were drier than normal; and the years 2000 (35.85 inches), 2001 (36.72 inches), 2002 (46.27 inches), 2004 (45.32 inches), and 2007 (47.25 inches) were wetter than normal.

Pressure transducers installed in monitoring wells measured environmental-water head, which is the actual head in each well. 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 conversion of measured environmental-water heads to equivalent freshwater heads can be done by applying the 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

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

where

l_f = length of equivalent freshwater column, in feet,
ρ_s = density of environmental water, in milligrams per cubic centimeter,
ρ_f = density of freshwater, in milligrams per cubic centimeter,
ρ_s/ρ_f = density correction factor, and
l_s = 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 for each well for a given temperature and salinity (as indicated by fluid conductivity) was obtained using a Web-based JavaScript calculator from the Johns-Hopkins University Applied Physics Laboratory (2005) to compute the United Nations Educational Scientific and Cultural Organization (UNESCO) International Equation of State as described in Fofonoff (1985) (hereinafter, density calculator). Values of length of the environmental-water column, fluid conductivity in the water column, and temperature in the water column were entered into the calculator to compute the density of environmental water. The values of those three variables for each well used in the density

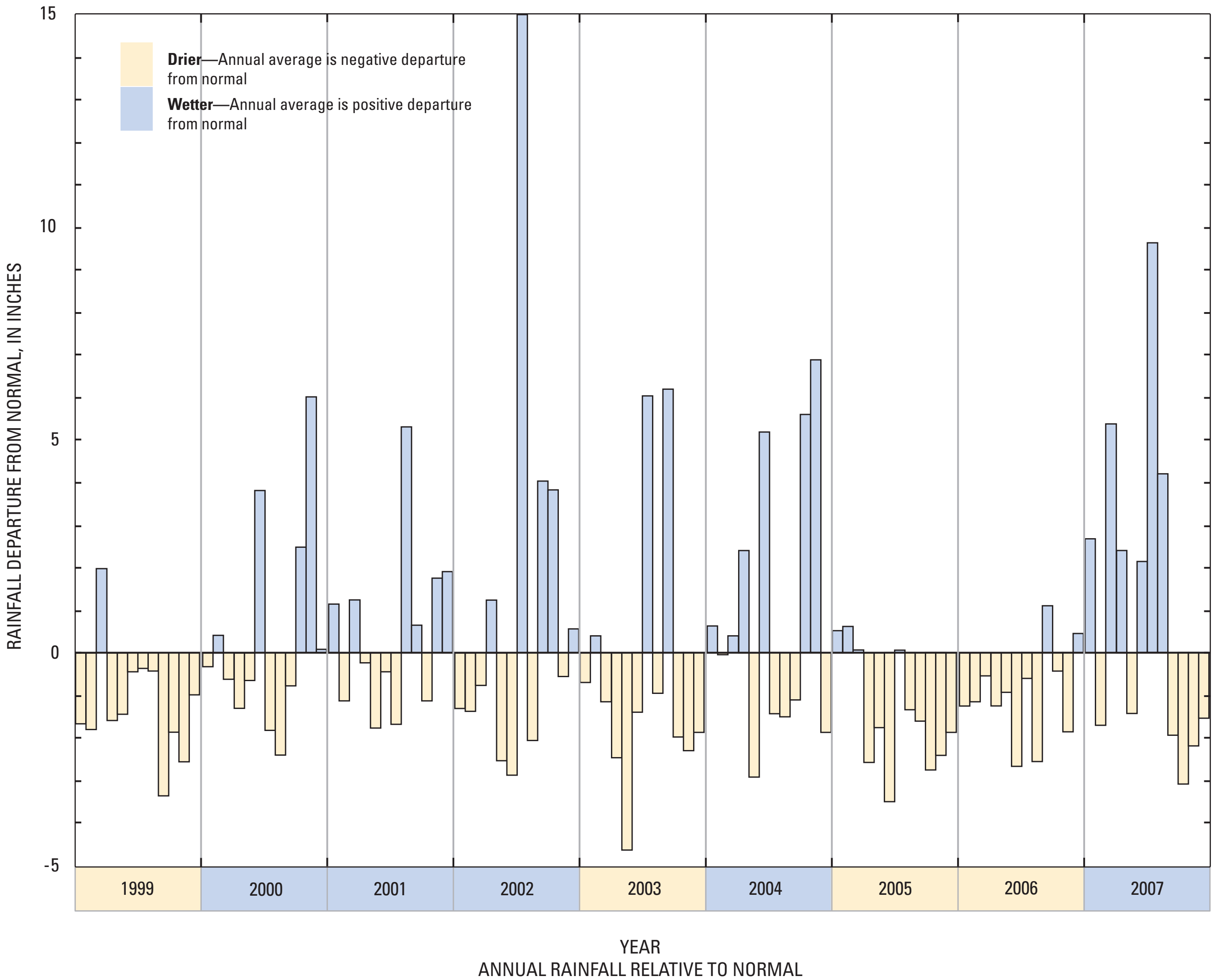


Figure 9. Monthly departure from normal (1971–2000) rainfall, National Weather Service station 417945/12921, San Antonio International Airport, Texas, 1999–2007.

calculator were averages of the length of the environmental-water column, depth-averaged conductivity, and depth-averaged temperature from all logs for the given well that were collected during 2002–07. Although values for length of the environmental-water column are available for each day of water-level record, depth-averaged conductivity and depth-averaged temperature values are available only for the several days when logs were run. The decision was made to average the depth-averaged conductivity and depth-averaged temperature values from all logs from each well, and for consistency the associated length of the environmental-water column values, and use those average values in the density calculator to obtain a density of environmental water for each well assumed to be representative of the period 1999–2007. The density of freshwater for each well, also assumed to be representative of the period 1999–2007, was interpolated from a table of density variation with temperature (van der Leeden and others, 1990, table 11–1) using the average temperature used in the density calculator. The density correction factor for each well needed to compute the length of the equivalent freshwater column was 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 using equation 2, the equivalent freshwater head was computed as

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

where h_f is freshwater head and h_s is the environmental-water head. Environmental-water head was computed as altitude of land-surface datum minus depth to water measured by the pressure transducer. Heads were reported as daily means in feet above North American Vertical Datum of 1988 (NAVD 88). Data for the 15 monitoring wells for the dates of geophysical log data collection used to compute equivalent freshwater heads, including the average values of the variables used to obtain the density correction factor for each well, and the resultant density correction factor are in table 2. Daily mean water-level and associated data used to compute equivalent freshwater head and the resultant equivalent freshwater heads for the 15 monitoring wells for the respective periods of water-level record are in appendixes 1.1–1.15.

Borehole Geophysical Log Data

The borehole geophysical methods discussed in this report were used to log wells in the East Uvalde, Tri-County, Fish Hatchery, and Kyle transects at various times (dates) over a range in hydraulic head conditions during 2002–07. Fluid conductivity and fluid temperature were collected using two methods. The first method, used in 2002, recorded the fluid conductivity and the second method, used during 2005–07, recorded fluid resistivity that was then converted to fluid conductivity. In addition to fluid conductivity and fluid temperature, other conventional geophysical logging methods were used to collect information from the monitoring wells. These methods included using the natural gamma, caliper, long and short normal resistivity, lateral resistivity, and induction conductivity tools. Advanced logging methods such as acoustic televiewer (ATV), heat pulse flowmeter, and electromagnetic (EM) flowmeter also were used. More in-depth descriptions of each of these logging tools and their applications are in Keys (1997) and Stanton and others (2007).

Fluid conductivity is the ability of a fluid to conduct an electrical current and is the inverse of fluid resistivity (Keys, 1997). Fluid conductivity logs were run in each of the wells in 2002 and are displayed in units of microsiemens per centimeter at the temperature encountered in the borehole (Lambert and others, 2009). Fluid resistivity logs run during 2005–07 in each of the wells were converted from fluid resistivity logs to fluid conductivity logs and also are displayed in units of microsiemens per centimeter at the temperature encountered in the borehole to allow for comparison to the 2002 fluid conductivity logs. A depth-averaged fluid conductivity and a depth-averaged fluid temperature in the borehole were computed for each logging run. The depth-averaged conductivity and temperature values from each logging run then were averaged to obtain a fluid conductivity value and a temperature value assumed to be representative for each well for 1999–2007 for computation of equivalent freshwater heads, as described in the previous section. The conversion of fluid resistivity logs to fluid conductivity logs allows for the qualitative comparison of the borehole data to other datasets including water-quality monitor data and discrete water-chemistry data but does not imply that these measurements are the equivalent of high-precision specific conductance measurements.

The different instrumentation and methods that were used during 2002–07 to measure or to calculate the borehole fluid conductivity in the monitoring wells constrained the accuracy of the calculated fluid conductivities. The limited accuracy of the borehole geophysical instrumentation to record very low fluid resistivities in high-salinity water limited the precision of the fluid conductivity datasets at relatively high salinities. Because of the differences in the magnitude of the borehole readings for each logging run and the limitations associated with using fluid resistivity logs to calculate the fluid conductivity logs at relatively high salinities, the computed fluid conductivity values for each logging run in each well are assumed to be representative of similar ranges in conductivity. The scales of the fluid conductivity and temperature logs were adjusted to normalize the log responses; that is, rather than common scales for conductivity and temperature logs, respectively, the scales were adjusted to overlay as many of the logs as possible to allow clearer visualization of differences in log response in relation to zones of possible inflow and outflow. Temperature logs were run concurrently with the fluid conductivity logs; the temperature logs are displayed in degrees Celsius.

Flow logs were collected in wells of all four transects under ambient conditions to evaluate the differences in hydraulic head of the various transmissive zones tapped by the wells. Heat pulse and EM flowmeter data were obtained in a stationary mode in which vertical flow in the borehole was recorded with the probe held stationary at a specified depth. In most cases, a trolling EM flowmeter log was used with caliper and fluid conductivity data to detect zones of optimum flow and best borehole conditions for isolation of flow zones.

Ambient flow stations were measured over a nearly 3-year period (2005–07) under differing hydraulic conditions to determine how vertical flow in the borehole changed with time and in relation to changes in the equivalent freshwater head in each well. Flow stations were chosen on the basis of previous logging runs to identify optimum flow zones and where there was a fairly competent section, or solid rock, in the borehole wall that allowed for a tight seal to make a measurement. Measured flows of less than 0.1 gallon per minute were considered estimated and within the error of the EM flowmeter instrumentation. By convention, positive low values on the logs indicate upward flow, and negative values indicate downward flow. Hydrographs of equivalent freshwater head for 2005–07, where available, are superimposed on diagrams showing vertical flow in wells to illustrate the relation between head in a particular well time and changes in fluid conductivity, temperature, and vertical flow in the borehole over time.

The 15 wells were logged at various times during 2002–07 by USGS personnel. All logs collected during 2002–07 were recorded digitally and archived in the Log ASCII Standard (LAS) version 2 format, which is the USGS standard for borehole geophysical data storage. The borehole

Table 2. Data from 15 monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–2007, used to compute average equivalent freshwater head.

[LSD, land-surface datum; ft, feet; 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 conductivity; 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; --, not applicable; e, estimated]

U.S. Geological Survey site number	Well name	Well identifier (fig. 1)	State well number	Data collection date	Altitude of LSD (ft above NAVD 88)	Well depth (ft below LSD)	Daily mean depth to water (ft below LSD)[1]	h_s (ft above NAVD 88)	l_s (ft)	T (°C)[2]	C (μS/cm)[2]	ρ_s (g/cm³)[3]	ρ_f (g/cm³)[4]	Density correction factor (ρ_s/ρ_f)	l_f (ft)[5]	$l_f - l_s$ (ft)	h_f (ft above NAVD 88)[6]
291443099325801	East Uvalde 1	EU1	YP–69–52–202	11/6/2002	874.02	1,500	67.84	806.18	1,432.16	21.93	418	0.999946	0.997786	1.0022	1,435.26	3.10	809.28
291443099325801	East Uvalde 1	EU1	YP–69–52–202	4/25/2005	874.02	1,500	50.90	823.12	1,449.10	33.17	356	.996725	.994639	1.0021	1,452.14	3.04	826.16
291443099325801	East Uvalde 1	EU1	YP–69–52–202	4/12/2006	874.02	1,500	100.55	773.47	1,399.45	30.34	146	.997505	.995542	1.0020	1,402.21	2.76	776.23
291443099325801	East Uvalde 1	EU1	YP–69–52–202	9/26/2006	874.02	1,500	122.46	751.56	1,377.54	28.58	394	.998088	.996065	1.0020	1,380.34	2.80	754.36
291443099325801	East Uvalde 1	EU1	YP–69–52–202	10/17/2007	874.02	1,500	48.85	825.17	1,451.15	28.23	633	.998373	.996166	1.0022	1,454.37	3.22	828.39
							Average	--	1,421.88	28.45	389	.998185	.996102	1.0021	--	--	--
291612099302001	East Uvalde 2	EU2	YP–69–44–902	11/6/2002	899.91	1,560	90.55	809.36	1,469.45	21.98	424	.999988	.997774	1.0022	1,472.71	3.26	812.62
291612099302001	East Uvalde 2	EU2	YP–69–44–902	4/11/2006	899.91	1,560	124.51	775.40	1,435.49	24.77	104	.999129	.997102	1.0020	1,438.41	2.92	778.32
291612099302001	East Uvalde 2	EU2	YP–69–44–902	9/28/2006	899.91	1,560	148.36	751.55	1,411.64	20.61	315	1.00018	.998074	1.0021	1,414.62	2.98	754.53
291612099302001	East Uvalde 2	EU2	YP–69–44–902	10/16/2007	899.91	1,560	73.15	826.76	1,486.85	22.91	365	.999765	.997559	1.0022	1,490.14	3.29	830.05
							Average	--	1,450.86	22.57	302	.999774	.997638	1.0021	--	--	--
291136099375801	East Uvalde 3	EU3	YP–69–51–606	11/7/2002	877.55	1,400	83.35	794.20	1,316.65	27.41	5,239	1.00020	.996397	1.0038	1,321.68	5.03	799.23
291136099375801	East Uvalde 3	EU3	YP–69–51–606	4/28/2005	877.55	1,400	46.06	831.49	1,353.94	34.00	1,652	.996723	.994371	1.0024	1,357.14	3.20	834.69
291136099375801	East Uvalde 3	EU3	YP–69–51–606	4/14/2006	877.55	1,400	92.01	785.54	1,307.99	30.96	4,975	.998886	.995352	1.0036	1,312.63	4.64	790.18
291136099375801	East Uvalde 3	EU3	YP–69–51–606	9/25/2006	877.55	1,400	114.98	762.57	1,285.02	31.58	2,398	.997710	.995157	1.0026	1,288.32	3.30	765.87
291136099375801	East Uvalde 3	EU3	YP–69–51–606	10/23/2007	877.55	1,400	52.01	825.54	1,347.99	29.26	3,426	.998935	.995867	1.0031	1,352.14	4.15	829.69
							Average	--	1,322.32	30.64	3,538	.998484	.995450	1.0030	--	--	--
291133099363801	East Uvalde 4	EU4	YP–69–52–404	11/7/2002	867.02	1,463	71.85	795.17	1,391.15	29.73	3,559	.998889	.995726	1.0032	1,395.57	4.42	799.59
291133099363801	East Uvalde 4	EU4	YP–69–52–404	3/3/2005	867.02	1,463	e32.70	834.32	1,430.30	32.37	1,335	.997279	.994905	1.0024	1,433.71	3.41	837.73
291133099363801	East Uvalde 4	EU4	YP–69–52–404	4/28/2005	867.02	1,463	35.81	831.21	1,427.19	33.75	4,348	.997821	.994452	1.0034	1,432.03	4.84	836.05
291133099363801	East Uvalde 4	EU4	YP–69–52–404	4/13/2006	867.02	1,463	81.08	785.94	1,381.92	32.53	741	.996967	.994854	1.0021	1,384.86	2.94	788.88
291133099363801	East Uvalde 4	EU4	YP–69–52–404	9/25/2006	867.02	1,463	104.18	762.84	1,358.82	32.24	1,939	.997429	.994947	1.0025	1,362.21	3.39	766.23
291133099363801	East Uvalde 4	EU4	YP–69–52–404	10/18/2007	867.02	1,463	40.27	826.75	1,422.73	30.35	3,070	.998546	.995539	1.0030	1,427.03	4.30	831.05
							Average	--	1,402.02	31.83	2,499	.997819	.995079	1.0028	--	--	--
293610098152701	Tri-County 1	TC1	KX–68–30–314	1/27/2003	871.01	920	191.45	679.56	728.55	23.40	908	.998806	.997442	1.0014	729.55	1.00	680.56
293610098152701	Tri-County 1	TC1	KX–68–30–314	4/18/2005	871.01	920	189.77	681.24	730.23	25.92	439	.997972	.996804	1.0012	731.09	0.86	682.10
293610098152701	Tri-County 1	TC1	KX–68–30–314	4/21/2005	871.01	920	190.81	680.20	729.19	24.67	1,614	.998757	.997128	1.0016	730.38	1.19	681.39
293610098152701	Tri-County 1	TC1	KX–68–30–314	10/26/2005	871.01	920	e205.3	665.71	665.71	26.34	333	.997731	.996691	1.0010	666.40	0.69	666.40
293610098152701	Tri-County 1	TC1	KX–68–30–314	6/23/2006	871.01	920	221.43	649.58	698.57	24.51	751	.998419	.997168	1.0013	699.45	0.88	650.46
293610098152701	Tri-County 1	TC1	KX–68–30–314	11/6/2006	871.01	920	221.08	649.93	698.92	22.74	608	.998810	.997598	1.0012	699.77	0.85	650.78
293610098152701	Tri-County 1	TC1	KX–68–30–314	10/29/2007	871.01	920	e192.76	678.25	678.25	24.89	550	.998216	.997072	1.0011	679.03	0.78	679.03
							Average	--	704.20	24.64	743	.998390	.997135	1.0013	--	--	--

Table 2. Data from 15 monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–2007, used to compute average equivalent freshwater head—Continued.

U.S. Geological Survey site number	Well name	Well identifier (fig. 1)	State well number	Data collection date	Altitude of LSD (ft above NAVD 88)	Well depth (ft below LSD)	Daily mean depth to water (ft below LSD)[1]	h_s (ft above NAVD 88)	l_s (ft)	T (°C)[2]	C (µS/cm)[2]	ρ_s (g/cm^3)[3]	ρ_f (g/cm^3)[4]	Density correction factor (ρ_s/ρ_f)	l_f (ft)[5]	$l_f - l_s$ (ft)	h_f (ft above NAVD 88)[6]
293424098134701	Tri-County 2	TC2	KX–68–31–403	1/30/2003	709.08	1,050	20.98	688.10	1,029.02	23.88	5,506	1.00104	.997327	1.0037	1,032.85	3.83	691.93
293424098134701	Tri-County 2	TC2	KX–68–31–403	5/17/2005	709.08	1,050	e26.07	683.01	1,023.93	28.22	2,928	.998638	.996169	1.0025	1,026.47	2.54	685.55
293424098134701	Tri-County 2	TC2	KX–68–31–403	10/20/2005	709.08	1,050	e37.48	671.60	1,012.52	27.01	1,846	.998577	.996509	1.0021	1,014.62	2.10	673.70
293424098134701	Tri-County 2	TC2	KX–68–31–403	11/2/2005	709.08	1,050	e37.55	671.53	1,012.45	28.23	2,928	.998619	.996166	1.0025	1,014.94	2.49	674.02
293424098134701	Tri-County 2	TC2	KX–68–31–403	4/20/2006	709.08	1,050	49.31	659.77	1,000.69	27.03	1,512	.998428	.996504	1.0019	1,002.62	1.93	661.70
293424098134701	Tri-County 2	TC2	KX–68–31–403	11/21/2006	709.08	1,050	52.40	656.68	997.60	23.59	3,135	1.00005	.997397	1.0027	1,000.25	2.65	659.33
293424098134701	Tri-County 2	TC2	KX–68–31–403	10/30/2007	709.08	1,050	24.45	684.63	1,025.55	25.42	1,381	.998869	.996934	1.0019	1,027.54	1.99	686.62
							Average	--	1,014.54	26.20	2,748	.999166	.996729	1.0024	--	--	--
293245098121001	Tri-County 3	TC3	KX–68–31–511	1/28/2003	674	1,222	2.62	671.38	1,219.38	25.32	13,019	1.00419	.996960	1.0073	1,228.22	8.84	680.22
293245098121001	Tri-County 3	TC3	KX–68–31–511	10/26/2005	674	1,222	e8.3	665.70	1,213.70	28.42	3,494	.999049	.996111	1.0029	1,217.28	3.58	669.28
293245098121001	Tri-County 3	TC3	KX–68–31–511	4/18/2006	674	1,222	16.28	657.72	1,205.72	28.05	2,508	.998778	.996218	1.0026	1,208.82	3.10	660.82
293245098121001	Tri-County 3	TC3	KX–68–31–511	10/25/2006	674	1,222	24.72	649.28	1,197.28	25.53	6,546	1.00120	.996906	1.0043	1,202.44	5.16	654.44
							Average	--	1,209.02	26.83	6,392	1.00072	.996558	1.0042	--	--	--
293058098110501	Tri-County 4	TC4	KX–68–31–808	1/30/2003	648.92	1,562	2.30	646.62	1,559.70	27.99	15,742	1.00476	.996235	1.0086	1,573.05	13.35	659.97
293058098110501	Tri-County 4	TC4	KX–68–31–808	10/21/2005	648.92	1,562	e-6.01	654.93	1,568.01	31.70	3,899	.998583	.995120	1.0035	1,573.47	5.46	660.39
293058098110501	Tri-County 4	TC4	KX–68–31–808	4/19/2006	648.92	1,562	-1.95	650.87	1,563.95	30.93	2,835	.998459	.995361	1.0031	1,568.82	4.87	655.74
293058098110501	Tri-County 4	TC4	KX–68–31–808	10/24/2006	648.92	1,562	6.62	642.30	1,555.38	29.34	7,085	1.00060	.995878	1.0047	1,562.75	7.37	649.67
							Average	--	1,561.76	29.99	7,390	1.00050	.995646	1.0049	--	--	--
293632098172401	Tri-County 5	TC5	KX–68–30–315	1/30/2003	782.22	975	103.02	679.20	871.98	21.60	438	.999252	.997859	1.0014	873.20	1.22	680.42
295019097592701	Fish Hatchery 1	FH1	LR–67–09–113	11/8/2002	714.73	280	112.20	602.53	167.80	21.37	545	.998366	.997910	1.0005	167.88	.08	602.61
295019097592701	Fish Hatchery 1	FH1	LR–67–09–113	4/20/2005	714.73	280	116.76	597.97	163.24	23.62	294	.997730	.997389	1.0003	163.30	.06	598.03
295019097592701	Fish Hatchery 1	FH1	LR–67–09–113	4/27/2006	714.73	280	125.99	588.74	154.01	24.14	155	.997538	.997262	1.0003	154.05	.04	588.78
295019097592701	Fish Hatchery 1	FH1	LR–67–09–113	9/21/2006	714.73	280	127.40	587.33	152.60	19.74	429	.998651	.998256	1.0004	152.66	.06	587.39
295019097592701	Fish Hatchery 1	FH1	LR–67–09–113	10/24/2007	714.73	280	117.13	597.60	162.87	22.28	464	.998117	.997705	1.0004	162.94	.07	597.67
							Average	--	160.10	22.23	377	.998091	.997717	1.0004	--	--	--
294946097574501	Fish Hatchery 2	FH2	LR–67–09–401	11/8/2002	642.51	1,030	46.59	595.92	983.41	24.97	15,236	1.00504	.997052	1.0080	991.29	7.88	603.80
294946097574501	Fish Hatchery 2	FH2	LR–67–09–401	4/19/2005	642.51	1,030	46.32	596.19	983.68	27.63	5,778	.999898	.996336	1.0036	987.20	3.52	599.71
294946097574501	Fish Hatchery 2	FH2	LR–67–09–401	5/2/2006	642.51	1,030	52.07	590.44	977.93	27.57	3,057	.998827	.996352	1.0025	980.36	2.43	592.87
294946097574501	Fish Hatchery 2	FH2	LR–67–09–401	9/20/2006	642.51	1,030	53.38	589.13	976.62	24.64	7,879	1.00178	.997135	1.0047	981.17	4.55	593.68
294946097574501	Fish Hatchery 2	FH2	LR–67–09–401	10/25/2007	642.51	1,030	46.88	595.63	983.12	25.87	15,663	1.00486	.996817	1.0081	991.05	7.93	603.56
							Average	--	980.95	26.14	9,523	1.00199	.996745	1.0053	--	--	--

Table 2. Data from 15 monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–2007, used to compute average equivalent freshwater head—Continued.

U.S. Geological Survey site number	Well name	Well identifier (fig. 1)	State well number	Data collection date	Altitude of LSD (ft above NAVD 88)	Well depth (ft below LSD)	Daily mean depth to water (ft below LSD)[1]	h_s (ft above NAVD 88)	l_s (ft)	T (°C)[2]	C (µS/cm)[2]	ρ_s (g/cm³)[3]	ρ_f (g/cm³)[4]	Density correction factor (ρ_s/ρ_f)	l_f (ft)[5]	$l_f - l_s$ (ft)	h_f (ft above NAVD 88)[6]
295853097532901	Kyle 1	KY1	LR–67–01–311	11/5/2002	770.52	810	174.87	595.65	635.13	23.77	1,111	.998664	.997353	1.0013	635.96	0.83	596.48
295853097532901	Kyle 1	KY1	LR–67–01–311	3/9/2005	770.52	810	182.27	588.25	627.73	26.49	500	.997697	.996650	1.0011	628.39	.66	588.91
295853097532901	Kyle 1	KY1	LR–67–01–311	3/1/2006	770.52	810	211.00	559.52	599.00	28.22	348	.997115	.996169	1.0009	599.57	.57	560.09
295853097532901	Kyle 1	KY1	LR–67–01–311	5/3/2006	770.52	810	e226.6	543.92	583.40	26.87	260	.997447	.996547	1.0009	583.93	.53	544.45
295853097532901	Kyle 1	KY1	LR–67–01–311	6/15/2006	770.52	810	227.79	542.73	582.21	24.76	1,556	.998507	.997105	1.0014	583.03	.82	543.55
295853097532901	Kyle 1	KY1	LR–67–01–311	9/6/2006	770.52	810	236.22	534.30	573.78	23.65	311	.998298	.997382	1.0009	574.31	.53	534.83
295853097532901	Kyle 1	KY1	LR–67–01–311	11/5/2007	770.52	810	191.63	578.89	618.37	25.33	308	.997929	.996958	1.0010	618.97	.60	579.49
							Average	--	602.80	25.58	628	.997957	.996893	1.0011	--	--	--
295858097521801	Kyle 2	KY2	LR–67–02–104	1/31/2003	674.32	975	76.12	598.20	898.88	23.13	6,361	1.00147	.997507	1.0040	902.45	3.57	601.77
295858097521801	Kyle 2	KY2	LR–67–02–104	7/28/2003	674.32	975	110.65	563.67	864.35	24.00	8,648	1.00219	.997298	1.0049	868.59	4.24	567.91
295858097521801	Kyle 2	KY2	LR–67–02–104	1/10/2005	674.32	975	e101.7	572.62	873.30	25.74	9,825	1.00212	.996851	1.0053	877.92	4.62	577.24
295858097521801	Kyle 2	KY2	LR–67–02–104	6/13/2006	674.32	975	128.13	546.19	846.87	22.53	4,841	1.00089	.997647	1.0033	849.62	2.75	548.94
295858097521801	Kyle 2	KY2	LR–67–02–104	9/12/2006	674.32	975	134.82	539.50	840.18	22.57	8,861	1.00273	.997638	1.0051	844.47	4.29	543.79
295858097521801	Kyle 2	KY2	LR–67–02–104	11/8/2007	674.32	975	98.20	576.12	876.80	24.68	2,841	.999456	.997125	1.0023	878.85	2.05	578.17
							Average	--	866.73	23.78	6,896	1.00147	.997351	1.0041	--	--	--
295829097512601	Kyle 3	KY3	LR–67–02–106	11/4/2002	678.28	1,100	89.60	588.68	1,010.40	23.86	14,324	1.00510	.997332	1.0078	1,018.27	7.87	596.55
295829097512601	Kyle 3	KY3	LR–67–02–106	5/18/2005	678.28	1,100	e98.43	579.85	1,001.57	27.94	11,290	1.00211	.996249	1.0059	1,007.46	5.89	585.74
295829097512601	Kyle 3	KY3	LR–67–02–106	6/19/2006	678.28	1,100	117.63	560.65	982.37	23.17	14,932	1.00564	.997497	1.0082	990.39	8.02	568.67
295829097512601	Kyle 3	KY3	LR–67–02–106	9/13/2006	678.28	1,100	121.13	557.15	978.87	22.56	14,571	1.00570	.997640	1.0081	986.78	7.91	565.06
295829097512601	Kyle 3	KY3	LR–67–02–106	11/7/2007	678.28	1,100	100.86	577.42	999.14	25.22	13,485	1.00401	.996987	1.0070	1,006.18	7.04	584.46
							Average	--	994.47	24.55	13,720	1.00452	.997158	1.0074	--	--	--
295730097503201	Kyle 4	KY4	LR–67–02–105	11/8/2002	646.7	970	63.65	583.05	906.35	24.11	29,075	1.01221	.997270	1.0150	919.93	13.58	596.63
295730097503201	Kyle 4	KY4	LR–67–02–105	5/19/2005	646.7	970	e66.08	580.62	903.92	26.05	15,008	1.00438	.996769	1.0076	910.82	6.90	587.52
295730097503201	Kyle 4	KY4	LR–67–02–105	6/20/2006	646.7	970	74.91	571.79	895.09	26.35	14,233	1.00389	.996688	1.0072	901.56	6.47	578.26
295730097503201	Kyle 4	KY4	LR–67–02–105	9/13/2006	646.7	970	76.66	570.04	893.34	23.39	13,842	1.00490	.997444	1.0075	900.02	6.68	576.72
295730097503201	Kyle 4	KY4	LR–67–02–105	11/6/2007	646.7	970	68.00	578.70	902.00	25.52	12,507	1.00345	.996908	1.0066	907.92	5.92	584.62
							Average	--	900.14	25.08	16,933	1.00569	.997023	1.0087	--	--	--

[1] Depth-averaged value from pressure transducer just deep enough in water column to remain submerged.

[2] Depth-averaged value from fluid-profile data collected for each well.

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

[4] Interpolated from table of pure water density variation with temperature (van der Leeden and others, 1990, table 11–1).

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

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

geophysical logs collected during 2005–07 were collected according to the following American Society for Testing and Materials (ATSM) standards: (1) ASTM standard D 6726–01 for borehole EM induction logging (American Society for Testing and Materials, 2001), (2) ASTM standard D 6274–98 for gamma logging (American Society for Testing and Materials, 2004a), and (3) ASTM standard D 6167–97 for caliper logging (American Society for Testing and Materials, 2004b).

Lithologic and Physicochemical Properties

Lithologic properties in each well were obtained from geophysical log data. These data were used to identify the stratigraphic units that contribute flow to the borehole and to determine vertical flow (magnitude and direction under ambient conditions) relative to the stratigraphic units in each well. Physicochemical properties (fluid conductivity and temperature) were obtained (and flow zones characterized) using an integrated analysis of the natural gamma, caliper, ATV, fluid conductivity (recorded as fluid resistivity), temperature, and EM flowmeter logs. Lithologic and physiochemical properties are discussed by transect in the following sections.

Lithologic Properties

East Uvalde Transect

For the freshwater wells EU1 and EU2, the natural gamma logs indicate carbonate rocks with a lack of contrast in the upper sections of the boreholes and increasing clayey material in the lower sections of the boreholes, as indicated by the greater variability in the gamma counts (figs. 10, 11). These wells are completed in the reefal facies of the Devils River Trend depositional province. In contrast, the gamma logs for saline-water wells EU3 and EU4 (figs. 12, 13) show greater variation in lithology down the boreholes than that in either wells EU1 or EU2, indicating that more clayey intervals are interbedded with carbonate rocks. The clayey intervals were more common in the bottom part of wells EU3 and EU4 corresponding to the McKnight Formation and the West Nueces Formation of the Maverick Basin depositional province. Wells EU3 and EU4 are completed in the basinal facies of the Maverick Basin depositional province.

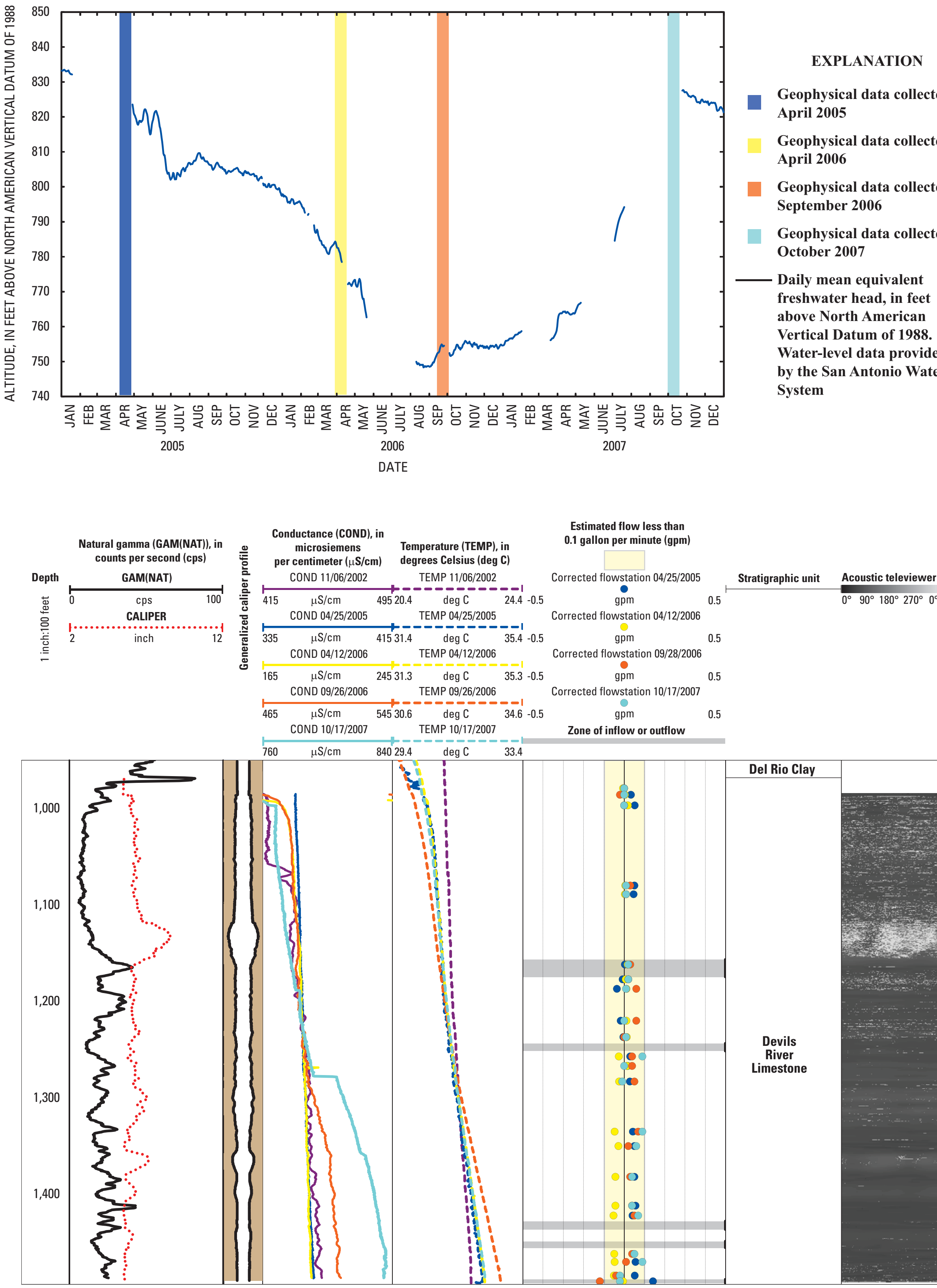
The caliper logs for all the East Uvalde transect wells confirm that the boreholes are about 6 inches in diameter along most of the lengths, except some intervals where the holes were enlarged beyond 6 inches to at least 7–9 inches in diameter. In EU1 and EU2, the larger-diameter intervals correspond to vuggy sections in the Devils River Limestone (figs. 10, 11). In 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 as well as the gamma logs indicate that most of the porosity and permeability in the East Uvalde wells are associated with cleaner (less clayey) limestone sections and are the result of secondary porosity development.

The ATV log for EU1 shows that the borehole was competent in the upper sections and more vuggy and fractured in the lower sections, with the greatest number of vugs occurring at the bottom of the well (fig. 10). In EU2, the ATV image shows secondary porosity development in the form of bedding-plane fractures and vugs in the Devils River Limestone (fig. 11). The ATV images for 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 EU3 and in the Salmon Peak and West Nueces Formations in EU4 (figs. 12, 13). The striping effects on the ATV images were an artifact of poor centralization, or nonuniform borehole roundness, and not necessarily an indicator of vugs.

Tri-County Transect

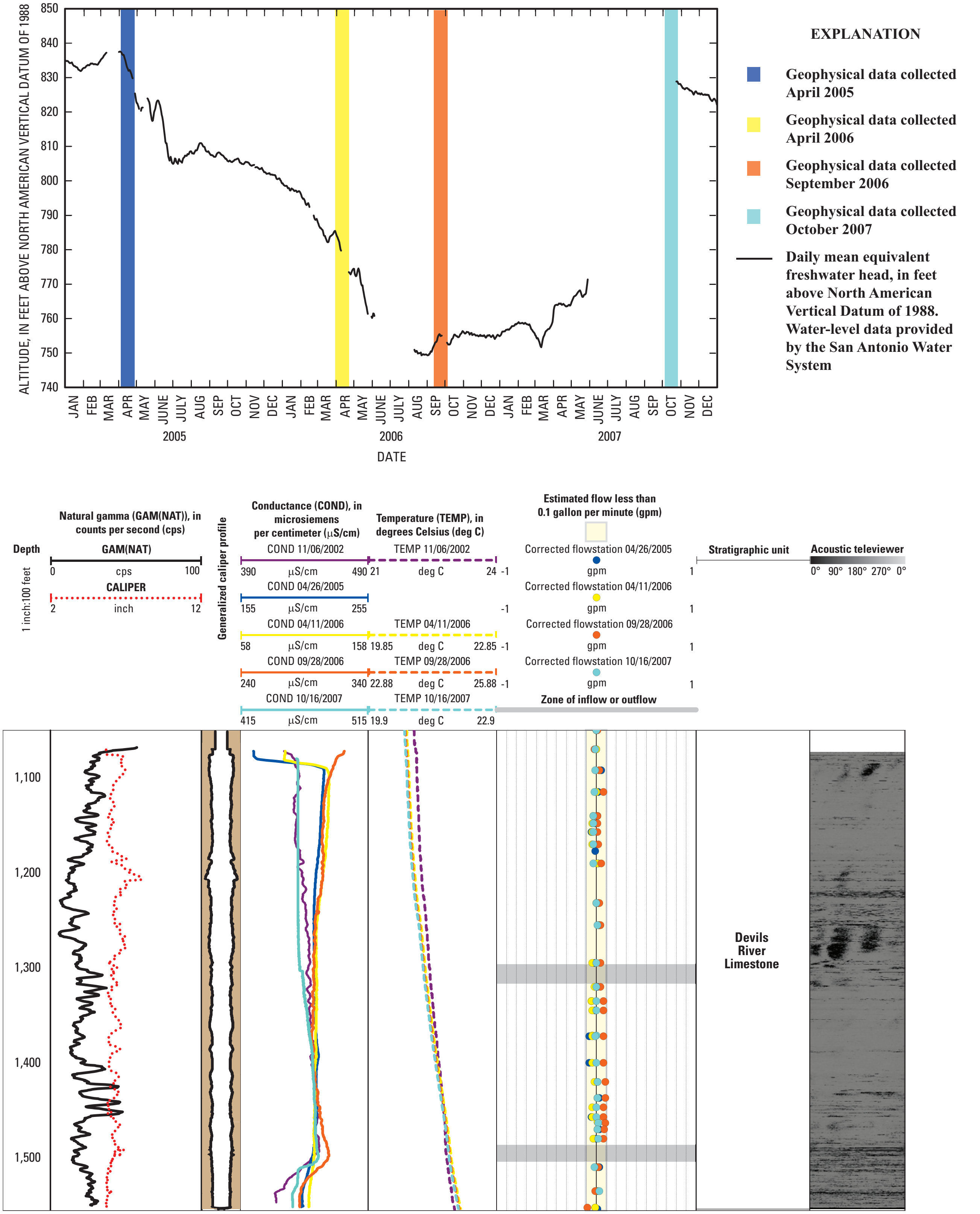
The natural gamma logs for Tri-County freshwater well TC1, interface well TC2, and saline-water wells TC3 and TC4 (figs. 14–17) indicate that Edwards aquifer rocks are composed predominantly of limestone with a few minor clayey sections without any major contrast in lithology, despite the layered structure 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 borehole beyond its 6-inch diameter to nearly 10 inches in diameter. The enlargements have a high roughness factor and are especially prevalent in the upper sections of the borehole that correspond to the Georgetown Formation, cyclic and marine members, and leached and collapsed members, and in the lower sections that correspond to the grainstone, Kirschberg evaporite, and dolomitic members.

The ATV 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 most common in the upper sections of the boreholes open to the Georgetown Formation, leached and collapsed members, cyclic and marine members, Kirschberg evaporite member, and dolomitic member. Small bedding-plane fractures and vugs or enlarged pores are interspersed throughout the remaining sections of the boreholes. The striping effect on the ATV image for well TC2 near about 600 to 620 feet is an artifact of poor centralization, or nonuniform borehole roundness, and not necessarily an indicator of vugs.



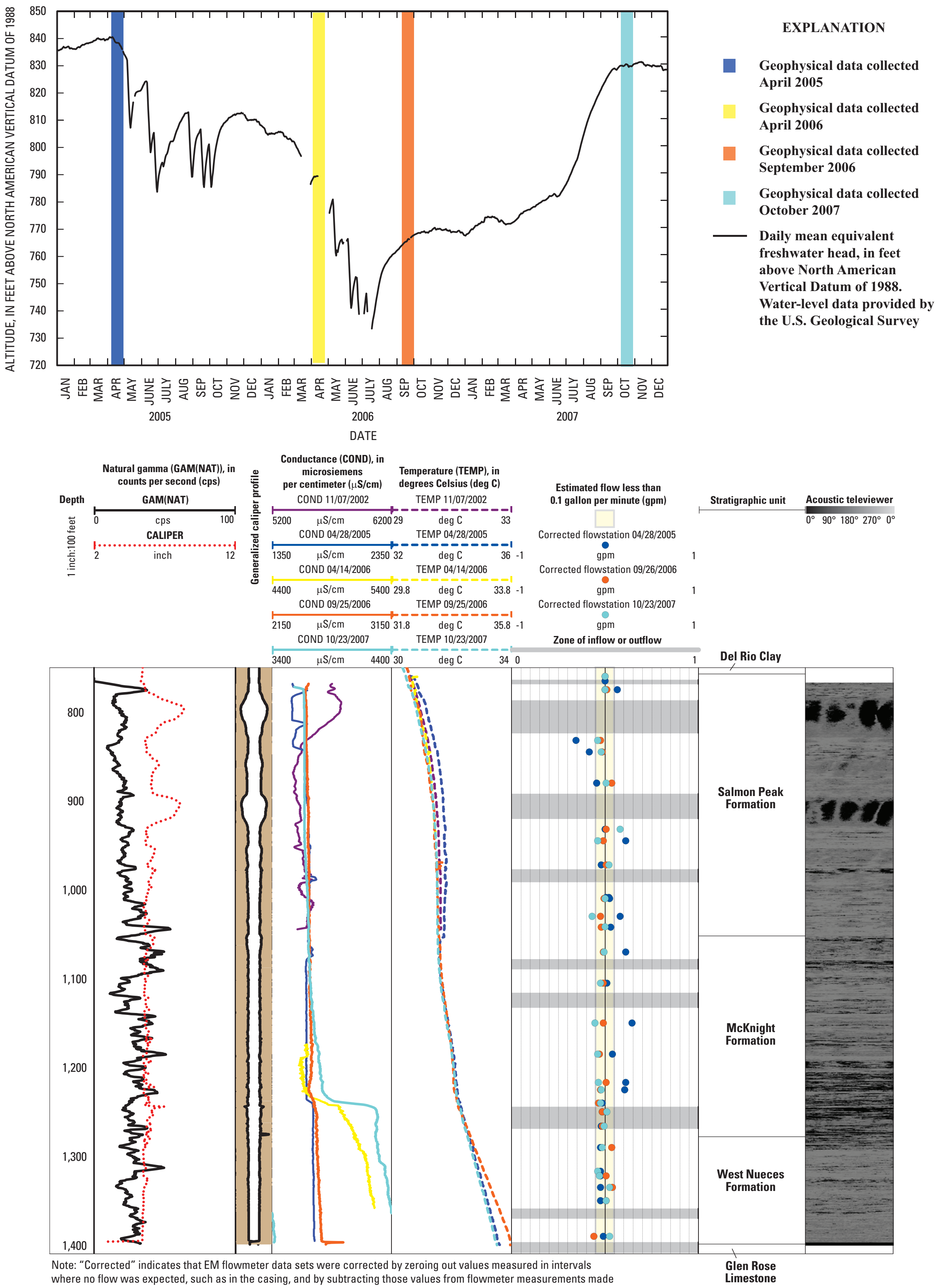
Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 10. Daily mean equivalent freshwater head and borehole geophysical data in East Uvalde 1 well (YP–69–52–202), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.



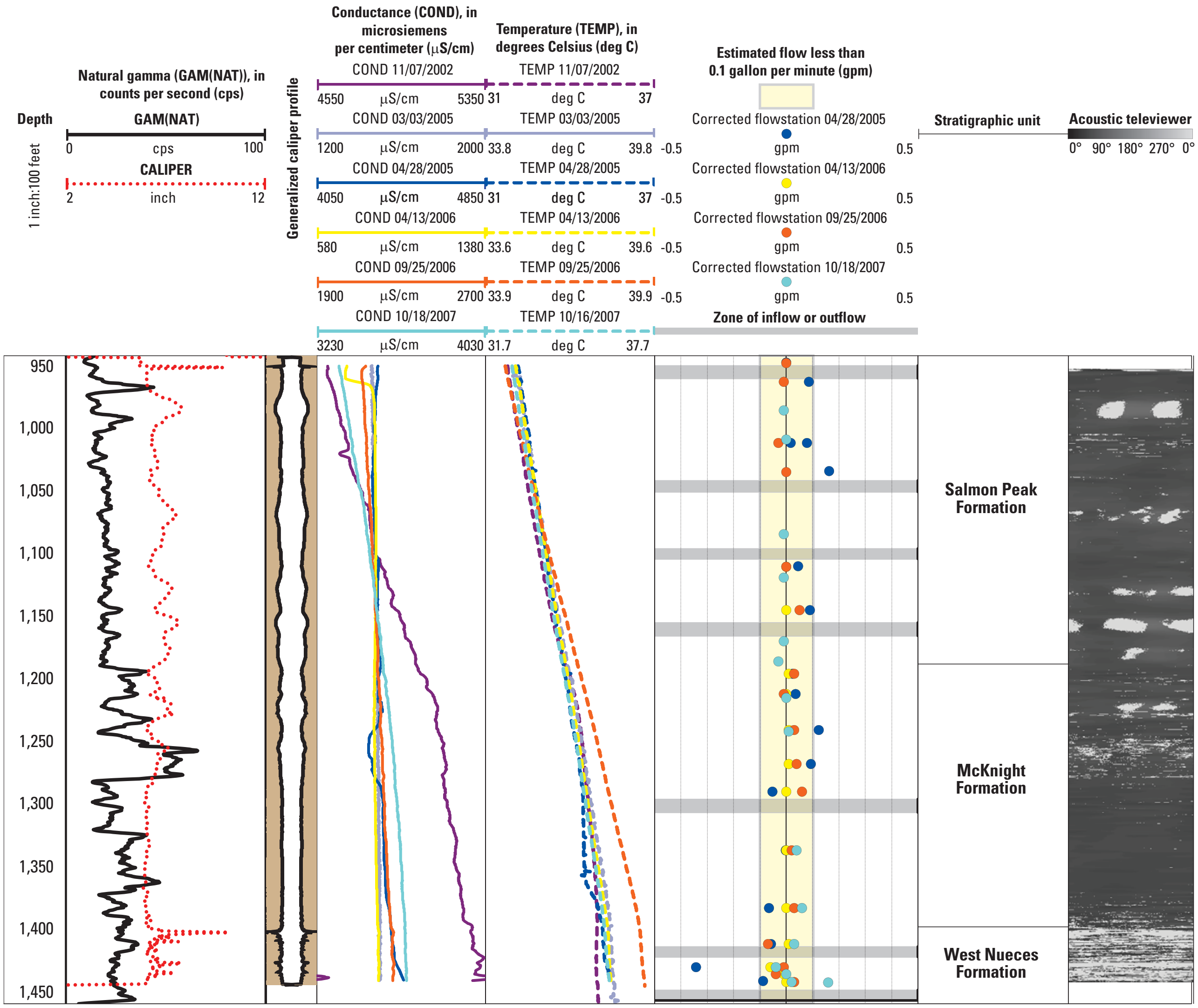
Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 11. Daily mean equivalent freshwater head and borehole geophysical data in East Uvalde 2 well (YP–69–44–902), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.



Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 12. Daily mean equivalent freshwater head and borehole geophysical data in East Uvalde 3 well (YP–69–51–606), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.

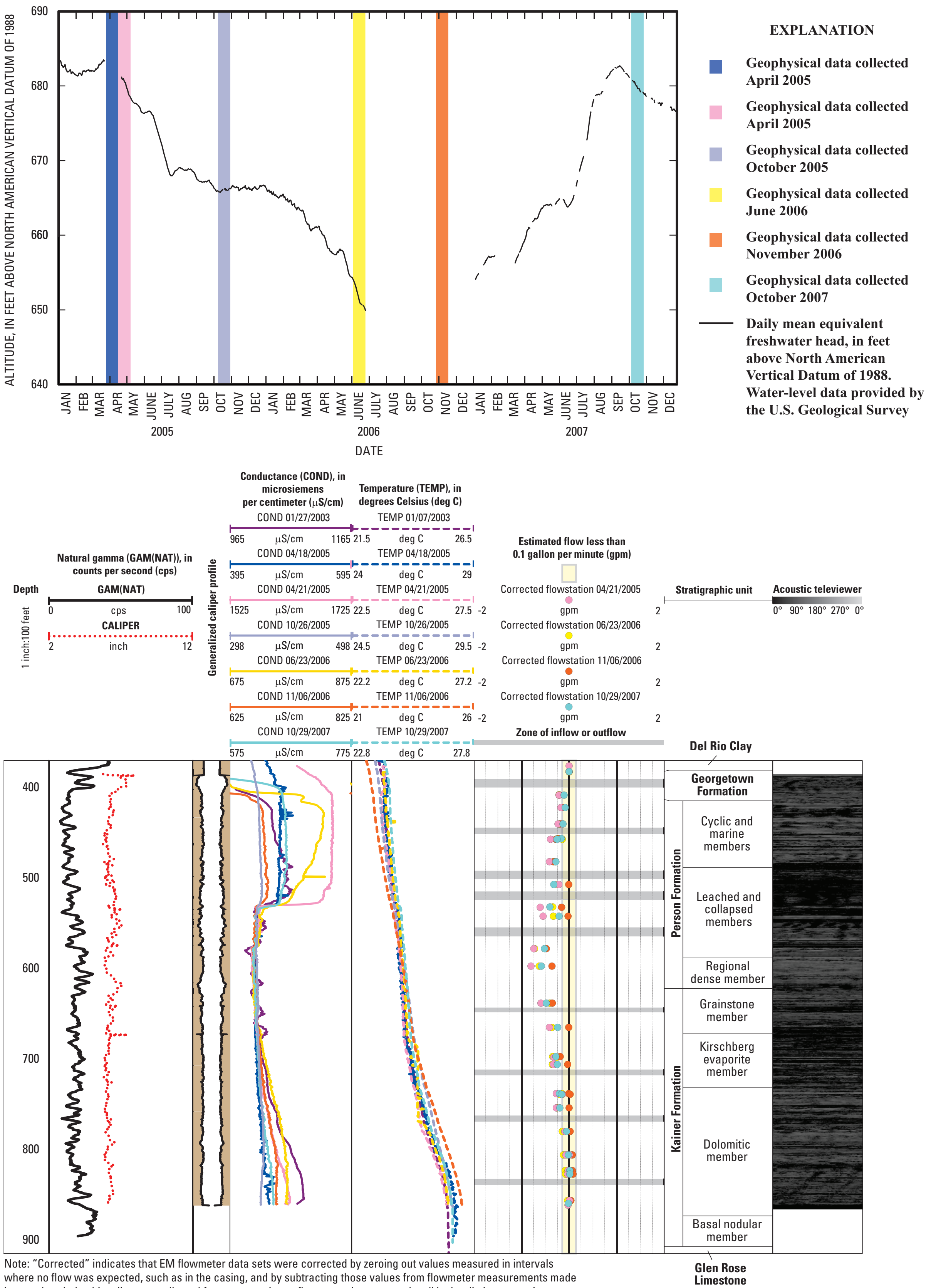


Note: “Corrected” indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 13. Borehole geophysical data in East Uvalde 4 well [YP–69–52–404], San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07. (Daily mean equivalent freshwater head data not available for East Uvalde 4 well (YP–69–52–404), 2002–07.)

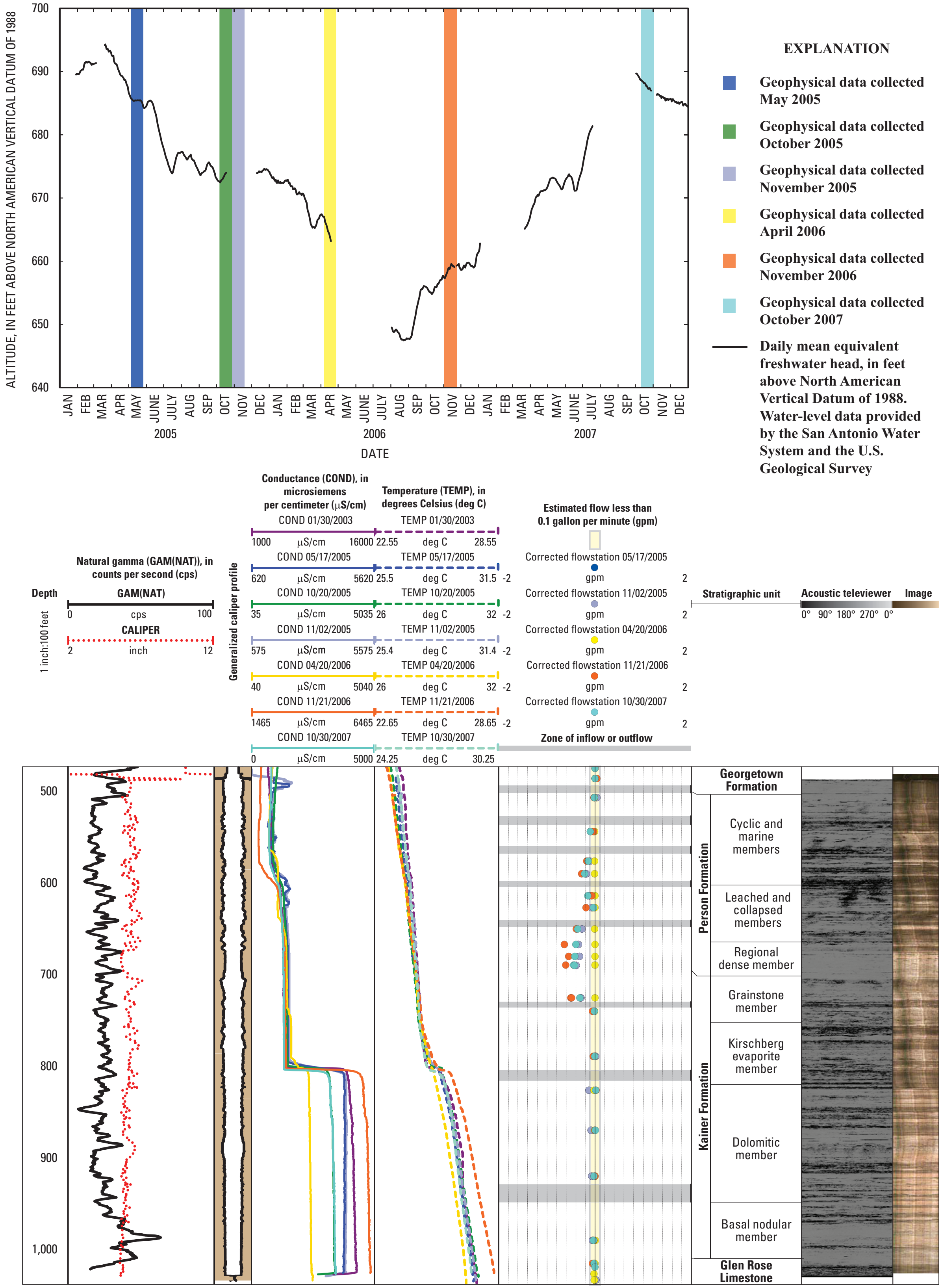
Fish Hatchery Transect

The natural gamma logs for freshwater well FH1 and saline-water well FH2 indicate that the borehole sections are composed of fairly clean limestone interbedded with clayey lenses (figs. 18, 19). These wells are completed in rocks of the San Marcos Platform depositional province (figs. 2, 3). Well FH1 is shallow compared to the other monitoring wells, which does not allow for in-depth analysis of the natural gamma log (fig. 18). The caliper log for well FH1 shows enlargements along the length of the nominal 6-inch-diameter borehole, with some enlargements increasing the diameter of the hole to at least 8–10 inches. These enlargements correspond to bedding-plane fractures and vugs in the cyclic and marine members and also appear on the ATV log (fig. 18). For 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. The caliper and ATV logs show enlargements of the hole diameter with rugose intervals in the lower part of the Georgetown Formation, cyclic and marine, leached and collapsed, grainstone, and Kirschberg evaporite members as well as small bedding-plane fractures in the Kirschberg evaporite and dolomitic members (fig. 19).



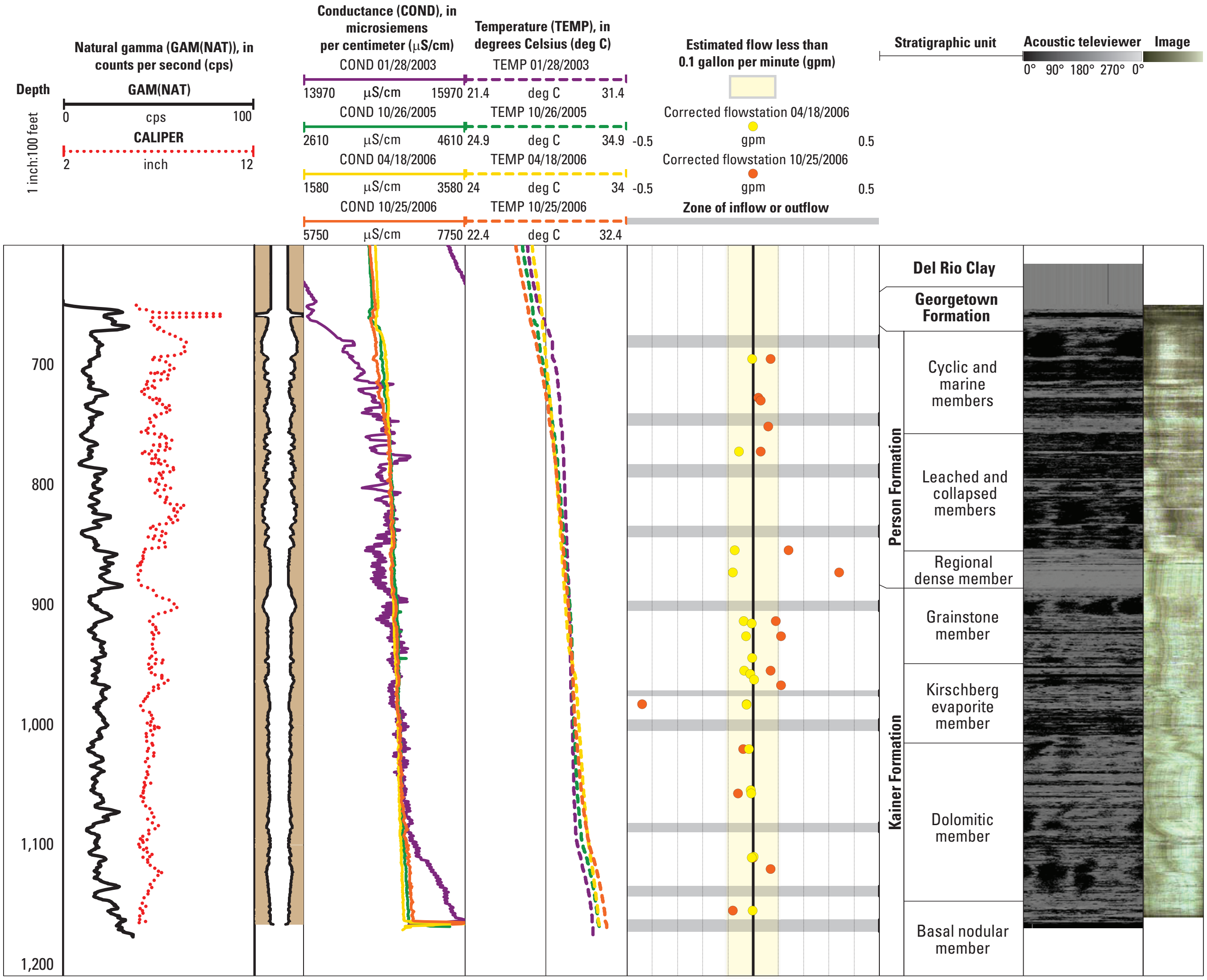
Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 14. Daily mean equivalent freshwater head and borehole geophysical data in Tri-County 1 well (KX–68–30–314), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–07.



Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 15. Daily mean equivalent freshwater head and borehole geophysical data in Tri-County 2 well (KX–68–31–403), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–07.



Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

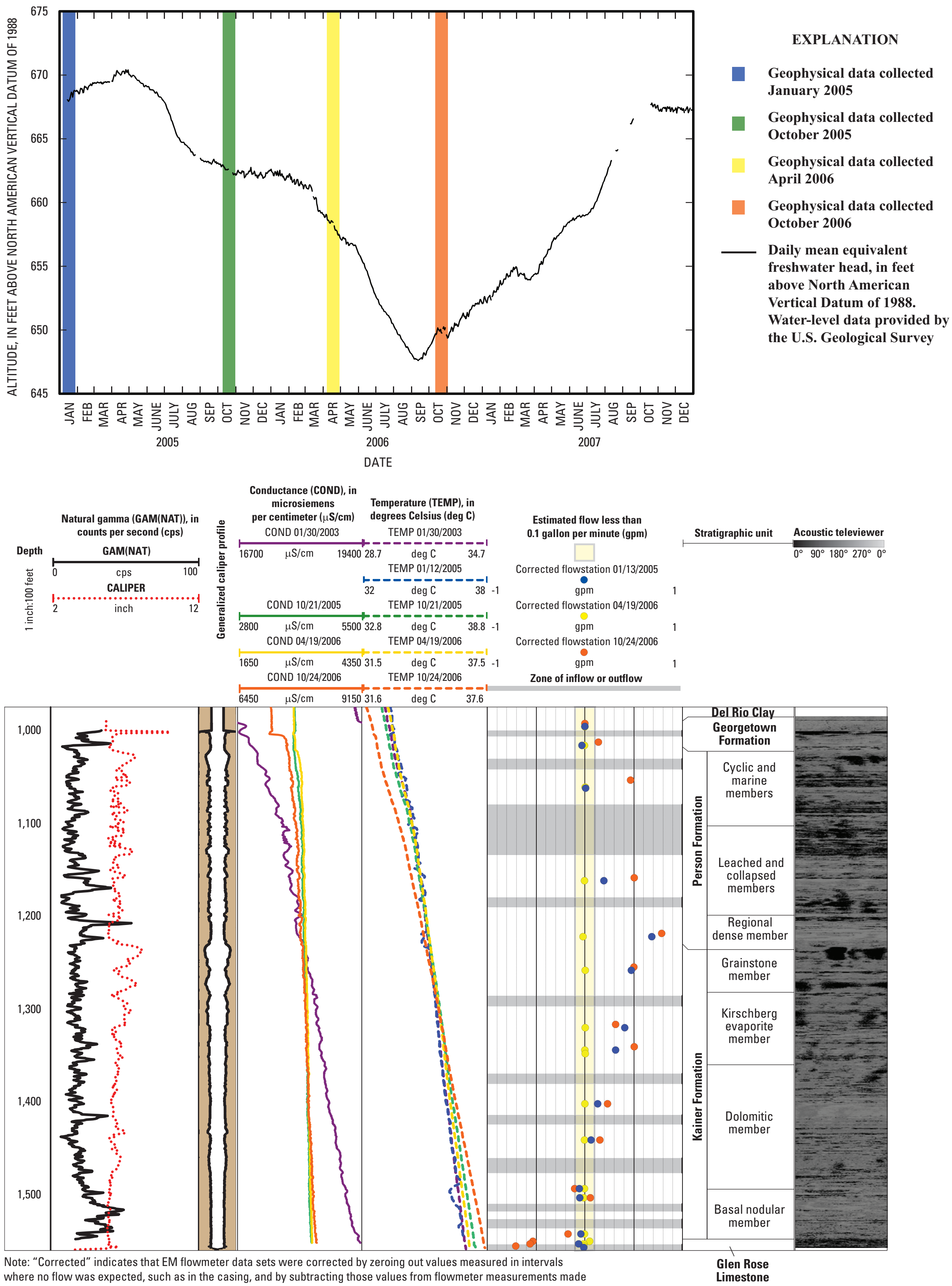
Figure 16. Borehole geophysical data in Tri-County 3 well (KX–68–31–511), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–06. (Daily mean equivalent freshwater head data not available for Tri-County 3 well [KX–68–31–511], 2003–06.)

Kyle Transect

The natural gamma logs for freshwater well KY1, interface well KY2, and saline-water wells KY3 and KY4 indicate that the wells are open to clean limestone with some clayey intervals in the cyclic and marine members and the leached and collapsed members in the upper part of the Edwards aquifer, and in the dolomitic and basal nodular members in the lower part of the Edwards aquifer (figs. 20–23). Wells KY1, KY2, and KY3 also are open to the Glen Rose Limestone (Trinity aquifer) at the base of the wells. The gamma logs for these wells indicate that the Glen Rose Limestone has greater clay content than the formations of the overlying Edwards aquifer (figs. 20–22).

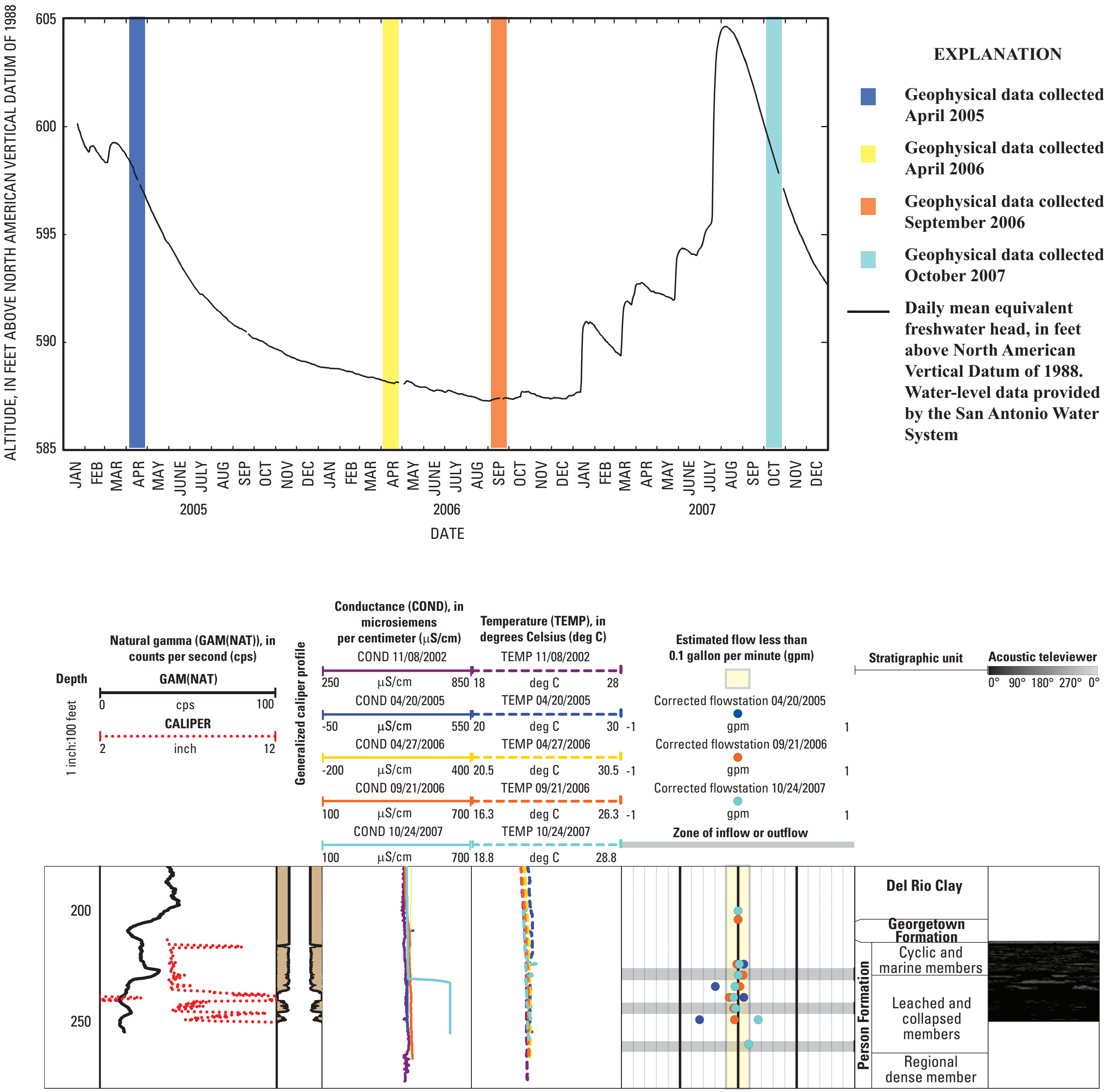
The caliper logs from wells KY1, KY2, and KY3 indicate borehole enlargement to diameters greater than the nominal 6 inches in the upper part of the borehole that corresponds to the cyclic and marine members and the leached and collapsed members, and to the grainstone, Kirschberg evaporite, and dolomitic members in the lower part of the borehole (figs. 20–22). 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. 23).

The ATV logs from the Kyle wells confirm the enlarged diameter areas that were recorded by the caliper log. Some of the enlarged intervals are relatively more porous and vuggy, and other enlarged intervals show small zones of



Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 17. Daily mean equivalent freshwater head and borehole geophysical data in Tri-County 4 well (KX–68–31–808), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–07.



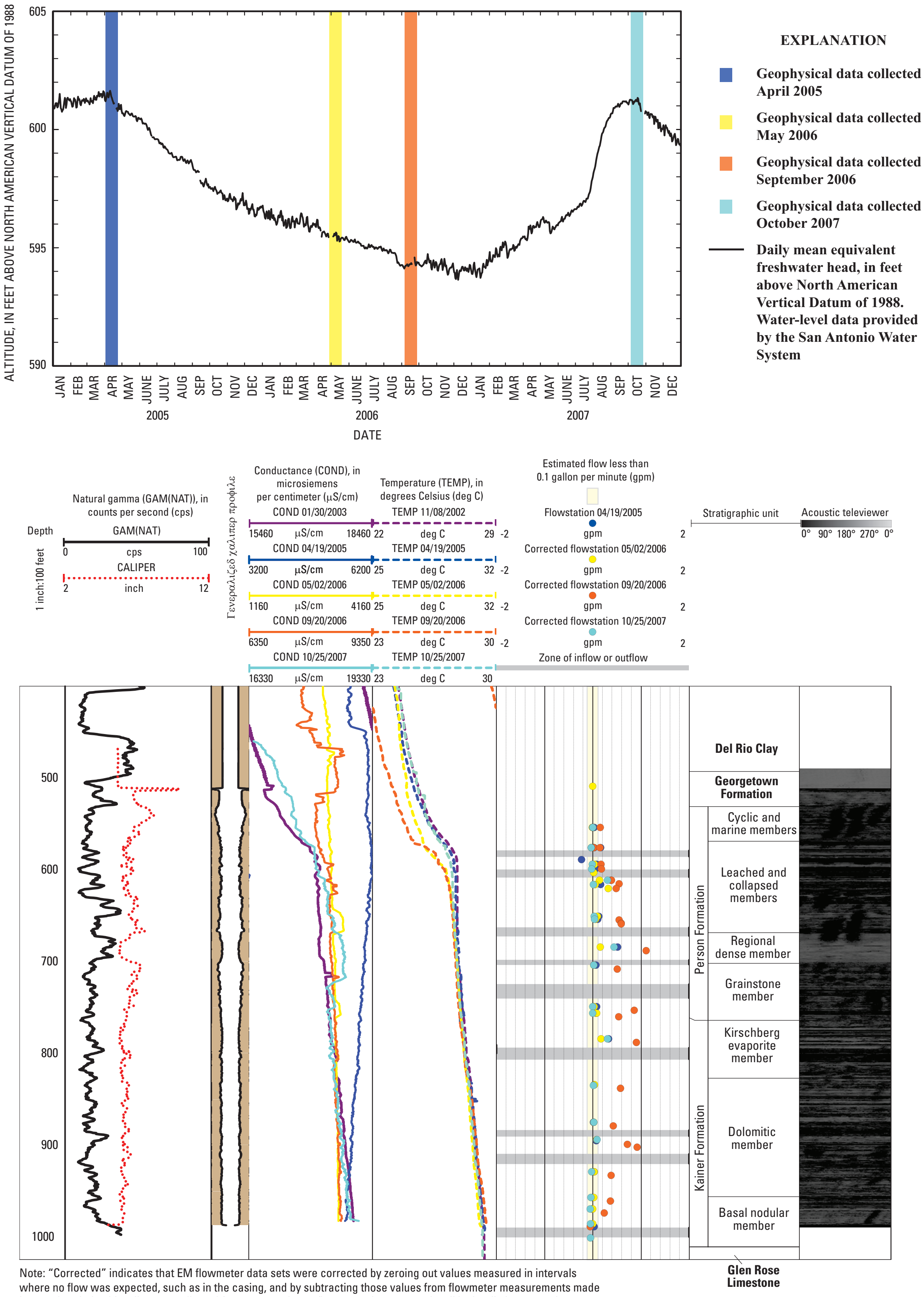
Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 18. Daily mean equivalent freshwater head and borehole geophysical data in Fish Hatchery 1 well (LR–67–09–113), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.

bedding-plane fractures and vugs. The striping effects on the ATV image 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. 23).

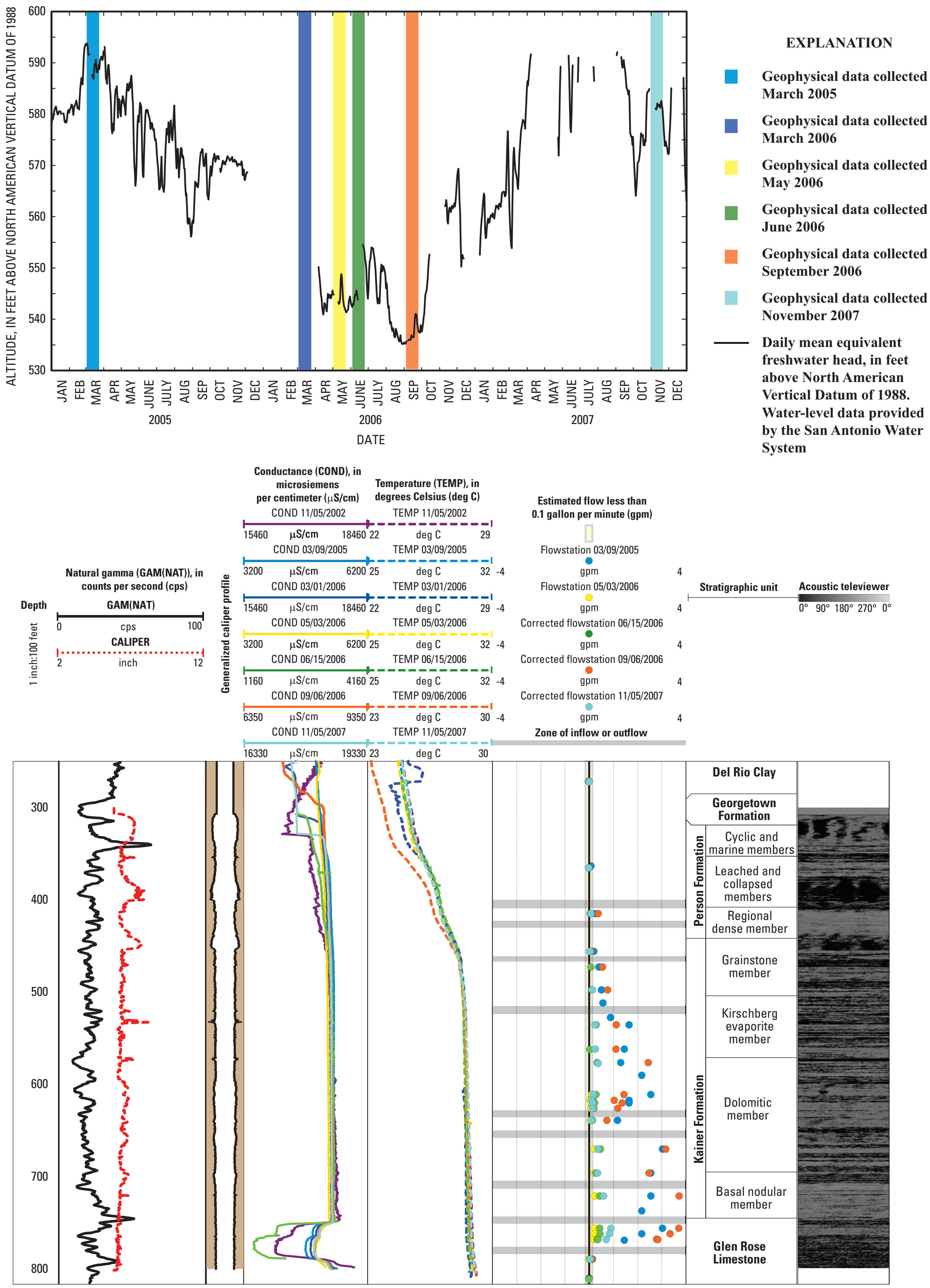
Physicochemical Properties

Fluid conductivity and temperature are discussed by transect in the following sections. The discussions might involve vertical borehole flow where it is considered relevant to the



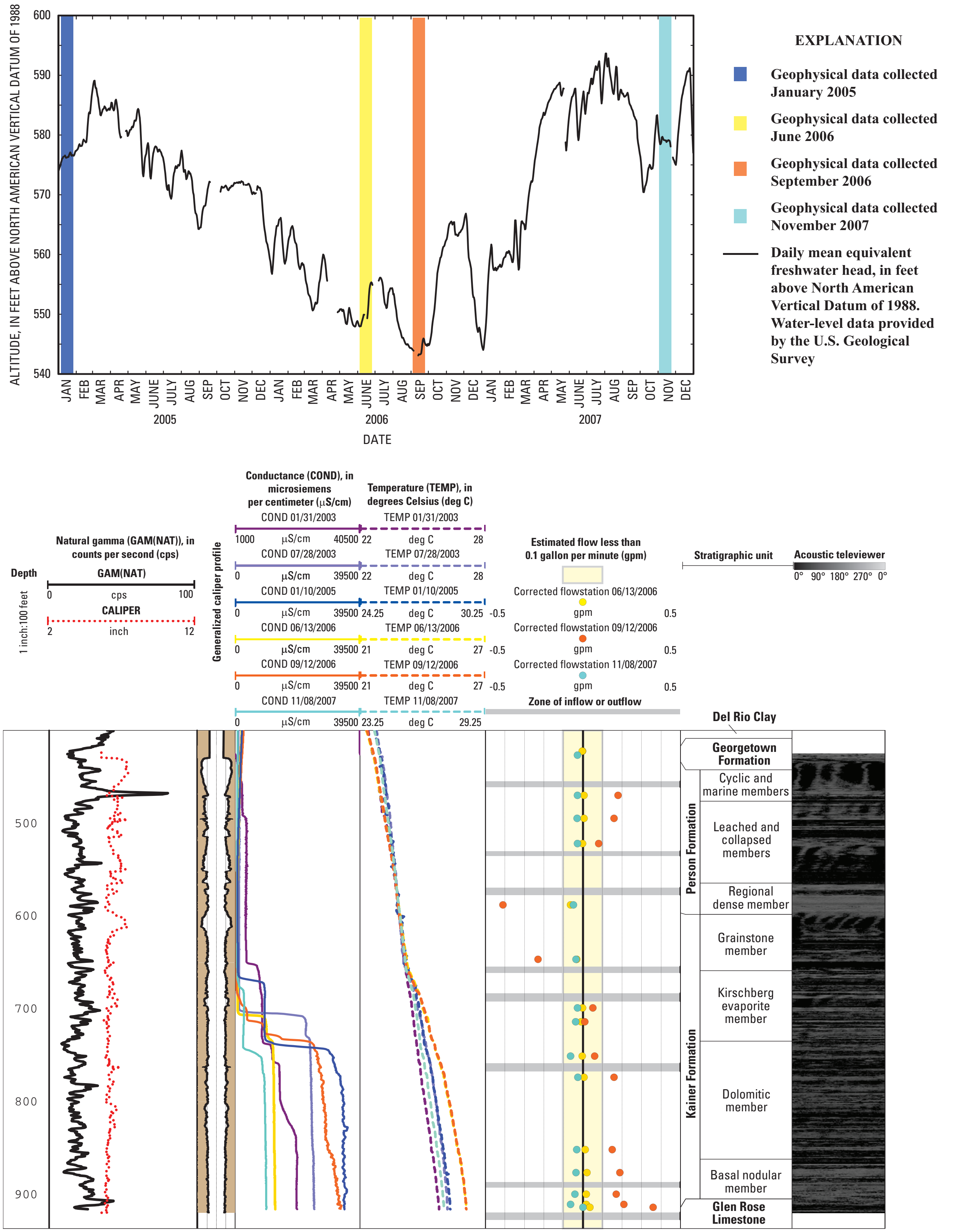
Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 19. Daily mean equivalent freshwater head and borehole geophysical data in Fish Hatchery 2 well (LR–67–09–401), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–07.



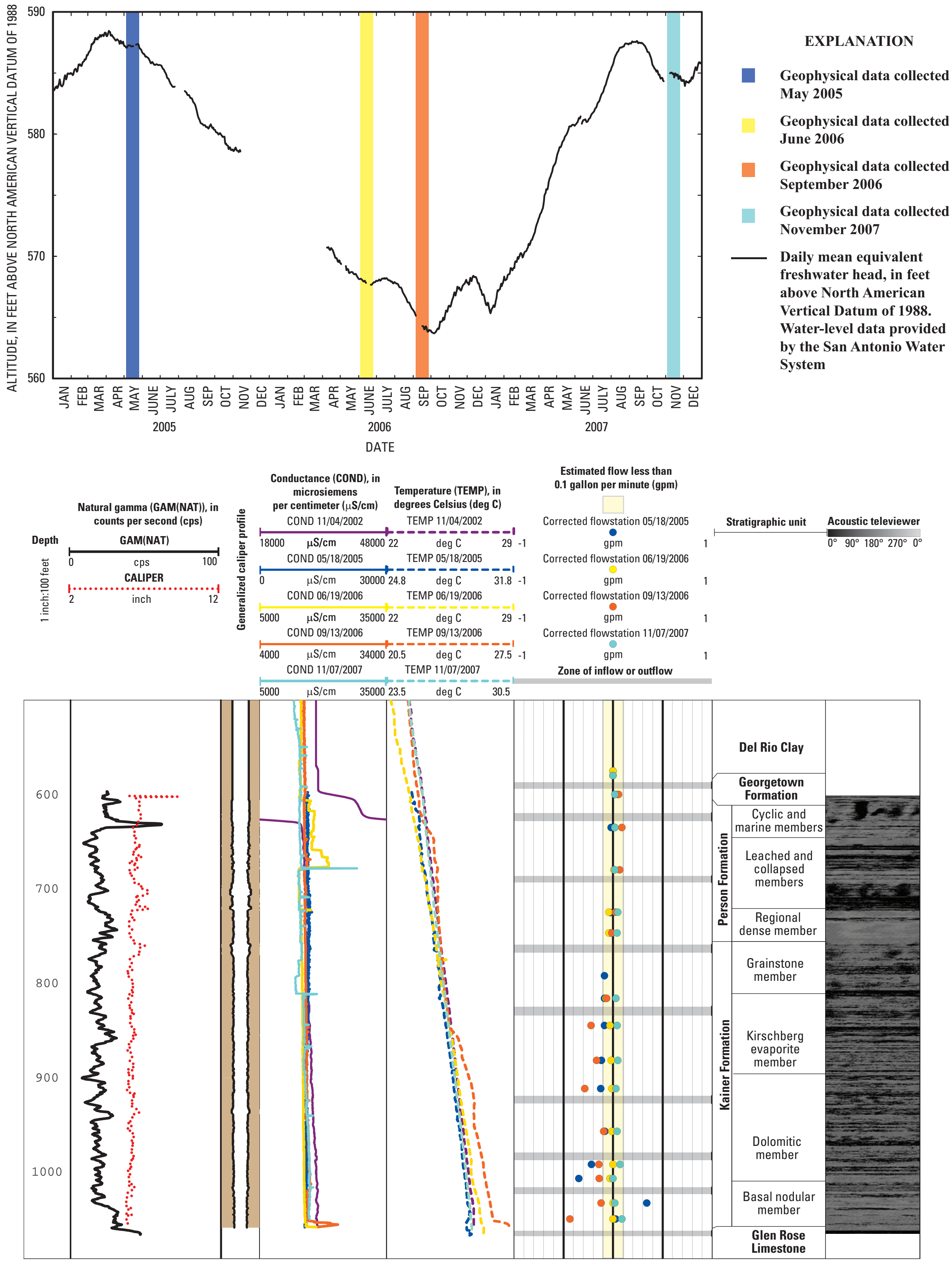
Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 20. Daily mean equivalent freshwater head and borehole geophysical data in Kyle 1 well (LR–67–01–311), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.



Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 21. Daily mean equivalent freshwater head and borehole geophysical data in Kyle 2 well (LR–67–02–104), San Antonio segment of the Edwards aquifer, south-central Texas, 2003–07.



Note: "Corrected" indicates that EM flowmeter data sets were corrected by zeroing out values measured in intervals where no flow was expected, such as in the casing, and by subtracting those values from flowmeter measurements made in open borehole; this adjustment allowed for more consistent flowmeter data sets and well hydraulic interpretations.

Figure 22. Daily mean equivalent freshwater head and borehole geophysical data in Kyle 3 well (LR–67–02–106), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.

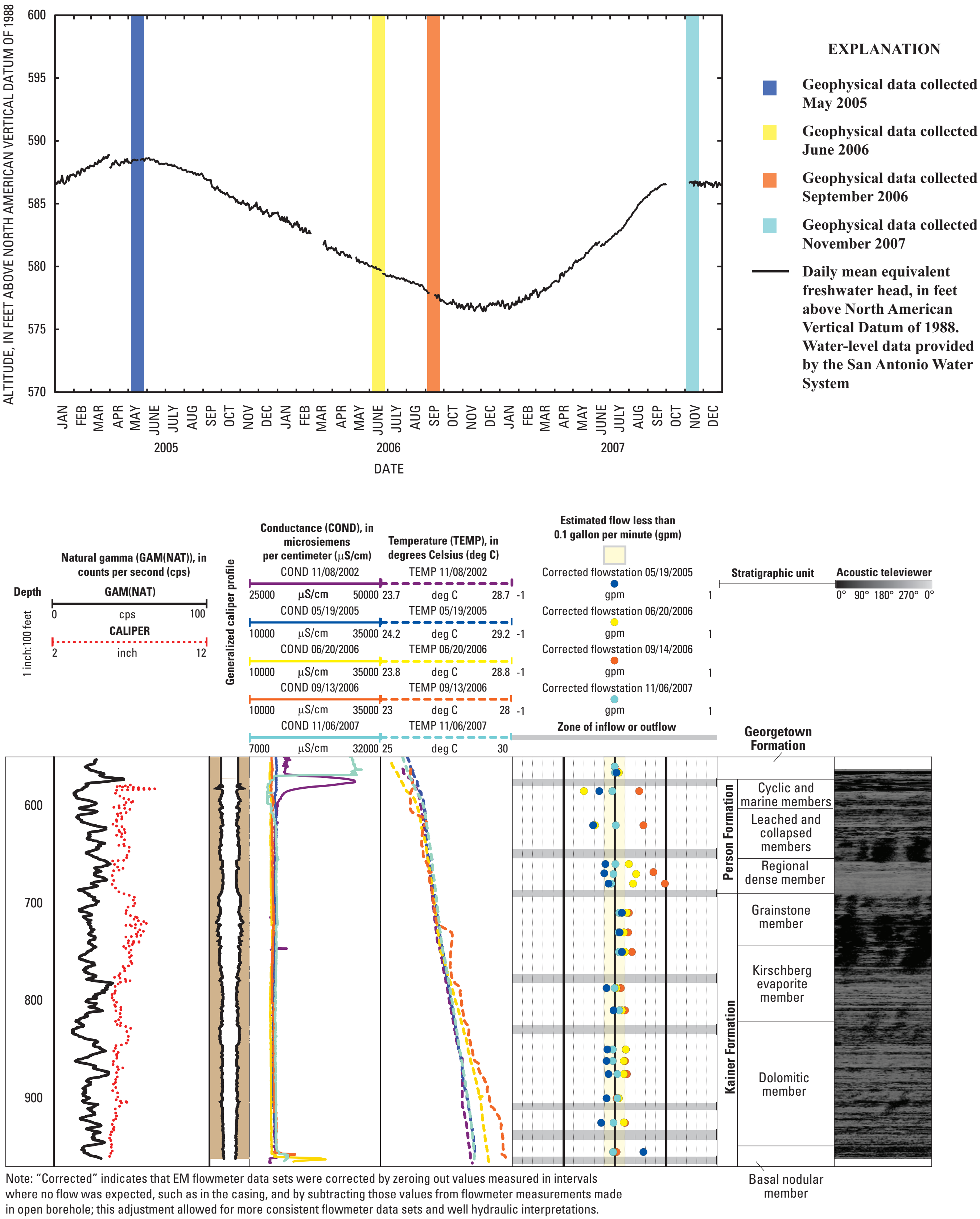


Figure 23. Daily mean equivalent freshwater head and borehole geophysical data in Kyle 4 well (LR–67–02–105), San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.

description of conductivity or temperature, but the principal discussion of vertical borehole flow is in the “Hydraulics of Flow” section.

Water in the boreholes is classified as fresh or saline on the basis of dissolved solids concentration. So that conductivity can be associated with the salinity descriptors based on dissolved solids concentration as noted in the “Introduction” section, specific conductance and dissolved solids concentration from monitoring well data (Lambert and others, 2009) were related by regression (not included here) to yield the following threshold values of conductivity corresponding to the threshold values of dissolved solids concentration that describe freshwater and saline water

Descriptor	Dissolved solids concentration (milligrams per liter)	Conductivity (microsiemens per centimeter at 25 degrees Celsius)
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

Fluid Conductivity

East Uvalde Transect

Well EU1 is close to the interface of the aquifer, and fluid conductivities recorded during 2002–07 in EU1 indicate freshwater down the entire length of the borehole (fig. 10). At about 1,280-foot depth, the October 2007 log (curve) shows a sharp increase in fluid conductivity, and the September 2006 log shows the beginning of a more subtle increase; no visible increase is evident on the three other logs. The increases do not appear to be related to heads measured at the time of the log runs, because the head in October 2007, when a sharp increase in conductivity at about 1,280 feet occurred, was near the head in April 2005, when no increase in conductivity at about 1,280 feet occurred. Minimal vertical flows (less than 0.1 gallon per minute) do not appear to affect conductivity in a consistent manner.

Fluid conductivities recorded in well EU2 indicate freshwater down the entire length of the borehole (fig. 11). The presence of freshwater in the borehole was expected, as EU2 is in a part of the freshwater zone of the aquifer that transmits substantial quantities of freshwater (fig. 4). Fluid conductivity of all the logs is relatively constant down the borehole, although slight variability at the top of the borehole decreases with depth, to about 1,500 feet where conductivity in all the logs decreases. As with well EU1, changes in conductivity do not appear to be related to heads measured at the time of the log runs. Also as with well EU1, vertical flow in the borehole for all log runs was less than 0.1 gallon per minute, and no consistent relation between conductivity and flow appears evident. An inflow/outflow zone is coincident with the inflection points in the conductivity curves at about 1,500 feet, where water in the borehole becomes fresher; the fresher water might be related to the coincident inflow/outflow zone. The inflection is more subdued in the April 2005 and April 2006 curves, which are associated with slight downward flow; whereas the inflection is more prominent in the October 2006 and October 2007 logs, which are associated with slight upward flow.

The logs run in well EU3 indicate saline water in the borehole during 2005–07 (fig. 12). The most salient feature of the fluid conductivity logs for well EU3 is a sharp increase in conductivity at about 1,240 feet visible in each of the logs. The increases for April 2006 and especially October 2007 are substantially larger than the increases for the other months. As with conductivity in wells EU1 and EU2, conductivity in EU3 does not appear to be related to head measured at the time of the log runs—the head when the largest sharp increase at about 1,240 feet occurred (October 2007) was about the same as the head when one of the smallest sharp increases at about 1,240 feet occurred (April 2005). Vertical flow in the borehole of well EU3 during the log runs was relatively large for the April 2005 log compared to that of the logs for September 2006 and October 2007 and mostly upward. Conductivity throughout the borehole was more consistent in April 2005, when flow was relatively large and upward, than in October 2007, when flow was minimal and mostly downward; but the conductivity log for September 2006, when flow also was minimal and mostly downward, is similar to the log of April 2005. So on the basis of these mixed results, the relation between vertical flow in the borehole and conductivity appears problematic. One other notable feature of the conductivity logs is the apparent coincidence between the sharp increases in conductivity at about 1,240 feet and an inflow/outflow zone in the lower part of the McKnight Formation.

Well EU4 contained saline water during four of six log runs, but for one of the runs (September 2006), salinity was entirely in the freshwater range and for another (March 2005) was in the fresh and slightly saline ranges (fig. 13). Except for the run in November 2002, the conductivity logs show consistency, or minimal variation, throughout the length of the borehole. No concurrent head data are available for comparison. Vertical flow in the borehole during the log runs was mostly less than 0.1 gallon per minute, and any salient effects of vertical flow on conductivity values are not apparent.

Tri-County Transect

The fluid conductivity logs for well TC1 indicate that the borehole fluid column contained freshwater with higher conductivities measured in the upper part of the borehole, above about 530 feet, associated with the cyclic and marine members and the leached and collapsed members (fig. 14). The fluid conductivity in the middle part of the borehole from about 530 to 660 feet was nearly constant with increasing depth. The lack of change in conductivity with depth is attributed to downward flow in the borehole, which appears to have entered the borehole from the cyclic and marine members and the leached and collapsed members, increased in magnitude down the borehole, moved past the regional dense member, and then exited into the grainstone member, Kirschberg evaporite member, and upper part of the dolomitic member. From about 660 feet to the bottom of the well, fluid conductivity increased with depth as downward flow in the borehole decreased. Relative differences between conductivity values in individual logs do not relate in a consistent manner to head measured at the time of the log runs. In other words, larger relative differences are not consistently related to relatively high head or relatively low head.

On the basis of fluid conductivity, well TC2 intersected the interface at a depth of about 800 feet, at or slightly above the contact between the Kirschberg evaporite member and the dolomitic member (fig. 15). Above about 800 feet, freshwater was in the borehole during all log runs, and below about 800 feet, saline water was in the borehole. At about 600 feet, there was an increase in fluid conductivity on all logs coincident with an inflow/outflow zone at the contact between the cyclic and marine members and the leached and collapsed members; downward flow in the borehole appears on the flow logs (except the April 2006 log) to begin at or near this inflow/outflow zone, increase at an inflow/outflow zone in the leached and collapsed members, and cease at about 740 feet as water appears to have entered the grainstone member at an inflow/outflow zone. From about 600 feet to the interface at about 800 feet, fluid conductivity indicated by all the conductivity logs was essentially constant with depth. Although the interface position in the borehole was about 60 feet below the zone at which borehole flow ceased, the relative increase in conductivity was least for the April 2006 log, the log for which no borehole flow was indicated. Whether or not borehole flow was occurring did not affect the position of the interface, which is essentially the same on all logs. Similarly, changes in head between the times the logs were run did not affect the position of the interface. If changes in borehole flow or changes in head affected relative increases in the conductivity values in the saline section of the borehole, it was not in a consistent or identifiable manner.

The fluid conductivity logs for well TC3 indicate saline water along the entire length of the borehole for all log runs (fig. 16). The shape of three of the four logs (2005 and 2006 logs) from top to bottom was consistent and nearly vertical, although the ranges of values reflected among the logs varied widely (slightly saline to very saline). No head data concurrent with the log runs are available. Whether mostly downward borehole flow (April 2006) or mostly upward borehole flow (October 2006) was occurring did not appear to affect the shape of the curves or the conductivity values. The January 2003 log, for which conductivity values are substantially larger than those of the 2005 and 2006 logs, shows increasing conductivity with depth beginning at about 1,100 feet, coincident with an inflow/outflow zone in the middle of the dolomitic member. But no borehole flow data are available concurrent with that log run, so whether borehole flow influenced conductivity changes cannot be assessed.

The fluid conductivity logs of well TC4 (fig. 17) indicate saline water down the entire length of the borehole and are generally similar in shape—consistent and nearly vertical—to corresponding logs of well TC3 (fig. 16); and as with well TC3, the ranges of values reflected among the logs varied widely (slightly saline to very saline). Conductivity values reflected in the three logs for which concurrent head data are available (October 2005, April 2006, and October 2006) do not relate in a consistent manner to head measured at the time of the log runs. In other words, relatively high conductivity values are not consistently related to relatively high head or relatively low head. There are two conductivity logs for which concurrent flow measurements are available, April 2006 and October 2006. Conductivity values reflected in the April 2006 log, when no borehole flow was measured, were about 3,000 to 4,000 microsiemens per centimeter at 25 degrees Celsius (μS/cm) less than conductivity values reflected in the October 2006 log, when upward borehole flow between 0.1 and 1 gallon per minute was measured throughout nearly all of the borehole (dolomitic member to Georgetown Formation). Head in the well during the April 2006 log run with no borehole flow was about was about 7–8 feet higher than head in the well during the October 2006 log run with upward borehole flow.

Fish Hatchery Transect

The fluid conductivity logs for well FH1 all indicate freshwater in the borehole (fig. 18). The logs were consistent in shape (vertical) and conductivity value down the short length of the borehole, except for the October 2007 log, which showed a sharp increase in conductivity (still well within the freshwater range) at about 225 feet. Other than the October 2007 logs, heads measured at the time of the log runs and vertical flow in the borehole, or lack of, did not affect the shape of conductivity logs or values in identifiable ways.

The fluid conductivity logs for well FH2 indicated saline water, ranging from slightly saline to very saline (fig. 19). The fluid conductivity curves from November 2002 and October 2007 show changes in slope to more vertical in the upper part of the borehole from about 575 to 580 feet; conductivity values for the two logs throughout the borehole were in the very saline range. The three other logs (April 2005, May 2006, and September 2006) do not show a similar change in slope, and measured conductivity values generally were lower, indicating slightly to moderately saline water. No identifiable relation between conductivities and heads at the times the logs were run is apparent. Concurrent flow logs are available for all the conductivity logs except November 2002. Flow among the logs, essentially all upward from the basal nodular member to the cyclic and marine members, ranges from negligible (October 2007, very saline water) to as much as about 1.1 gallons per minute (September 2006, moderately saline water). The relation between conductivity and flow among the logs is not consistent.

Kyle Transect

Fluid conductivity logs for well KY1 indicate freshwater throughout the borehole during all log runs (fig. 20). In the upper part of the borehole from about 350 to 460 feet, most of the fluid conductivity curves show a series of “steps” of increasing fluid conductivity with depth from the top of the borehole (Georgetown Formation) to about 400 feet (near the base of the leached and collapsed members). Fresher water near the bottom of the borehole at about 750 feet is indicated on each of the logs. This fresher water appears to be in the Glen Rose Limestone (Trinity aquifer). Upward flow from the Glen Rose Limestone to the base of the leached and collapsed members is indicated on all available flow logs, ranging from negligible (May 2006) to nearly 4 gallons per minute (September 2006). The consistent and similar shapes of the fluid conductivity curves down the length of the borehole from about 400 to about 750 feet and the nearly vertical slopes of the curves are attributed to the substantial (relative to flows in boreholes of wells in other transects) upward flow from the Trinity aquifer that exits the borehole into numerous inflow/outflow zones of the Edwards aquifer.

Well KY2 is the second of two wells of this report that intersects the interface. Fluid conductivity logs show that the interface intersected the borehole in the lower part at a depth of about 650 to 750 feet, corresponding to inflow/outflow zones in the Kirschberg evaporite member and upper part of the dolomitic member (fig. 21). The range in salinity of water between the upper and lower sections of the borehole indicated by most of the logs is large—from fresh to very saline. Unlike in interface well TC2, the position of the interface in the borehole changed about 50 feet over time. The position of the interface in the borehole during the June 2006 conductivity log (about 700 feet) was close to that of the September 2006 log, and the heads at the times of the two logs are similar (540–550 feet above NAVD 88); the position of the interface in the borehole during the January 2005 log (about 750 feet) was close to that of the November 2007 log, and the heads at the times of those two logs are similar (570–580 feet above NAVD 88). Although the position of the interface bears some relation to head at the time the logs were run, the conductivity values below the interface do not. The lowest conductivity values below the interface among the logs (November 2007) occurred when head was relatively high; and the highest conductivity values below the interface among the logs (January 2005) also occurred when head was relatively high, about the same as that in November 2007.

Fluid conductivity logs run in well KY3 indicate that water in the borehole at the times of the log runs was moderately to very saline (fig. 22). The shapes of the conductivity curves are mostly consistent among the logs and show little variation with depth. No identifiable relation between conductivity values and head at the times the logs were run is evident; and no identifiable relation between conductivity values and the mostly upward flow in the borehole concurrent with the times the logs were run is evident.

The fluid conductivity logs run in well KY4 indicate moderately to very saline water, with little variation in fluid conductivity down the length of the borehole (fig. 23). In the November 2002 log, a spike in the fluid conductivity in the upper part of the cyclic and marine members is associated with a fracture at about 580 feet and identified as an inflow/outflow zone. At the bottom of the borehole at about 980 feet, a small spike in the fluid conductivity is associated with an inflow/outflow zone in the basal nodular member. This spike in conductivity might have been higher-salinity water that entered the borehole from a fracture or a vug. No identifiable relation between conductivity values and head at the times the logs were run is evident; and no identifiable relation between conductivity values and flow in the borehole (mixed among the logs between upward and downward) concurrent with the times the logs were run is evident.

Temperature

East Uvalde Transect

The temperature logs run in well EU1 indicate a gradual increase in the temperature down the borehole for all logging runs and slight changes in slope of the temperature curves occurring at about 1,250 feet (fig. 10). Most temperatures measured were between about 29 and 33 degrees Celsius (°C), although temperatures indicated by the November 2002 log were about 22 °C. The greatest range in temperature among the temperature curves is at the top and bottom of the borehole. The changes in slope of the temperature curves at about 1,250 feet coincide with an inflow/outflow zone in the middle part of the Devils River Limestone. Below the 1,250-foot inflow/outflow zone, the borehole temperature increases correlate with increases in the fluid conductivity that occur at about 1,280 feet in the September 2006 and October 2007 logs.

The temperature logs run in well EU2 show a pattern similar to the pattern of temperature logs run in well EU1, indicating increasing borehole temperature with increasing depth (fig. 11). The temperatures measured in well EU2 logging runs ranged from about 20 to 24 °C, generally cooler than the temperatures measured in well EU1. In the lowermost section of the borehole, the temperature curves are consistent with the fluid conductivity curves in that they reflect change to slightly warmer temperatures and slightly fresher water, respectively.

For well EU3, the range in temperature in the borehole was from about 29 to 36 °C for all logging runs (fig. 12). Three distinct segments of the temperature curves are indicated down the length of the borehole. The first section is in the upper part of the borehole (from about 790 to 1,000 feet) associated with the Salmon Peak Formation. The concave-upward configuration of the temperature curves might be related to downward flow that entered the borehole from an inflow/outflow zone in the Salmon Peak Formation at about 790–825 feet and upward flow that entered the borehole from an inflow/outflow zone in the McKnight Formation at about 1,090 feet, both of which appear to have converged to exit the borehole in an inflow/outflow zone in the Salmon Peak Formation at about 900–920 feet. The second distinct temperature section occurred from about 1,070 to 1,240 feet and is associated with the McKnight Formation. The temperature logs in this depth range show more-vertical slopes, which do not appear to be associated with borehole flow because flow directions were mixed among the similarly shaped temperature logs. The third and lowermost segment of the temperature logs from about 1,240 feet to the bottom of the borehole, associated with the West Nueces Formation, shows temperatures increasing with depth at a greater rate than in the overlying borehole segment. Temperatures increasing with depth at a greater rate are consistent with increases in fluid conductivity and minimal flows (estimated to be less than 0.1 gallon per minute) in this lowermost borehole segment.

The fluid temperatures in well EU4 were the warmest of any of the wells of this report, with a range in temperature from about 32 to nearly 40 °C (fig. 13). All the temperature logs indicate a steady increase in temperature with depth until the lower part of the McKnight Formation, where the rate of increase lessens. The curves reflect relatively undisturbed water in the borehole, which is consistent with the lack of substantial variation in all but one of the conductivity logs and minimal flows in the borehole.

Tri-County Transect

The fluid temperature logs for well TC1 show increasing temperature with depth and range from about 21 to 26 °C (fig. 14). The logs are similar in shape, each indicating subtle points of inflection (changes in slope) at about 560 feet, coincident with an inflow/outflow zone in the lower part of the leached and collapsed members, and at about 680 feet, coincident with the contact between the grainstone member and the Kirschberg evaporite member. The zone between the points of inflection thus described is generally that of maximum vertical slope of the temperature logs and maximum downward flow in the borehole, as indicated on all flow logs. The relatively greater rates of increase in temperature with depth below about 680 feet are consistent with relatively greater rates of increase in conductivity in generally the same section of the borehole.

The fluid temperature logs for well TC2 show generally consistent and gradual increases in temperature with depth in the upper part of the borehole from about 500 to about 800 feet (fig. 15); temperatures range from about 23 to 31 °C. At about 800 feet, where the interface intersects the borehole, a “shoulder” in the temperature curves coincides with a similar shoulder in the fluid conductivity curves. In the saline-water zone below the interface, temperature increased with depth at a slightly greater rate than in the freshwater zone above the interface. As with conductivity values, temperatures do not appear to have been affected by downward flow in the borehole (except on the April 2006 flow log) that originated in the leached and collapsed members and ceased in the grainstone member.

The fluid temperature logs in well TC3 show increasing temperature with depth and range from about 24 to 33 °C (fig. 16). Slight changes in slope (to more vertical) of the temperature curves occur in the upper part of the borehole at about 690 feet, and more pronounced changes in slope (to less vertical) occur near the bottom of the well at about 1,100 feet. The changes in slopes at about 690 and 1,100 feet correspond to inflow/outflow zones near the top of the cyclic and marine members and in the middle of the dolomitic member, respectively. Mostly upward flow from the dolomitic member to the cyclic and marine members occurred during the October 2006 temperature log, and mostly downward flow from and to the same units occurred during the April 2006 log; relatively vertical temperature-log slopes with negligible variation might be associated with borehole flow in either direction.

As with other temperature logs, temperature logs for well TC4 show increasing temperatures with depth (fig. 17); temperatures range from about 29 to 39 °C. Slight changes in slope to more vertical occurred in the temperature logs at about 1,100 feet, coincident with a relatively large inflow/outflow zone at the contact between the cyclic and marine members and the leached and collapsed members. The slope of the October 2006 temperature log over the length of the borehole, associated with upward flow in the borehole over most of its length, is slightly less than the slope of the April 2006 temperature log, associated with negligible flow in the borehole over most of its length.

Fish Hatchery Transect

The temperature logs for well FH1 were consistent down the length of the borehole and ranged from about 18 to 24 °C (fig. 18); slopes were essentially vertical, and variation was minimal. Vertical flow in the borehole, or lack of, did not affect the temperature curves in identifiable ways.

For well FH2, the temperature curves show changes in slope of the curves to more vertical at about 575–580 feet (fig. 19); temperatures range from about 23 to 32 °C. The temperature from about 580 to about 980 feet increased uniformly with depth for each log. Upward flow in the borehole from the basal nodular member to the leached and collapsed members (to depths coincident with the changes in slope of the temperature curves to more vertical) during the temperature logs ranged from negligible (October 2007) to about 1 gallon per minute (September 2006); because shapes of the temperature curves were about the same whether borehole flow was negligible or measurable, the effect of flow on fluid temperature is unclear.

Kyle Transect

The borehole temperature logs for well KY 1 show a step-like pattern of increasing temperature in the upper part of the aquifer from about 350 to 460 feet, similar to but more subdued than the step-like pattern of the conductivity logs for the same section of the borehole (fig. 20); temperatures range from about 20 to 29 °C. From about 460 to 750 feet, the temperature curves indicated near-vertical slopes with negligible variation in temperature values. The temperatures in this section of the borehole might have been influenced by substantial (relative to flows in boreholes of wells in other transects) upward flow from the Trinity aquifer that exits the borehole into numerous inflow/outflow zones of the Edwards aquifer.

The temperature logs for well KY2, the second of two wells that intersect the interface, show consistency and increasing temperature with depth down the borehole to about 650 feet (fig. 21); temperatures range from about 21 to 27 °C. Changes in slope of the temperature curves to less vertical (temperatures increasing with depth at a greater rate than in the overlying, upper borehole segment) occurred at about 650 feet. The points of inflection are coincident with the uppermost depth of the interface recorded on a fluid conductivity log (January 2003 log). Vertical flows in the borehole concurrent with temperature logs were less than 0.5 gallon per minute and mixed with regard to direction, so evaluating the influence of borehole flow on temperature in this interface well is problematic.

The temperature logs for well KY3 also show increasing temperature with depth, with temperatures ranging from about 21 to 28 °C (fig. 22). The temperature logs show little variation in slope with depth, except for the September 2006 log, which indicates minor variability at about 630 feet and an inflection point at about 850 feet that begins a generally greater rate of increase in temperature with depth to the bottom of the borehole. Flow in the borehole during the September 2006 temperature log was less than 0.05 gallon per minute, mostly downward, and somewhat greater in the segment below about 850 feet coincident with the greater rate of increase in temperature with depth to the bottom of the borehole.

The temperature logs in well KY4, as with the logs in other wells, show increasing temperature with depth (fig. 23); temperatures range from about 23 to 30 °C. As with temperature logs for well KY3, the most variability is evident in the September 2006 log. Also like the September 2006 log for well KY3, the rate of increase in temperature with depth in the lower segment of the borehole is generally greater than that in the upper segment of the borehole; the same applies to the June 2006 temperature log, although to a lesser degree. Vertical borehole flow is mixed among the logs with regard to direction and did not affect temperatures in an identifiable way.

Hydraulics of Flow

Hydraulics of flow in and near the freshwater/saline-water transition zone of the aquifer in this report focuses on two topics: (1) lateral head gradients computed from equivalent freshwater heads to evaluate the potential for lateral flow at the interface; and (2) measurements of vertical flow in boreholes to indicate the directions of vertical gradients in the aquifer and thus the potential for upward movement of water. The interface 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 implies horizontal and vertical components of head gradient across the interface.

Lateral Head Gradients at the Interface

Lateral head gradients, computed from equivalent freshwater heads for periods of coincident water-level data for 2000–2007, are used to indicate whether potential lateral flow at the interface in the East Uvalde, Tri-County, and Kyle transects was into the freshwater zone, out of the freshwater zone, or mixed with regard to direction (head higher or lower at the interface than on either side) for the respective periods of record. Lateral 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; in other words, the difference in vertical altitude between the open-hole sections of the two monitoring wells was considered too large for accurate equivalent freshwater heads to be computed. The assumption of a horizontal aquifer, necessary for computation of accurate equivalent heads, was judged not applicable for the Fish Hatchery transect.

East Uvalde Transect

Daily mean equivalent freshwater heads for the four East Uvalde transect monitoring wells for coincident periods of record during the study period generally were higher from November through May and lower from June through October for most years. Heads in all monitoring wells followed a similar pattern except when irrigation withdrawals in the Uvalde County area affected heads (caused drawdowns) in wells EU3 and EU4, which occurred for the most part in the summer (June–September) of each year (fig. 24). Heads in wells EU1 and EU2 were very similar, indicating that a hydraulic connection between these two wells is likely. Heads in wells EU3 and EU4 were similar, indicating that a hydraulic connection between the two saline-water wells also is likely (fig. 24).

The directions of lateral head gradient at the interface in the transect for 19 coincident periods of record for 2000–2007 indicate a nearly even split between into and out of the freshwater zone (table 3). The direction of the lateral head gradient along the East Uvalde transect was out of the freshwater zone into the transition zone during a majority of coincident periods of record (10 of 13) during January 2000–November 2005 (table 3). Annual rainfall at San Antonio (fig. 9) was above normal for 4 of the 6 years of 2000–2005, and the lateral head gradients computed for January 2000–November 2005 likely reflect, on average, a period of above-normal (wet) hydrologic

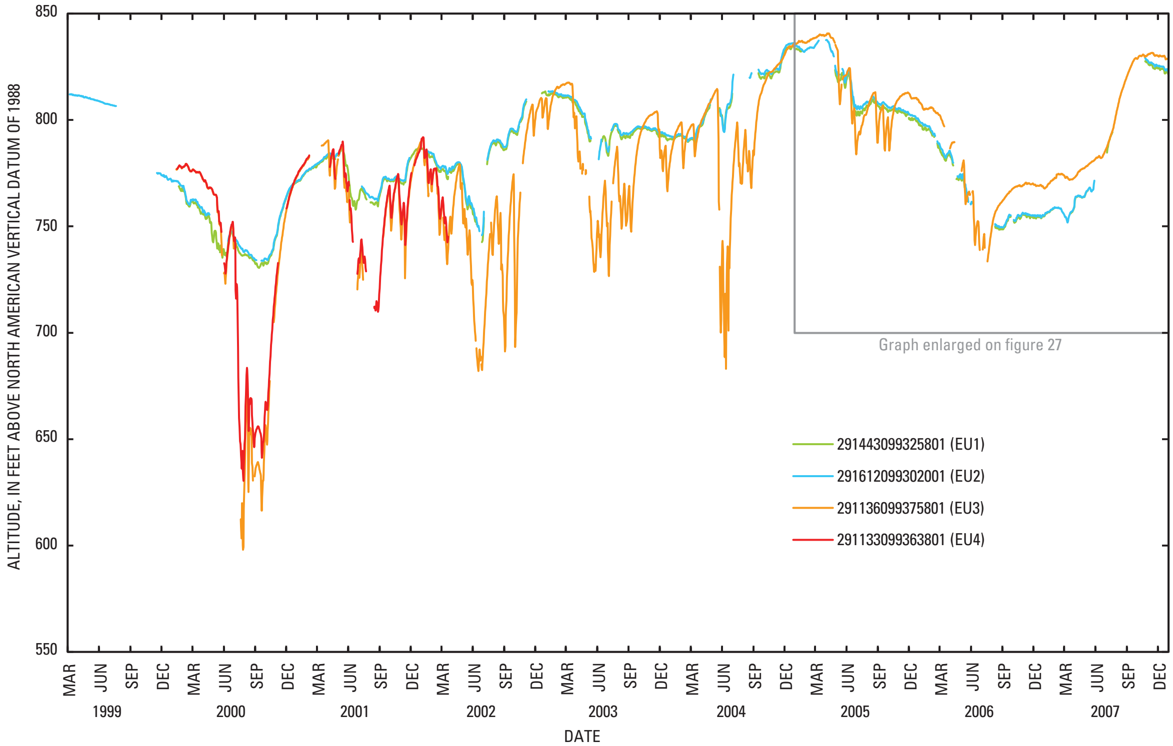


Figure 24. Daily mean equivalent freshwater head in monitoring wells of the East Uvalde transect, San Antonio segment of the Edwards aquifer, south-central Texas, 1999–2007.

conditions, implying relatively high recharge. Despite likely above-normal conditions on average, the hydrographs in figure 24 indicate relatively substantial influence of irrigation withdrawals on the heads in wells EU3 and EU4; without the effects of irrigation withdrawals, the lateral gradients during much of the 2000–2005 period of record might have been reversed.

During December 2005–December 2007, the direction of the lateral head gradient was from the transition zone into the freshwater zone (six of six coincident periods of record). Annual rainfall at San Antonio was below normal for 2006 and above normal for 2007 (fig. 9); and rainfall during 2005 was only 50 percent of normal. The lateral head gradients computed for coincident periods during December 2005–December 2007 likely reflect, on average, a period of below-normal (dry) hydrologic conditions, implying relatively low recharge. However, the hydrographs in figure 24 indicate relatively less influence of irrigation withdrawals on the heads in wells EU3 and EU4 during 2005–07 than during 2000–2005. Relatively less irrigation withdrawals during dry conditions is counterintuitive: It might be that the effect of irrigation withdrawals on heads is correlated more closely with antecedent hydrologic conditions (antecedent recharge) than concurrent conditions. Regardless, the directions of the gradient at the interface along the East Uvalde transect during all 19 coincident periods of record are affected to a greater or lesser degree by hydrologic conditions (antecedent and concurrent recharge) and relatively greater and smaller withdrawals. Based on these findings, albeit for a relatively short composite period of record, the direction of the head gradient and thus the potential lateral flow at the interface in the vicinity of the East Uvalde transect fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals. Whether the prevailing direction on average is into or out of the freshwater zone is not clearly indicated; previously, Maclay (1995, p. 37) reported on the basis of "limited" 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."

Tri-County Transect

Equivalent freshwater heads in all five monitoring wells in the Tri-County transect for coincident periods of record from April 2000 through December 2007 show similar patterns of response (fig. 25). The lowest equivalent freshwater heads generally were during the summer (June–September) of each year and drier-than-normal periods. Equivalent freshwater heads in freshwater wells TC1 and TC5 were consistently lower than those in saline-water well TC3 and interface well TC2 and generally higher relative to altitudes of equivalent freshwater heads in saline-water well TC4. The greatest

Table 3. Summary of average daily mean equivalent freshwater heads and directions of lateral head gradients for coincident periods of record for East Uvalde monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–2007.

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

Period number	Period start date	Period end date	Length of period (days)	Average daily mean equivalent freshwater head for 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	77	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	272	794.97	794.03	--	787.46	Out of
12	9/15/2004	1/18/2005	125	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

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

variation in equivalent freshwater head was in the freshwater and interface wells (TC5, TC1, and TC2), although head in saline-water well TC3 was similar to that in the three wells during 2000–2002.

The directions of the lateral head gradient in the transect are indicated for 30 coincident periods of record for 2000–2007 (table 4). The direction of the lateral head gradient in all but one of the coincident periods was either mixed (25) or uncertain (four) (table 4). Equivalent freshwater heads at the interface (well TC2) were higher on average than heads on the freshwater side of the interface (wells TC1 and TC5) and on the saline-water side of the interface (wells TC3 and TC4), regardless of whether hydrologic conditions were wet or dry. Why equivalent freshwater heads generally were higher at the interface than on either side of it cannot be explained with available data. There does not appear to have been a prevailing direction of the lateral gradient at the interface in the vicinity of the Tri-County transect.

A factor that might adversely affect the accuracy of equivalent freshwater heads, and thus computed gradients along the transect, is that altitudes of the open intervals of the wells are substantially different because of faulting (fig. 6), which might make the assumption of a horizontal aquifer (necessary for computation of accurate equivalent freshwater heads) not valid. Other factors also add uncertainty to the computations: for example, structural complexity associated with faulting could result in compartmentalization of the aquifer into zones of differing head; the simplifications necessary in the computation of fluid density (depth-averaging of fluid conductivity and temperature); the assumption that a single fluid density correction factor is applicable for each well, despite variable hydrologic conditions, as discussed in the section "Water-Level Data—Computation of Equivalent Freshwater Heads."

Kyle Transect

Equivalent freshwater heads during coincident periods for freshwater well KY1 and interface well KY2 responded similarly to varying hydrologic conditions and withdrawals from a nearby public-supply well (fig. 26). In general, when heads in the two wells peaked (reflecting relatively wet conditions), the

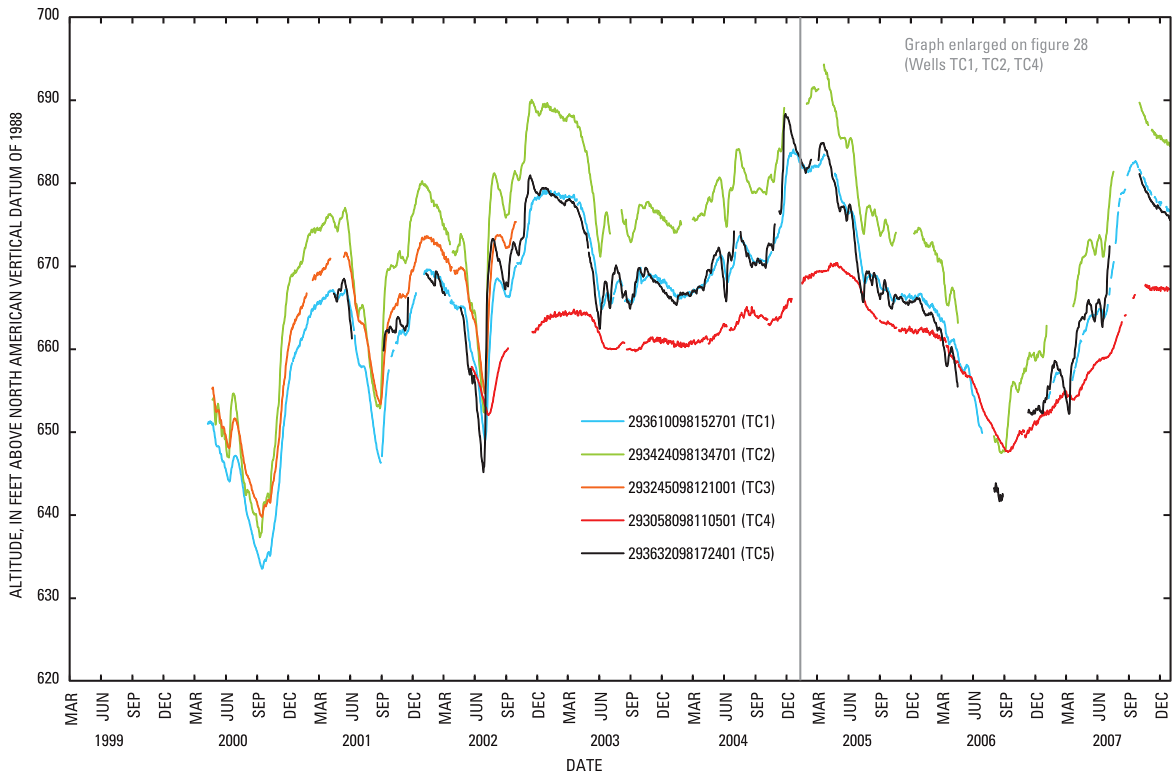


Figure 25. Daily mean equivalent freshwater head in monitoring wells of the Tri-County transect, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–2007.

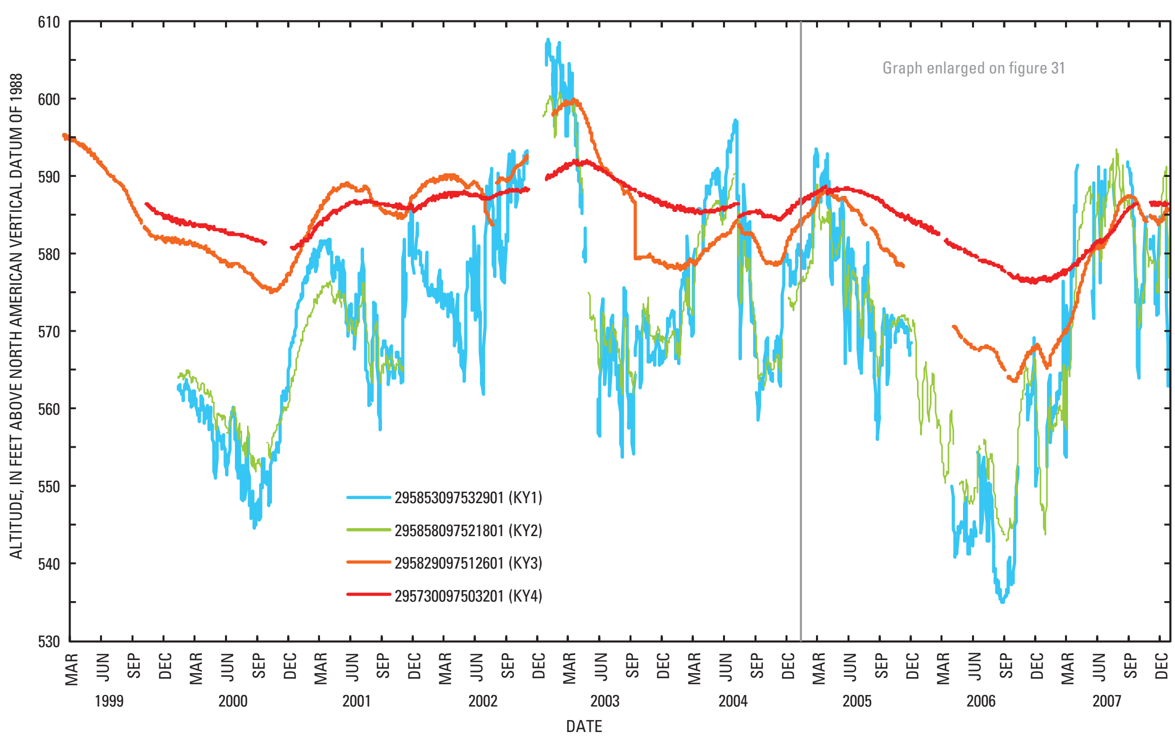


Figure 26. Daily mean equivalent freshwater head in monitoring wells of the Kyle transect, San Antonio segment of the Edwards aquifer, south-central Texas, 1999–2007.

Table 4. Summary of average daily mean equivalent freshwater heads and directions of lateral head gradients for coincident periods of record for Tri-County monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–2007.

[NAVD 88, North American Vertical Datum of 1988; grayshade represents interface location; --, no data; ?, uncertain (cannot be determined with available data)]

Period number	Period start date	Period end date	Length of period (days)	Average daily mean equivalent freshwater head for 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	46	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
11	10/3/2002	11/15/2002	44	676.06	672.81	684.51	--	--	?
12	11/16/2002	2/23/2003	99	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
19	11/25/2004	12/16/2004	22	687.51	682.03	--	--	665.59	?
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
22	10/27/2005	12/9/2005	44	665.79	666.30	--	--	662.29	?
23	12/10/2005	4/16/2006	129	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
26	1/23/2007	2/12/2007	21	657.98	656.87	--	--	653.65	?
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

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

head in well KY2 at the interface was lower than the head at KY1 on the freshwater side of the interface; and when heads in the two wells were at low points (reflecting relatively dry conditions), the head in KY2 was higher than the head at KY1. Equivalent freshwater heads from saline-water wells KY3 and KY4 in the transition zone were, for the most part, consistently higher than those of wells KY1 and KY2 and fluctuated considerably less than the heads in KY1 and KY2.

The directions of lateral head gradient at the interface are indicated for 42 coincident periods of record (table 5). The direction of equivalent freshwater head gradients for coincident periods in the Kyle transect was into the freshwater zone for about one-half the periods (22), mixed for one-third of the periods (14), out of the freshwater zone for three periods, and uncertain for three. The longest continuous period of gradient into the freshwater zone (May 2005–December 2006) coincided with the middle and latter parts of the longest sustained period of below-normal hydrologic conditions during the study period (figs. 9, 26). The January 2000–November 2000 continuous period of gradient into the freshwater zone followed

Table 5. Summary of average daily mean equivalent freshwater heads and directions of lateral head gradients for coincident periods of record for Kyle monitoring wells transecting the freshwater/saline-water interface, San Antonio segment of the Edwards aquifer, south-central Texas, 2000–07.

[NAVD 88, North American Vertical Datum of 1988; grayshade represents interface location; --, no data; ?, uncertain (cannot be determined with available data)]

Period number	Period start date	Period end date	Length of period (days)	Average daily mean equivalent freshwater head for 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	36	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)
12	8/2/2002	11/3/2002	94	587.12	--	590.69	588.16	?
13	1/27/2003	2/10/2003	25	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
37	4/8/2007	5/22/2007	45	--	585.63	577.82	580.05	?
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
41	11/8/2007	11/22/2007	15	581.11	579.06	584.88	586.67	Mixed
42	11/26/2007	12/31/2007	36	--	583.84	584.82	586.55	?

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

and partly coincided with a period of below-normal hydrologic conditions. The August 2001–July 2002 continuous period of gradient into the freshwater zone likely was a period of normal or slightly above-normal hydrologic conditions. Mixed gradients tended to prevail during above-normal conditions; and for periods of mixed conditions on average, equivalent freshwater heads on the transition-zone side of the interface (wells KY3 and KY4) usually were higher than heads on the freshwater side of the interface (well KY1). Gradients out of the freshwater zone occurred during what likely were periods of well-above-normal hydrologic conditions (winter 2003, spring 2004, summer 2007) (figs. 9, 26). The direction of the lateral gradient at the interface in the vicinity of the Kyle transect, like that in the vicinity of the East Uvalde transect, probably fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals; but the prevailing direction on average of the lateral gradient and thus potential lateral flow at the interface in the vicinity of the Kyle transect likely is from the transition zone into the freshwater zone.

Vertical Flow in the Boreholes

The magnitude and direction of vertical flow in the boreholes is a reflection of head differences between zones, or stratigraphic units, in and adjacent to the Edwards aquifer that can change in response to changing hydrologic conditions over time. Vertical flows in the boreholes were measured under ambient conditions and differing hydraulic conditions to indicate the directions of vertical gradients in the aquifer and thus the potential for upward movement of water.

Equivalent freshwater heads are used in this section primarily to indicate hydrologic conditions (wet or dry) and for consistency with other sections of the report (one set of heads throughout). Although environmental-water heads (unadjusted field-measured heads), not equivalent freshwater heads, define hydraulic gradients in the vertical direction (Lusczynski, 1961), the directions of vertical gradients here are indicated by the directions of measured flows.

East Uvalde Transect

The flowmeter logs for well EU1 indicate estimated flow less than 0.1 gallon per minute, with minor exceptions, in the borehole at the times logs were run during 2005–07 (fig. 10). The exceptions involved slightly larger flows (0.1 to 0.5 gallon per minute) at the bottom of the borehole during the April 2005 and September 2006 logs. The flow at the bottom of the borehole was upward in April 2005, when the equivalent freshwater head was high (about 824 feet above NAVD 88), and downward in September 2006, when the equivalent freshwater head was low (about 753 feet above NAVD 88). However, the flow at the bottom of the borehole was negligible during the other two flow logs (April 2006 and October 2007), when the head in the well was relatively low (about 775 feet above NAVD 88) and high (about 828 feet above NAVD 88), respectively; a lack of consistency in magnitude or direction of vertical flow at the bottom of the borehole relative to head and minimal flow throughout the remainder of the borehole preclude identifying a relation between vertical flow and head at the time the log was run in well EU1.

The flowmeter logs for well EU2 indicate estimated flow less than 0.1 gallon per minute for the entire length of the borehole at the times logs were run during 2005–07 (fig. 11). The vertical direction of the minimal flows recorded was mixed, and no clear relation between vertical flow and head at the time the log was run in well EU2 is evident.

The flowmeter logs for well EU3 (fig. 12) indicate slightly greater magnitudes of flow (as much as 0.3 gallon per minute) than in the boreholes of wells EU1 and EU2 for the April 2005 log when head in the well was high (about 838 feet above NAVD 88). The direction of flow for the April 2005 log was upward from an inflow/outflow zone near the base of the McKnight Formation to an inflow/outflow zone in the middle of the Salmon Peak Formation; and downward from an inflow/outflow zone in the upper part of the Salmon Peak Formation to the same inflow/outflow zone in the middle of the Salmon Peak Formation that was the sink for the upward flow. Flows indicated by the two other logs (September 2006 and October 2007) were almost all less than 0.1 gallon per minute and of mixed direction. The head in the well in September 2006 was low (about 765 feet above NAVD 88), and the head in October 2007 was high (about 825 feet above NAVD 88). No consistent relation between vertical flow and head at the time the log was run in well EU3 is evident.

The flowmeter logs for well EU4 (fig. 13) indicate mostly flows less than 0.1 gallon per minute. Although head data for well EU4 concurrent with the times of the log runs are not available, hydrographs of equivalent freshwater head for wells EU3 and EU4 for coincident periods of record during 2000–2002 match closely (fig. 24). Assuming heads in well EU4 were close to those in well EU3 at the times of log runs in well EU4, again as with the three other wells, no consistent relation between vertical flow and head at the time the log was run in well EU4 is evident. For example, near the bottom of the borehole, the April 2005 log during high head in well EU3 indicates flow of 0.3 to 0.4 gallon per minute into the West Nueces Formation; but the October 2007 log, also during high head in well EU3, shows flow of 0.1 to 0.2 gallon per minute out of the same zone in the West Nueces Formation.

Rather than assessing vertical borehole flow by comparing flow logs for the same well at different times as in figures 10–13, another way is to compare flow logs for the different wells in the transect at the same times, as in figure 27. Figure 27 shows representations of the flow logs for wells EU1–EU4 superimposed on four hydrogeologic sections of the transect, one section for each of the four times a series of flow logs was run. Concurrent hydrographs of equivalent freshwater head for wells EU1–EU3 (no concurrent head data available for well EU4) also are shown to indicate relative hydrologic conditions for each of the four series of flow logs.

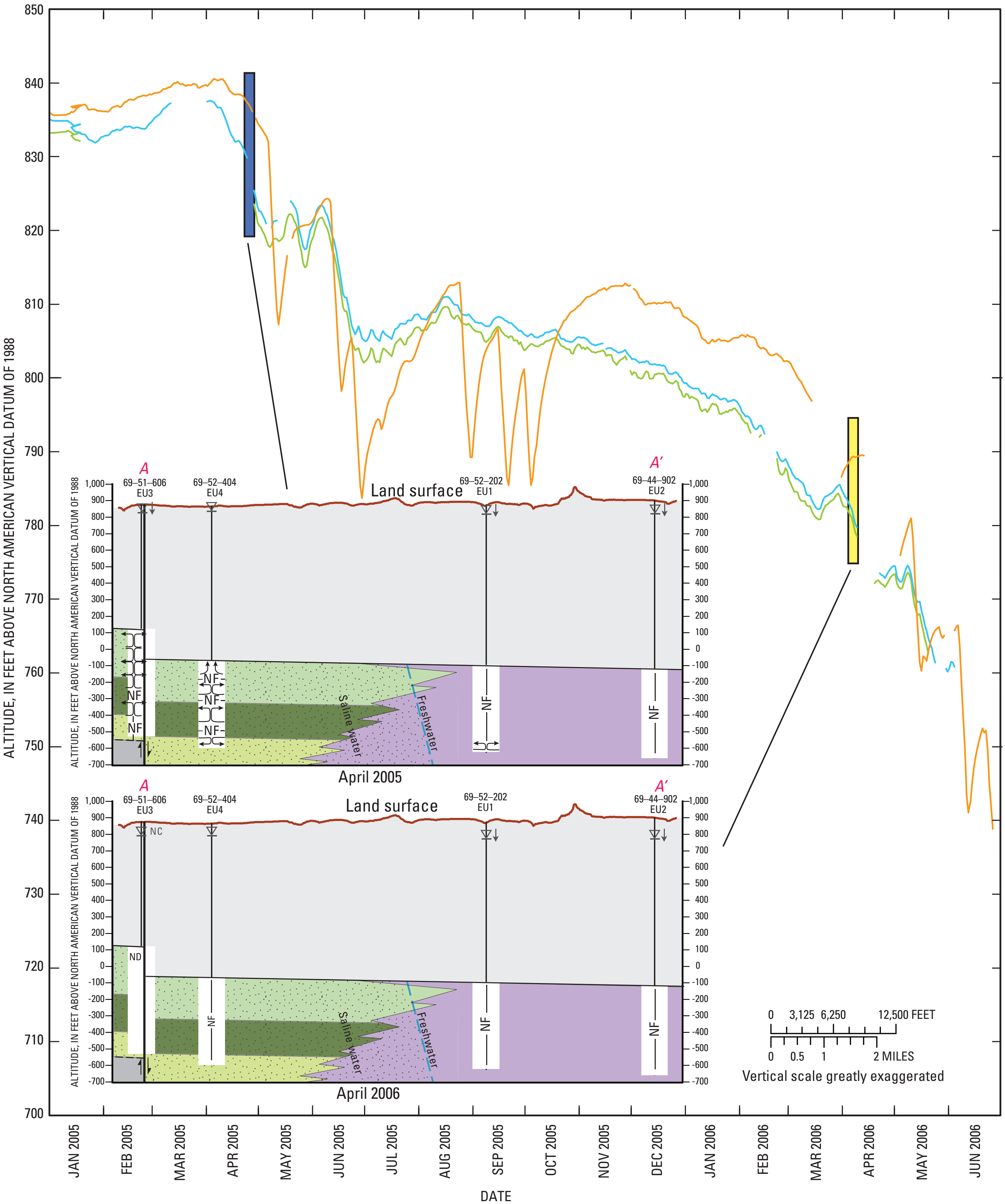
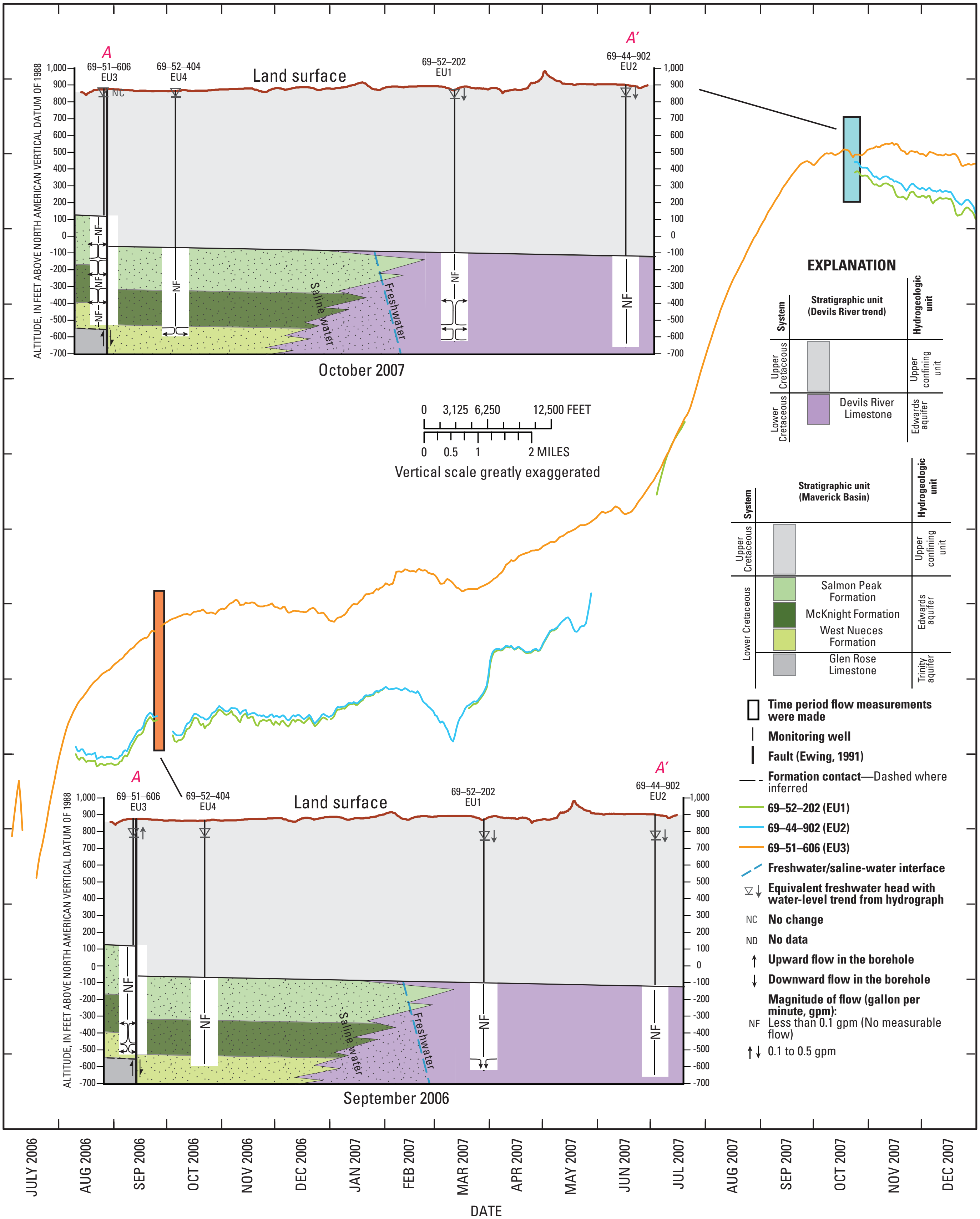


Figure 27. Conceptual diagram showing vertical flow in monitoring wells in the East Uvalde transect (*A–A′*), San Antonio segment of the



Edwards aquifer, south-central Texas, 2005–07.

The sections and hydrographs in figure 27 allow regional visualization of vertical flows relative to hydrologic conditions that is not apparent in the flow logs of figures 10–13.

Several observations can be made on the basis of the head and flow data in figure 27. In general, the flow data for three of the four times logs were run (excluding April 2006 because of missing data) indicate more vertical flow (regardless of direction) on the saline-water side of the interface than on the freshwater side. The section diagrams indicate that the direction of vertical flow in all the wells with measurable flow was mostly upward, and magnitude of flow generally was greater when equivalent freshwater heads were high than when they were low. Equivalent freshwater heads at the times of each of the four flow logs, whether relatively high or relatively low, were higher in saline-zone well EU3 than in freshwater wells EU1 and EU2. Although equivalent freshwater heads were about the same for the October 2007 log as for the April 2005 log, vertical flows were larger in April 2005 than in October 2007 probably because antecedent heads were substantially higher during the months before April 2005 than during the months before October 2007 (fig. 24).

As indicated in the sections, the interface is assumed to be a sloping surface, which implies horizontal and vertical components of head gradient across it. The equivalent freshwater head data and the vertical flow data indicate that, under the hydraulic head conditions at the times the flow logs were run (equivalent freshwater heads in the transition zone higher than those in the freshwater zone), the directions of the lateral and vertical components of the head gradient at the interface were into the freshwater zone and upward (thus also into the freshwater zone), respectively. If vertical flow data were available for times (or antecedent conditions) when equivalent freshwater heads in the freshwater zone were higher than those in the transition zone, the direction of the gradient likely would have been downward, out of the freshwater zone. The hypothesis regarding the vertical gradient in the vicinity of the East Uvalde transect, and thus the potential for vertical flow near the interface, is that the potential for vertical flow (like the potential for lateral flow) fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals.

Tri-County Transect

The flowmeter logs for freshwater well TC1 show downward flow in the borehole for each of the four logs run (fig. 14). Flow entered the borehole from the Georgetown Formation and the formation members above the regional dense member and exited the borehole into the formation members below the regional dense member, except the basal nodular member into which no flow was recorded for any log. Flow was less than 1 gallon per minute and maximum as it passed the regional dense member during all logs; there is no identifiable relation between flow and head in well TC1 at the time the logs were run.

Three of the four flowmeter logs for interface well TC2 (fig. 15) show downward flow entering the borehole from the cyclic and marine members and the leached and collapsed members and most flow exiting the borehole immediately beneath the regional dense member into the grainstone member; no flow was recorded in the April 2006 log. As was the case for well TC1, flow was less than 1 gallon per minute, maximum as it passed the regional dense member, and does not show an identifiable relation to head at the time the logs were run. The interface during all logs was about at the contact between the Kirschberg evaporite member and the underlying dolomitic member. No flow was recorded in any of the logs in the saline zone beneath the interface.

The two flowmeter logs for saline-water well TC3 (fig. 16) show essentially no flow (less than 0.1 gallon per minute) for the April 2006 log and mixed-direction flow for the September 2006 log. Flow during the September 2006 log entered the borehole from the grainstone member, moved upward past the regional dense member, and exited the borehole into the leached and collapsed members. Downward flow was recorded over a short vertical distance between inflow/outflow zones within the Kirschberg evaporite member. Flowmeter logs were not run in well TC3 in April 2005 and October 2007, periods of relatively high heads, because the well was flowing. No concurrent head data are available for well TC3.

Two of the three flowmeter logs for saline-water well TC4 (January 2005 and October 2006) show upward flow that entered the borehole from the formation members below the regional dense member (mostly excluding the basal nodular member), was maximum (about 0.8 gallon per minute) as it passed the regional dense member, and exited the borehole into the formation members above the regional dense member and the Georgetown Formation. The upward flow pattern in these two logs is roughly a mirror image of the downward flow pattern shown in the logs for freshwater well TC1. The April 2006 log, as with wells TC2 and TC3, shows essentially no flow. January 2005 and October 2006 flow logs generally are similar, although the equivalent freshwater head in well TC4 at the time of the January 2005 log was near the highest of the period of record and at the time of the October 2006 log was near the lowest of the period of record; thus no identifiable relation between head in well TC4 and flow at the time of the logs is evident. No flow data were available for well TC4 for October 2007.

A more regional perspective is illustrated by representations of the flow logs for wells TC1–TC4 superimposed on hydrogeologic sections of the transect, one for each of the four times a flow log was run, and concurrent hydrographs of equivalent freshwater head for wells TC1, TC2, and TC4 (no concurrent head data available for well TC3) (fig. 28). At all four times the flow logs were run, which encompassed a range of hydrologic conditions from wet (April 2005) to dry (September 2006) for the period of record (2000–2007) (fig. 25), the interface was essentially in the same position in well TC2, below the regional dense member about at the contact between the grainstone member and the Kirschberg evaporite member; some combination of head gradient and permeability (each with lateral and vertical components) was functioning to keep the interface stable as heads changed. The permeability of the regional dense member is low enough to create a head gradient that drives water across it under the range of hydrologic conditions that occurred at the times the logs were run. The gradient was downward on the freshwater side of the interface and upward on the saline-water side of the interface at the times logs were run (except the April 2006 flow log [relatively dry conditions] for saline-water well TC3 in which, for unknown reasons, essentially no flow was recorded). The downward gradient on the freshwater side of the interface and the upward gradient on the saline-water side (upward gradient at well TC3 indicated directly by the well flowing when heads were high) are evidence of opposing potentials that appear to have stabilized the position of the interface over the range of hydrologic conditions that occurred at the times the logs were run. Regionally, the data indicate a classic flow-system configuration with recharge conditions in the relatively high-altitude, updip parts of the aquifer and discharge conditions in the relatively low-altitude, downdip parts of the aquifer; in this case, the inflection point (inflection surface in three dimensions) probably is coincident with the interface.

Fish Hatchery Transect

The three flow logs for relatively shallow freshwater well FH1 (fig. 18) show small vertical borehole flows within the leached and collapsed member of mixed direction: downward flow less than 0.5 gallon per minute in the April 2005 log when equivalent freshwater head was high (fig. 29), essentially no flow (less than 0.1 gallon per minute) in the September 2006 log when equivalent freshwater head was low, and minimal upward flow (less than 0.2 gallon per minute) in the October 2007 log when equivalent freshwater head was once again high. Thus no identifiable relation between head in well FH1 and flow at the time of the logs is evident.

The four flow logs for saline-water well FH2 (fig. 19) show vertical borehole flows ranging from no flow to upward flow of about 1.1 gallons per minute. The largest upward flow, generally increasing from the basal nodular member to the maximum at the regional dense member and then decreasing to the cyclic and marine members, was recorded in the September 2006 log when equivalent freshwater head in the well was low. Smaller upward flow, again maximum (about 0.5 gallon per minute) at the regional dense member, was recorded in the April 2005 log when equivalent freshwater head in the well was high; and upward flow recorded in the October 2007 log, when equivalent freshwater head in the well again was high, was about the same as that recorded in April 2005. The potential for an inverse relation between upward flow and head in the well from the data of these three logs is negated by the data for the May 2006 log when head was relatively low: The early May 2006 log, like the April 2006 logs for wells TC2–TC4, shows essentially no flow. As with the Tri-County transect, the permeability of the regional dense member appears low enough to create a head gradient that drives water across it under the range of hydrologic conditions that occurred at the times the logs were run.

From a regional perspective, the head and flow data for the Fish Hatchery transect (fig. 30) yield some additional observations. Because well FH1 is freshwater and well FH2 is saline water, the interface, conceptualized as a sloping surface as indicated in the sections in figure 30, must occur between the two wells. Heads and possibly also structure (fault offset) combined to keep the interface beneath the bottom of well FH1 at the times the logs were run. Because well FH1 is open only to the uppermost part of the Edwards aquifer, the small, mixed-direction vertical flows over the short segment of borehole offer little information about vertical flow throughout the aquifer near the interface on the freshwater side. Vertical flows in the borehole of well FH2 were upward whether hydrologic conditions were wet or dry. There appears to have been an upward gradient on the saline-water side of the interface under a wide range of hydrologic conditions. This upward gradient, coupled with the assumption of a sloping interface as conceptualized on the sections in figure 30, implies a vertical gradient from the transition zone into the freshwater zone. This potential for vertical movement of saline water into the freshwater zone (vertical movement of the interface) apparently was opposed by the potential (head) on the freshwater side of the interface that kept the interface beneath the bottom of well FH1 over the range of hydrologic conditions during which the logs were run. It is possible that fault offset near the interface also helps to restrict the movement of saline water by reducing the area of contact between adjacent blocks of aquifer. Although the hydrographs of wells FH1 and FH2 (fig. 29) reflect the same general pattern, the hydrograph of well FH2 is attenuated compared to that of well FH1, indicating hydraulic communication between the two wells is somewhat restricted.

Kyle Transect

The five flow logs for freshwater well KY1 (fig. 20) all indicate upward flow ranging from negligible (less than 0.1 gallon per minute, May 2006) to nearly 4 gallons per minute (September 2006). The upward flow originates from the Glen Rose Limestone, the uppermost unit of the Trinity aquifer. These flow data constitute evidence of the potential for flow from the Trinity aquifer into the Edwards aquifer in the vicinity of well KY1. Upward flow in the borehole was largest adjacent to the Glen Rose Limestone, the basal nodular member, and the lower part of the dolomitic member; flow slowed as it likely exited the borehole into the units from the dolomitic member upward to the regional dense member and had essentially ceased by the time it reached the leached and collapsed members. The largest upward flow occurred during the September 2006 log when equivalent freshwater head in the well was about at its lowest level for the period of record

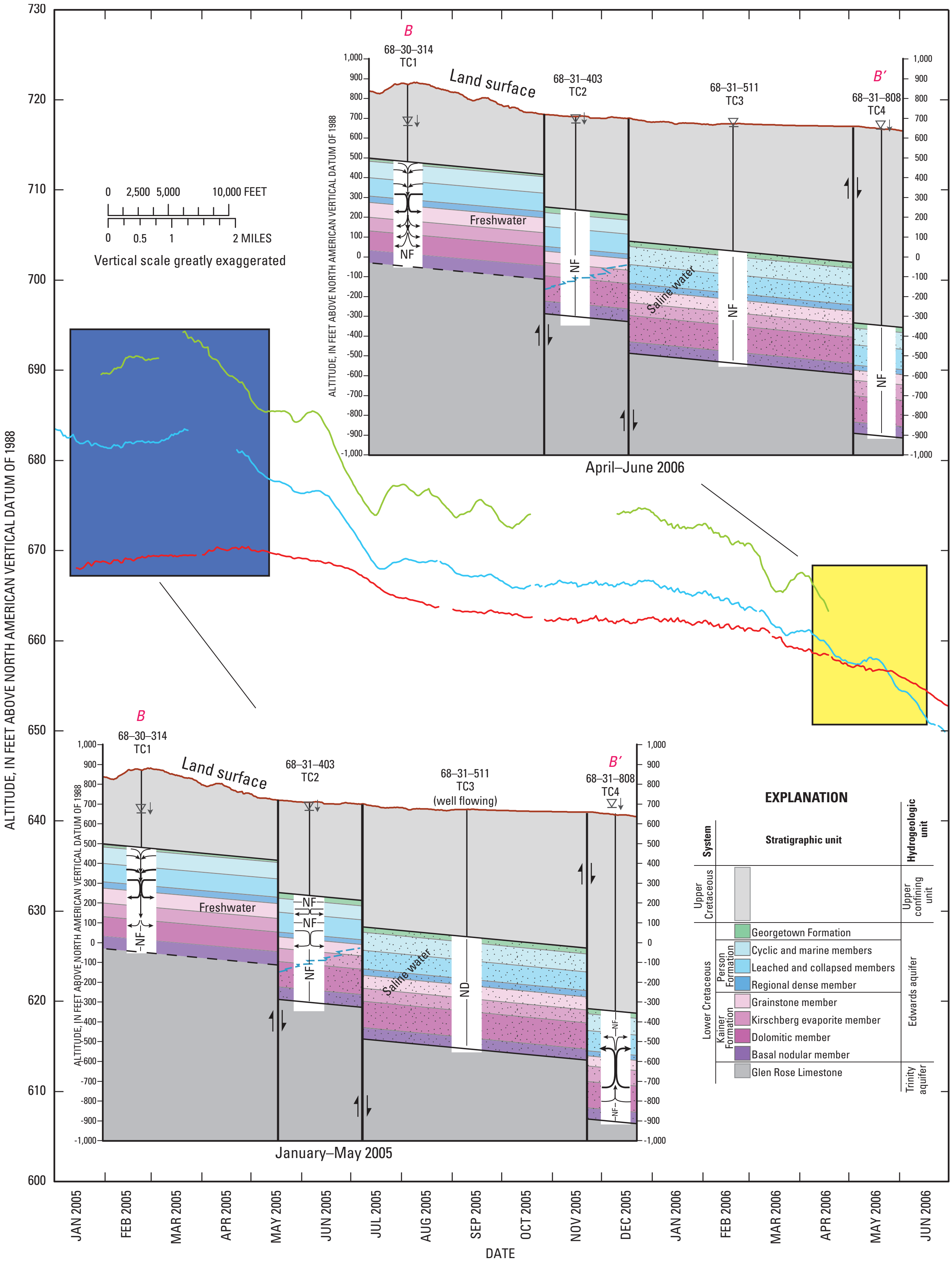
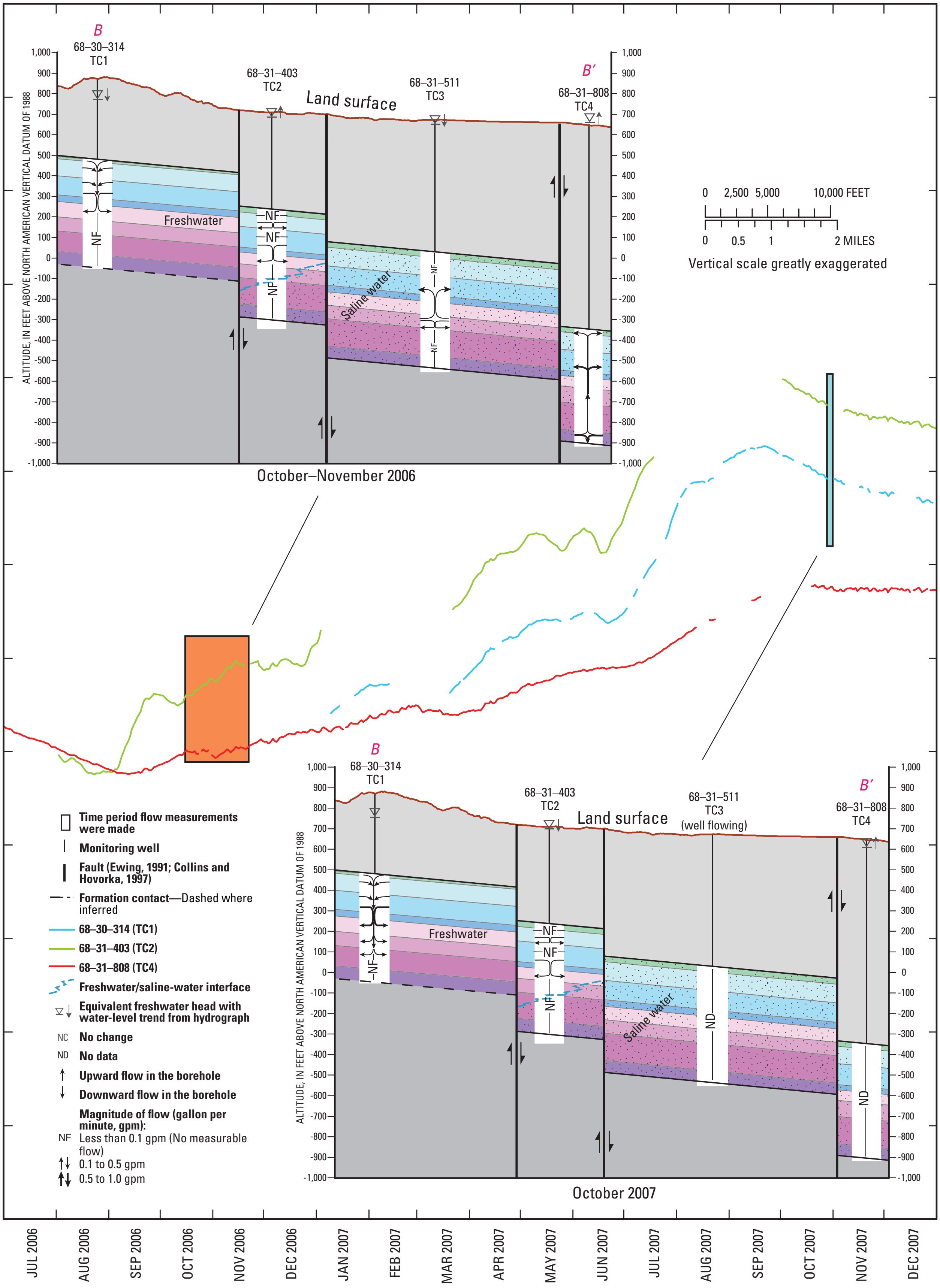


Figure 28. Conceptual diagram showing vertical flow in monitoring wells in the Tri-County transect (*B–B′*), San Antonio segment of the



Edwards aquifer, south-central Texas, 2005–07.

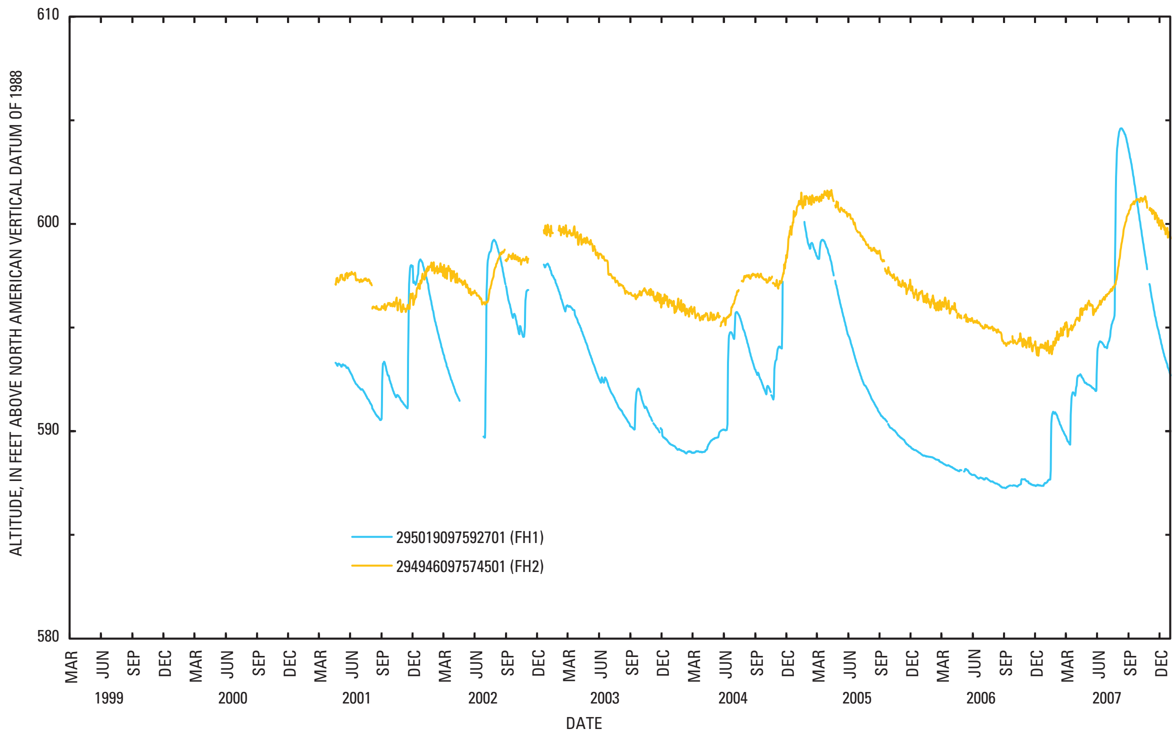


Figure 29. Daily mean equivalent freshwater head in monitoring wells of the Fish Hatchery transect, San Antonio segment of the Edwards aquifer, south-central Texas, 2001–07.

(fig. 26). However, upward flow was nearly as large during the March 2005 log when equivalent freshwater head in the well was relatively high for the period of record.

As shown by the associated conductivity logs, the relatively strong upward flow originating from the Glen Rose Limestone was fresher than the water in the borehole adjacent to the overlying members of the Edwards aquifer. The relatively fresh water is an indication that the source of the Trinity aquifer water entering the borehole likely was infiltration of streamflow or direct recharge on the outcrop of the Trinity aquifer (aided in entering the Trinity aquifer by faults or fractures) rather than upward leakage from deeper, likely more-saline parts of the Trinity aquifer.

The three flow logs for interface well KY2 (fig. 21) show differing vertical flow patterns. Two of the three logs (June 2006 and November 2007) recorded essentially no flow and downward flow less than 0.1 gallon per minute, respectively. The September 2006 log shows upward flow of 0.3–0.4 gallon per minute entering the borehole from the Glen Rose Limestone and exiting the borehole into the upper part of the dolomitic member and the overlying Kirschberg evaporite member, at about the same level as the interface, as indicated by the associated conductivity log. Above the interface, downward flow of about 0.4 gallon per minute occurred from the lower part of the leached and collapsed members, past the regional dense member, and probably into the Kirschberg evaporite member at about the same level as the interface; there was slight (less than 0.2 gallon per minute) upward flow from the leached and collapsed members toward the cyclic and marine members. The position of the interface in well KY2 was not quite as stable as that in well TC2, varying over several tens of feet among the times the logs were run.

The four flow logs for saline-water well KY3 (fig. 22) show mostly downward borehole flow at relatively low rates, exceeding 0.1 gallon per minute beginning at the Kirschberg evaporite member and increasing to as much as 0.4 gallon per minute at the basal nodular member. As in wells KY1 and KY2, the largest flow, although in the opposite direction, was recorded during the September 2006 log when equivalent freshwater head in the well was about at its lowest level for the period of record (fig. 26). Flows recorded during the June 2006 and November 2007 logs, when equivalent freshwater heads were relatively low and relatively high, respectively, were less than 0.1 gallon per minute throughout the length of the borehole.

The four logs for saline-water well KY4 (fig. 23) show mixed-direction flows in the 0–0.5 gallon per minute range. Flow during the May 2005 log, when equivalent freshwater head in the well was relatively high, was mostly downward throughout the borehole, except adjacent to the grainstone member and the basal nodular member; flow during the June and September 2006 logs was mostly upward throughout the borehole, the maximum occurring adjacent to the regional dense member. The largest upward flow occurred, as in wells KY1 and KY2, during the September 2006 log when equivalent freshwater head in the well was at about its lowest level for the period of record (fig. 26). There was essentially no vertical flow in the borehole during the November 2007 log.

Considering the head and flow data for the four monitoring wells of the Kyle transect together from a regional perspective (fig. 31), the salient observation remains the upward borehole flow in freshwater well KY1, and to a lesser extent in interface well KY2, that originated from the Glen Rose Limestone of the Trinity aquifer. Upward flow of water occurred in well KY1 that was lower in conductivity than the overlying freshwater in the borehole under all head conditions at the times the logs were run and that was relatively strong (3–4 gallons per minute) during two of the logs (March 2005 and September 2006). No clear relation between rate of upward borehole flow from the Trinity aquifer and heads in the transect monitoring wells is apparent, however. Equivalent freshwater head in well KY1 at the time of the March 2005 log was about the third highest of the 2000–2007 period of record (fig. 26); and heads in the three other Kyle wells were within a few feet of the head in KY1. In contrast, equivalent freshwater head in well KY1 at the time of the September 2006 log was the lowest of the period of record, and heads in wells KY3 and KY4 were about 30 and 45 feet higher, respectively, than that in well KY1. If the source of the Trinity aquifer water flowing into the borehole of well KY1 (and KY2) was infiltration of streamflow or direct recharge on the outcrop of the Trinity aquifer as hypothesized, then the head driving the upward flow into the boreholes might have been more closely related to the head in the outcrop of the Trinity aquifer rather than the head in the Trinity aquifer in the vicinity of the Kyle transect.

The patterns of vertical flow in the vicinity of the Kyle transect might be the most complex of the patterns among the transects. On the freshwater side of the interface, the relatively strong upward borehole flow of water from the Trinity aquifer masked any downward vertical flow that might have occurred as a result of recharge conditions in the relatively high-altitude, updip parts of the Edwards aquifer; the transect is close to the recharge zone of the Edwards aquifer. On the saline-water side of the interface, the directions of vertical flow were mixed, or there was essentially no flow, under the hydrologic conditions during 2005–07, and no identifiable relation between flow direction and conditions. The structure of the aquifer, the fact of offset fault blocks (fig. 31), might contribute to the complexity by affecting hydraulic communication in the vicinity of the transect. In other words, the heads causing vertical flows in the different wells of the transect might reflect zones of the aquifer not strongly connected hydraulically. The fact that hydrographs of saline-water wells KY3 and KY4 are attenuated relative to those of freshwater well KY1 and interface well KY2 (figs. 26, 31), and less affected by withdrawals, indicates some degree of hydraulic "insulation" between the saline-water and freshwater sides of the interface.

Relative Groundwater Flow Based on Temperature

Subsurface temperature data can provide information about groundwater flow rates (Anderson, 2003). Heat is transported upward by conduction throughout the Earth's crust. 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." In the case of a conductive thermal gradient, temperature increases linearly with depth at a rate dependent on regional heat flow from the Earth's interior into the base of the crust, heat production in the crust, and the thermal conductivity of the material composing the crust.

If groundwater flow is appreciable, heat is transported in the subsurface by convection as well as by conduction. Convective heat flow typically causes a subsurface temperature gradient to diverge from a conductive thermal gradient and become nonlinear. Conductive thermal gradients become disturbed by convective heat flow when groundwater flow rates are on the order of centimeters per year or greater (Ingebritsen and Sanford, 1998). Subsurface temperature data therefore can be used to indicate zones of negligible groundwater flow (temperature [thermal] gradients greater than or equal to the conductive thermal gradient) and zones of active groundwater flow (temperature gradients less than the conductive thermal gradient or the absence of a temperature gradient).

The conductive thermal gradient can be defined as

$$dT/dz = (T2-T1)/\Delta z, \qquad (4)$$

where T1 and T2 are the temperatures at two points (depths) separated by a distance Δz. The term dT/dz is expressed in units of temperature per unit distance (degrees Celsius per 100 feet [°C/100 ft] or degrees Celsius per 100 meters [°C/100 m]) and is a vector quantity that has both magnitude and direction (Beardsmore and Cull, 2001, p. 12). By convention, a positive gradient is in the direction of increasing temperature. Thermal gradients for the open intervals of wells were computed for each well (table 6) using geophysical log data collected for this report (Lambert and others, 2009).

Subsurface temperature data collected by King and Simmons (1972, p. 138) indicate that the conductive thermal gradient in Uvalde County typically is 2.16 °C/100 m. Temperature data in Woodruff and Foley (1985, p. 138) collected at depth in the Balcones fault zone (below the zone of potential groundwater flow) indicate that conductive thermal gradients in the study area ranged from 2.05 to 2.46 °C/100 m. On the basis of these studies, a conductive thermal gradient of 2.19 °C/100 m was assumed for the transition zone.

The average temperature gradients computed from temperatures measured during 2002–07 for this report ranged from 0.67 to 2.11 °C/100 m for the freshwater wells and from 1.44 to 3.07 °C/100 m for the interface and saline-water wells (table 6). The temperature gradients in five of the six freshwater wells (no data for freshwater well TC5) were lower than the assumed conductive thermal gradient, indicating active groundwater flow on the freshwater side of the interface (freshwater zone). Temperature gradients

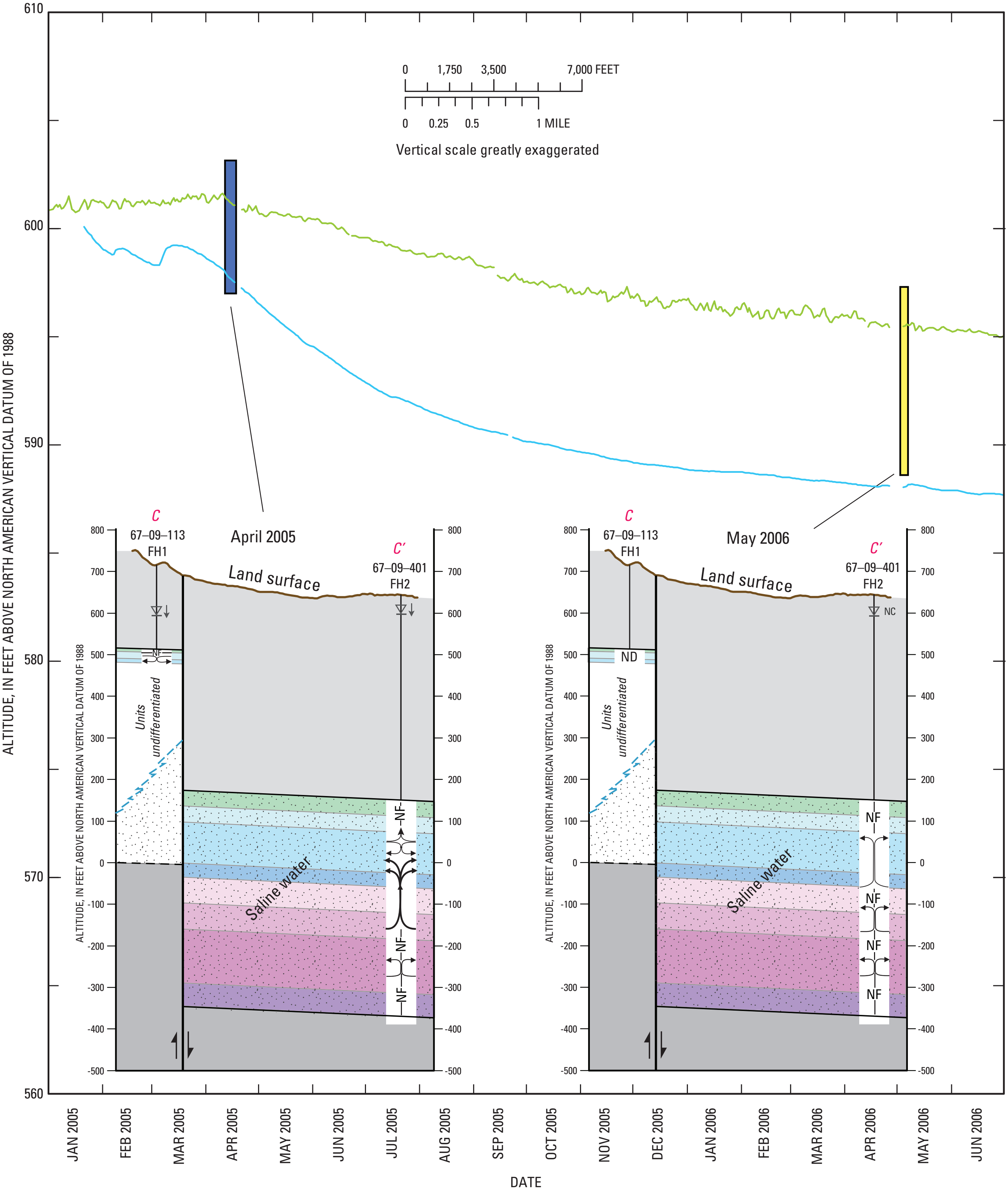
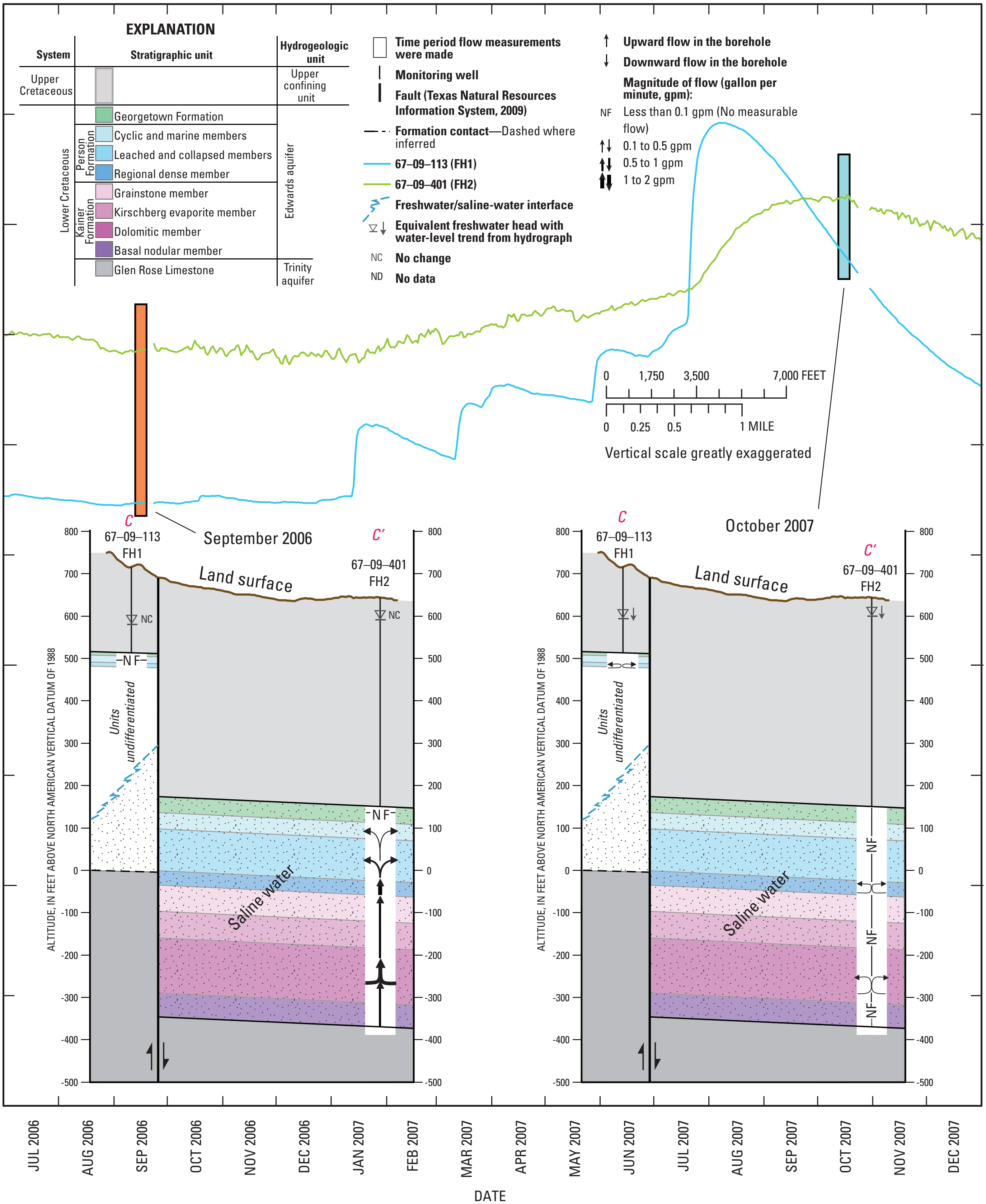


Figure 30. Conceptual diagram showing vertical flow in monitoring wells in the Fish Hatchery transect (*C–C′*), San Antonio segment of



the Edwards aquifer, south-central Texas, 2005–07.

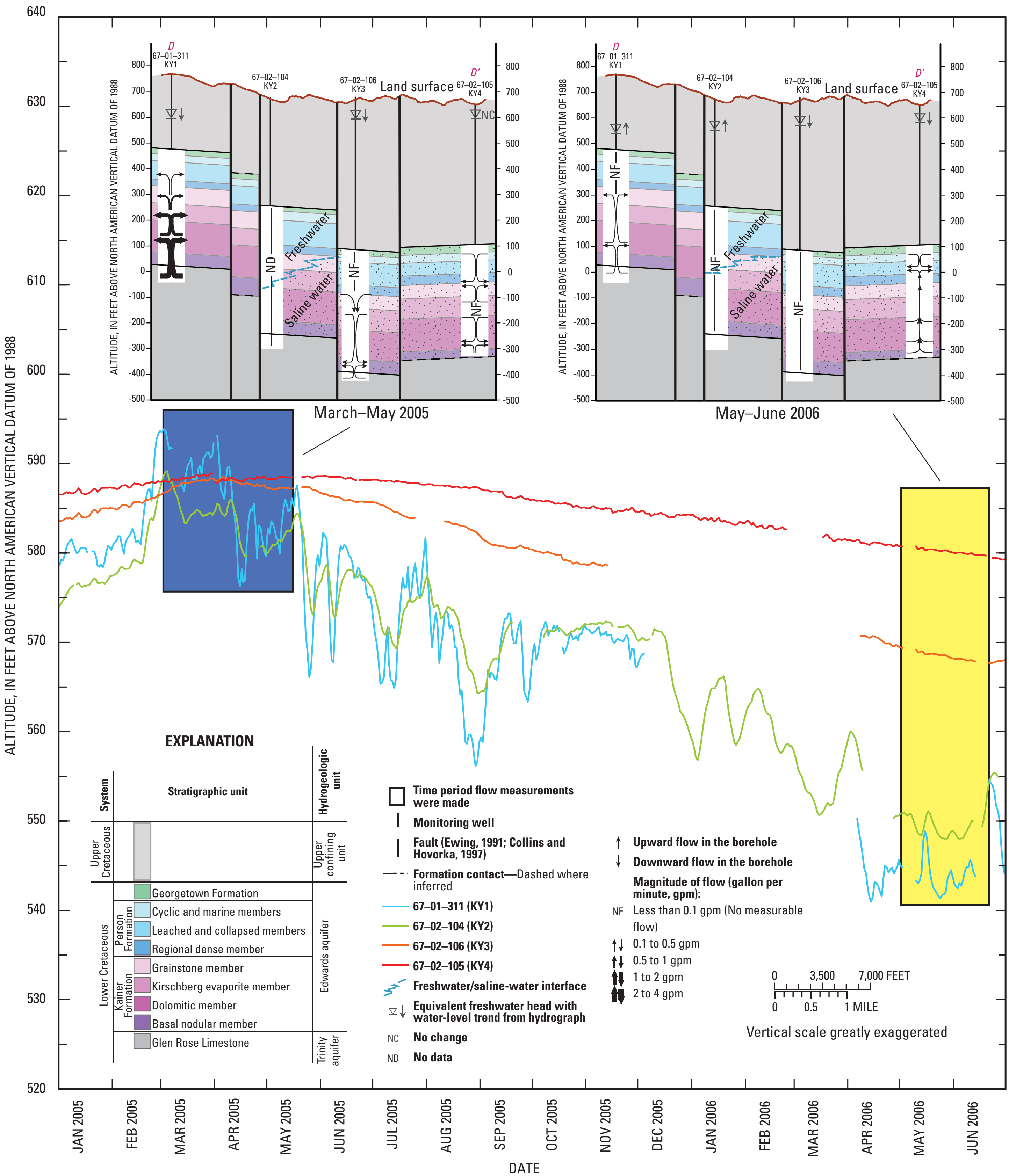
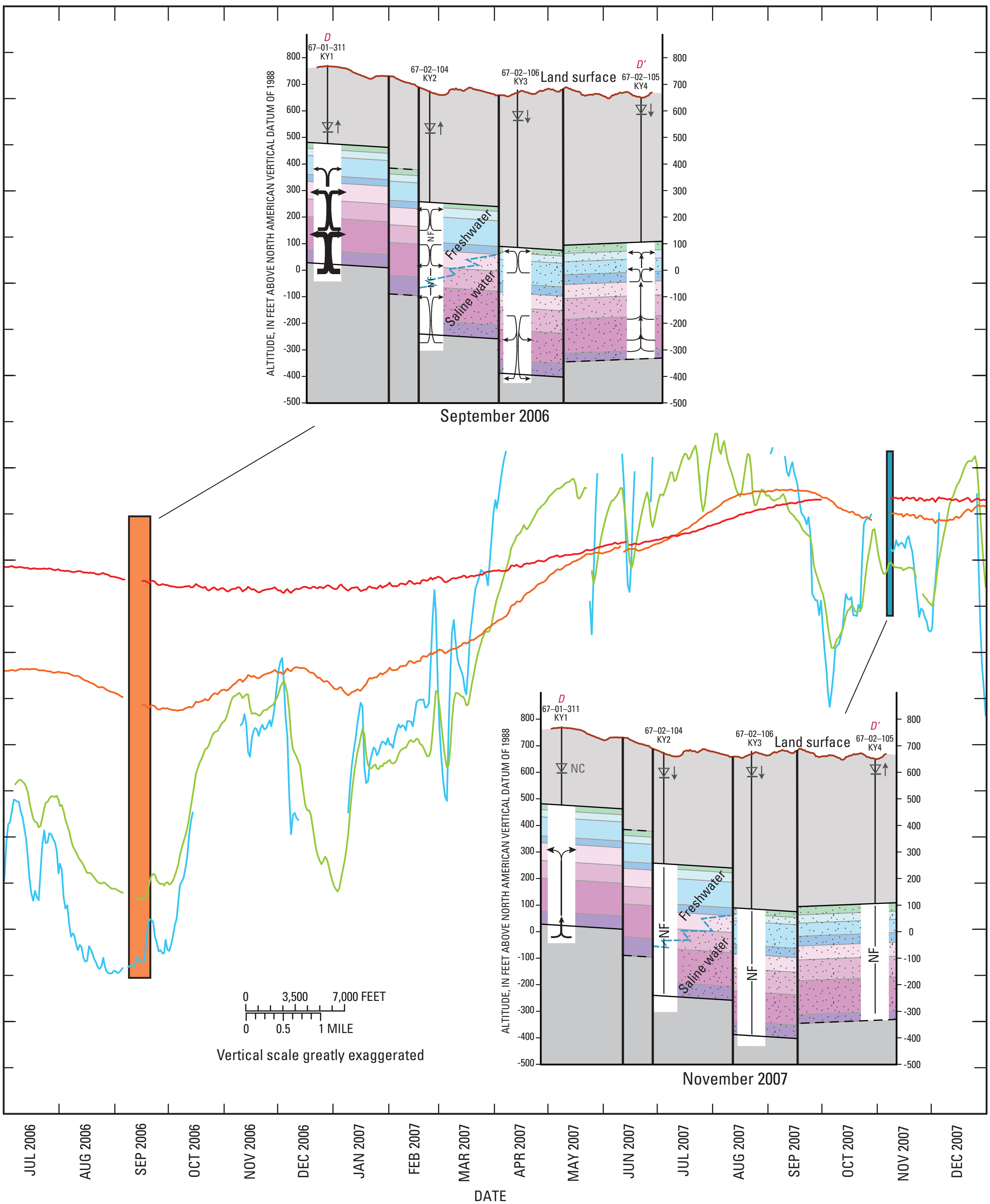


Figure 31. Conceptual diagram showing vertical flow in monitoring wells in the Kyle transect (*D–D′*), San Antonio segment of the



Edwards aquifer, south-central Texas, 2005–07.

Table 6. Temperature gradients in monitoring wells transecting the freshwater/saline-water transition zone, San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07.

[ft, feet; T1, temperature at first point; °C, degrees Celsius; D1, depth at first point; T2, temperature at second point; D2, depth at second point; m, meters]

Well identifier (fig. 1)	Date	Well descriptor based on water type	Depth of well (ft)	T1 (°C)	D1 (ft)	T2 (°C)	D2 (ft)	T2–T1 (°C)	D2–D1 (ft)	D2–D1 (m)	Temperature gradient (°C/100 ft)	Temperature gradient (°C/100 m)
EU1	11/6/2002	Freshwater	1,500	22.02	985	22.83	1,500	0.81	515	157	0.16	0.52
	4/25/2005	Freshwater	1,500	32.29	985	33.90	1,493	1.61	508	155	.32	1.04
	4/12/2006	Freshwater	1,500	32.28	985	34.14	1,491	1.86	506	154	.37	1.21
	9/26/2006	Freshwater	1,500	31.99	985	33.95	1,491	1.96	506	154	.39	1.27
	10/17/2007	Freshwater	1,500	30.30	985	32.25	1,491	1.95	506	154	.39	1.26
										Average	.32	1.06
EU2	11/6/2002	Freshwater	1,560	22.10	1,072	23.02	1,558	0.92	486	148	.19	.62
	4/11/2006	Freshwater	1,560	24.89	1,072	25.79	1,554	0.90	482	147	.19	.61
	9/28/2006	Freshwater	1,560	20.78	1,072	22.01	1,554	1.23	482	147	.26	.84
	10/16/2007	Freshwater	1,560	23.03	1,072	23.92	1,554	0.89	482	147	.18	.61
										Average	.20	.67
EU3	11/7/2002	Saline water	1,400	29.71	768	30.64	1,045	0.93	277	84	.34	1.10
	4/28/2005	Saline water	1,400	32.83	768	35.62	1,400	2.79	632	193	.44	1.45
	4/14/2006	Saline water	1,400	30.50	768	31.25	945	0.75	177	54	.42	1.39
	9/25/2006	Saline water	1,400	32.43	768	35.75	1,400	3.32	632	193	.53	1.72
	10/23/2007	Saline water	1,400	30.54	768	33.51	1,400	2.97	632	193	.47	1.54
										Average	.44	1.44
EU4	11/7/2002	Saline water	1,463	31.78	950	35.00	1,460	3.22	510	155	.63	2.07
	3/3/2005	Saline water	1,463	34.86	950	38.36	1,459	3.50	509	155	.69	2.26
	4/28/2005	Saline water	1,463	32.16	950	35.42	1,440	3.26	490	149	.66	2.18
	4/13/2006	Saline water	1,463	34.67	950	38.07	1,446	3.40	496	151	.69	2.25
	9/25/2006	Saline water	1,463	34.60	950	39.56	1,445	4.96	495	151	1.00	3.29
	10/18/2007	Saline water	1,463	32.64	950	36.13	1,445	3.49	495	151	.71	2.32
										Average	.73	2.39
TC1	1/27/2003	Freshwater	920	22.72	385	25.46	915	2.74	530	162	.52	1.69
	4/18/2005	Freshwater	920	25.33	385	28.17	896	2.84	511	156	.56	1.82
	4/21/2005	Freshwater	920	23.83	385	26.36	861	2.53	476	145	.53	1.74
	10/26/2005	Freshwater	920	25.55	385	28.65	868	3.10	483	147	.64	2.10
	6/23/2006	Freshwater	920	23.49	385	26.15	860	2.66	475	145	.56	1.84
	11/6/2006	Freshwater	920	21.73	385	25.55	861	3.82	476	145	.80	2.63
	10/29/2007	Freshwater	920	24.26	385	26.93	903	2.67	518	158	.52	1.69
										Average	.59	1.93
TC2	1/30/2003	Interface	1,050	23.90	486	27.49	1,036	3.59	550	168	.65	2.14
	5/17/2005	Interface	1,050	26.51	486	30.28	1,035	3.77	549	167	.69	2.26
	10/20/2005	Interface	1,050	26.86	486	31.03	1,030	4.17	544	166	.77	2.52
	11/2/2005	Interface	1,050	26.51	486	30.28	1,034	3.77	548	167	.69	2.26
	4/20/2006	Interface	1,050	26.75	486	30.42	1,038	3.67	552	168	.67	2.18
	11/21/2006	Interface	1,050	23.35	486	28.43	1,026	5.08	540	164	.94	3.09
	10/30/2007	Interface	1,050	25.48	486	28.93	1,038	3.45	552	168	.63	2.05
										Average	.72	2.36

Table 6. Temperature gradients in monitoring wells transecting the freshwater/saline-water transition zone, San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07—Continued.

Well identifier (fig. 1)	Date	Well descriptor based on water type	Depth of well (ft)	T1 (°C)	D1 (ft)	T2 (°C)	D2 (ft)	T2–T1 (°C)	D2–D1 (ft)	D2–D1 (m)	Temperature gradient (°C/100 ft)	Temperature gradient (°C/100 m)
TC2 - upper	1/30/2003	Interface	1,050	23.90	486	25.09	799	1.19	313	95	0.38	1.25
	5/17/2003	Interface	1,050	26.51	486	28.18	797	1.67	311	95	.54	1.76
	10/20/2005	Interface	1,050	26.86	486	28.82	800	1.96	314	96	.62	2.05
	11/2/2005	Interface	1,050	26.51	486	28.17	797	1.66	311	95	.53	1.75
	4/20/2006	Interface	1,050	26.75	486	28.75	801	2.00	315	96	.63	2.08
	11/21/2006	Interface	1,050	23.35	486	25.71	803	2.36	317	97	.74	2.44
	10/30/2007	Interface	1,050	25.48	486	26.84	804	1.36	318	97	.43	1.40
										Average	.55	1.82
TC2 - lower	1/30/2003	Interface	1,050	25.08	799	27.49	1,036	2.41	238	72	1.01	3.33
	5/17/2003	Interface	1,050	28.18	797	30.28	1,035	2.10	237	72	.89	2.90
	10/20/2005	Interface	1,050	28.82	800	31.03	1,030	2.21	229	70	.96	3.16
	11/2/2005	Interface	1,050	28.26	798	30.28	1,034	2.02	236	72	.86	2.81
	4/20/2006	Interface	1,050	28.75	801	30.42	1,038	1.67	237	72	.71	2.31
	11/21/2006	Interface	1,050	25.71	803	28.43	1,026	2.72	223	68	1.22	4.01
	10/20/2007	Interface	1,050	26.84	804	28.93	1,038	2.09	234	71	.89	2.93
										Average	.93	3.07
TC3	1/28/2003	Saline water	1,222	26.06	656	29.35	1,213	3.29	557	170	.59	1.94
	10/26/2005	Saline water	1,222	29.10	656	33.19	1,169	4.09	513	156	.80	2.62
	4/18/2006	Saline water	1,222	28.73	656	32.29	1,171	3.56	515	157	.69	2.27
	10/25/2006	Saline water	1,222	26.31	656	31.15	1,170	4.84	514	157	.94	3.09
										Average	.76	2.48
TC4	1/30/2003	Saline water	1,562	30.05	1,000	33.69	1,559	3.64	559	170	.65	2.14
	10/21/2005	Saline water	1,562	33.98	1,000	38.25	1,560	4.27	560	171	.76	2.50
	4/19/2006	Saline water	1,562	32.98	1,000	36.68	1,558	3.70	558	170	.66	2.17
	10/24/2006	Saline water	1,562	32.14	1,000	37.49	1,558	5.35	558	170	.96	3.15
										Average	.76	2.49
FH1	11/8/2002	Freshwater	280	21.61	216	21.72	277	0.11	61	19	.18	.59
	4/20/2005	Freshwater	280	24.06	216	24.12	255	0.06	39	12	.16	.51
	4/27/2006	Freshwater	280	24.30	216	24.43	267	.13	51	16	.25	.84
	9/21/2006	Freshwater	280	19.93	216	20.12	267	.19	51	16	.37	1.22
	10/24/2007	Freshwater	280	22.48	216	22.59	262	.11	46	14	.24	.78
										Average	.24	.79
FH2	11/8/2002	Saline water	1,030	24.61	510	28.34	1,025	3.73	515	157	.72	2.37
	4/19/2005	Saline water	1,030	27.32	510	31.08	998	3.76	488	149	.77	2.53
	5/2/2006	Saline water	1,030	26.93	510	31.14	988	4.21	478	146	.88	2.89
	9/20/2006	Saline water	1,030	24.14	510	29.59	989	5.45	479	146	1.14	3.74
	10/25/2007	Saline water	1,030	25.55	510	29.22	1,025	3.67	515	157	.71	2.34
										Average	.85	2.77

Table 6. Temperature gradients in monitoring wells transecting the freshwater/saline-water transition zone, San Antonio segment of the Edwards aquifer, south-central Texas, 2002–07—Continued.

Well identifier (fig. 1)	Date	Well descriptor based on water type	Depth of well (ft)	T1 (°C)	D1 (ft)	T2 (°C)	D2 (ft)	T2–T1 (°C)	D2–D1 (ft)	D2–D1 (m)	Temperature gradient (°C/100 ft)	Temperature gradient (°C/100 m)
KY1	11/5/2002	Freshwater	810	22.16	307	25.24	807	3.08	500	152	0.62	2.02
	3/1/2005	Freshwater	810	25.89	307	29.37	808	3.48	501	153	.69	2.28
	3/9/2005	Freshwater	810	24.78	307	27.07	810	2.29	503	153	.46	1.49
	5/3/2006	Freshwater	810	24.91	307	28.03	801	3.12	494	151	.63	2.07
	6/15/2006	Freshwater	810	22.66	307	25.66	789	3.00	482	147	.62	2.04
	9/6/2006	Freshwater	810	20.83	307	25.21	810	4.38	503	153	.87	2.86
	11/5/2007	Freshwater	810	23.58	307	26.67	810	3.09	503	153	.61	2.02
										Average	.64	2.11
KY2	1/31/2003	Interface	975	22.64	427	25.86	930	3.22	503	153	.64	2.10
	7/28/2003	Interface	975	22.97	427	26.23	931	3.26	504	153	.65	2.12
	1/10/2005	Interface	975	25.22	427	28.57	918	3.35	491	150	.68	2.24
	6/13/2006	Interface	975	21.64	427	26.13	931	4.49	504	154	.89	2.92
	9/12/2006	Interface	975	21.67	427	26.13	933	4.46	506	154	.88	2.89
	11/8/2007	Interface	975	24.17	427	27.31	933	3.14	506	154	.62	2.04
										Average	.73	2.39
KY2 - upper	1/31/2003	Interface	975	22.64	427	24.13	651	1.49	224	68	.66	2.18
	7/28/2003	Interface	975	22.97	427	24.82	704	1.85	277	84	.67	2.20
	1/10/2005	Interface	975	25.22	427	26.77	670	1.55	243	74	.64	2.10
	6/13/2006	Interface	975	21.64	427	24.11	707	2.47	280	85	.88	2.89
	9/12/2006	Interface	975	21.67	427	24.17	712	2.50	285	87	.88	2.87
	11/8/2007	Interface	975	24.17	427	26.20	745	2.03	318	97	.64	2.10
										Average	.73	2.39
KY2 - lower	1/31/2003	Interface	975	24.13	651	25.86	930	1.73	279	85	.62	2.03
	7/28/2003	Interface	975	24.82	704	26.23	931	1.41	227	69	.62	2.04
	1/10/2005	Interface	975	26.77	670	28.57	918	1.80	248	76	.73	2.38
	6/13/2006	Interface	975	24.11	707	26.13	931	2.02	224	68	.90	2.97
	9/12/2006	Interface	975	24.17	712	26.13	933	1.96	220	67	.89	2.92
	11/8/2007	Interface	975	26.20	745	27.31	933	1.11	188	57	.59	1.94
										Average	.72	2.38
KY3	11/4/2002	Saline water	1,100	24.00	600	26.8	1,094	2.80	494	151	.57	1.86
	5/18/2005	Saline water	1,100	26.20	600	29.39	1,067	3.19	467	142	.68	2.24
	6/29/2006	Saline water	1,100	23.28	600	27.33	1,066	4.05	466	142	.87	2.85
	9/13/2006	Saline water	1,100	22.24	600	27.24	1,059	5.00	459	140	1.09	3.57
	11/7/2007	Saline water	1,100	25.48	600	28.19	1,061	2.71	461	141	.59	1.93
										Average	.76	2.49
KY4	11/8/2002	Saline water	970	24.55	562	27.18	967	2.63	405	123	.65	2.13
	5/18/2005	Saline water	970	25.36	562	27.79	955	2.43	393	120	.62	2.03
	6/20/2006	Saline water	970	24.32	562	27.91	966	3.59	404	123	.89	2.92
	9/13/2006	Saline water	970	24.15	562	27.75	961	3.60	399	122	.90	2.96
	11/6/2007	Saline water	970	25.99	562	28.56	965	2.57	403	123	.64	2.09
										Average	.74	2.43

in the nine interface or saline-water wells, with one exception (well EU3), were greater than the conductive thermal gradient, indicating negligible groundwater flow on the saline-water side of the interface (transition zone) when the geophysical logs were run. If the freshwater (upper) and saline-water (lower) sections of the two interface wells (TC2 and KY2) are considered separately, the average temperature gradient in the upper section of well TC2, 1.82 °C/100 m, indicates active flow in the freshwater zone, and the average temperature gradient in the lower section of well TC2, 3.07 °C/100 m, indicates negligible flow in the transition zone. For well KY2, the average temperature gradient on both sides of the interface is essentially the same, 2.39 and 2.38 °C/100 m, and in the range indicating negligible flow. The findings regarding relative groundwater flow based on temperature, that flow on average is more active, or vigorous, on the freshwater side of the interface than on the saline-water side, are consistent with previous studies (for example, Maclay and Land, 1988; Lindgren and others, 2004) that indicate substantially more-sluggish flow (resulting from lower lateral permeability) in the transition zone than the freshwater zone.

Relation Between the Transition Zone and the Freshwater Zone

The freshwater zone and transition zone of the Edwards aquifer are connected by stratigraphy, structure, and hydraulics. Stratigraphic units, faults, and the groundwater flow system extend seamlessly at the interface. Thus, a hydraulic connection between the transition zone and the freshwater zone, as indicated by similar patterns of hydrographs of monitoring wells in the transition zone (transect interface and saline-water wells) and monitoring wells in the freshwater zone (transect freshwater wells and, for example, county index wells [fig. 2]) (fig. 32), would be expected. The hydrographs of the 15 transect monitoring wells and three county index wells generally show the same seasonal lows and seasonal highs in varying degrees in response to combinations of hydrologic stresses and withdrawals; for example, the low of summer 2000, the high of winter 2002–03, the high of winter 2004–spring 2005, the low of summer-fall 2006. The relative strength of the hydraulic connection among wells is assumed to be indicated by how closely hydrographs match one another (excluding hydrographs obviously influenced by withdrawals such as those for wells EU3 and EU4).

Except for the hydrograph of the Uvalde County index well (possibly because of structural complexity associated with the Uvalde salient [Clark, 2003]), the hydrographs of the monitoring well in each transect farthest from the interface into the transition zone (TC4, FH2, and KY4) are the most attenuated in response to hydrologic stresses (recharge, natural discharge, and withdrawals). The attenuated response to stresses is attributed to relatively low permeability in the transition zone (possibly aided by fault offset). This hypothesis of relatively low permeability in the transition zone relative to that in the freshwater zone is consistent with the findings regarding relative groundwater flow based on temperature, that flow on average is relatively vigorous on the freshwater side of the interface and relatively sluggish on the saline-water side.

The hydrographs of figure 32, showing equivalent freshwater heads decreasing from southwest to northeast, support the long-established understanding that regional flow in the freshwater zone is from southwest to northeast, generally parallel to the faulting (fig. 2) and the interface. Because of the indicated hydraulic connection between the transition zone and the freshwater zone, logic would suggest that regional flow in the transition zone, to the extent that it occurs assuming relatively low permeability, also is from southwest to northeast.

Assuming potential regional flow in the transition zone (however small relative to that in the freshwater zone) is most likely from southwest to northeast, for this to occur on average, water would enter the transition zone from the freshwater zone in the western part of the Edwards aquifer, flow toward the northeast, and discharge to the freshwater zone in the eastern part of the aquifer. Maclay (1995, p. 32) hypothesizes on the basis of geologic and hydrochemical information that, “A small flux of fresh groundwater enters the saline-water [transition] zone in the western part of the study area [San Antonio and Barton Springs segments of the Edwards aquifer];” and “In the eastern part of the [study] area, small flows from the saline-water zone of the aquifer might be entering the freshwater zone of the aquifer . . . .” Maclay (1995) does not explicitly note regional flow toward the northeast in the transition zone; however, Lindgren and others (2004, plates 5–7) graphically indicates simulated regional flow entering the transition zone from the freshwater zone in an area west of the East Uvalde transect, flowing toward the northeast in the transition zone, and converging on the interface in the area between Comal and San Marcos Springs (fig. 2) as the transition zone (in two dimensions) narrows greatly to funnel flow toward the area of the Kyle transect.

The data for this report in part support the conceptualization of regional flow in and near the transition zone thus described. At the East Uvalde transect, the direction of the lateral head gradient at the interface likely fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals, on the basis of the directions of the lateral gradient for coincident periods of head record during 2000–2007. The probable fluctuating gradient over time, or a gradient on average from the freshwater zone into the transition zone as Maclay (1995) and Lindgren and others (2004) have implied, could result in a net inflow of freshwater into the transition zone in the vicinity of the East Uvalde transect. At the Tri-County transect, equivalent freshwater heads generally were higher at the interface than on either side of it for coincident periods of head record during 2000–2007. Thus these data do not indicate a potential for lateral flow at the interface in the vicinity of the Tri-County transect, which is consistent with flow in the transition zone primarily parallel to the interface

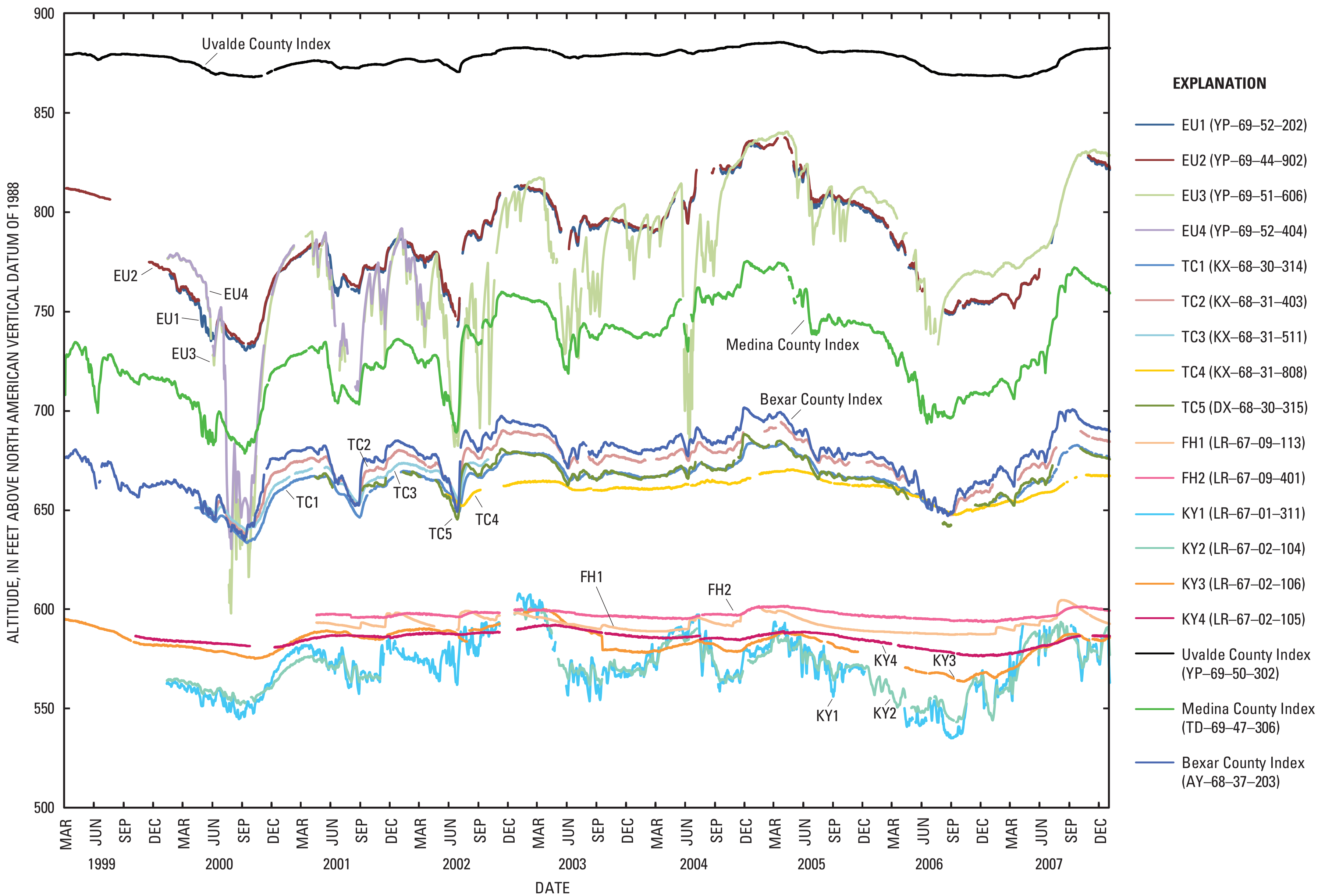


Figure 32. Daily mean equivalent freshwater head in monitoring wells of the East Uvalde, Tri-County, Fish Hatchery, and Kyle transects, and index wells of Uvalde County, Medina County, and Bexar County in the freshwater zone and the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 1999–2007.

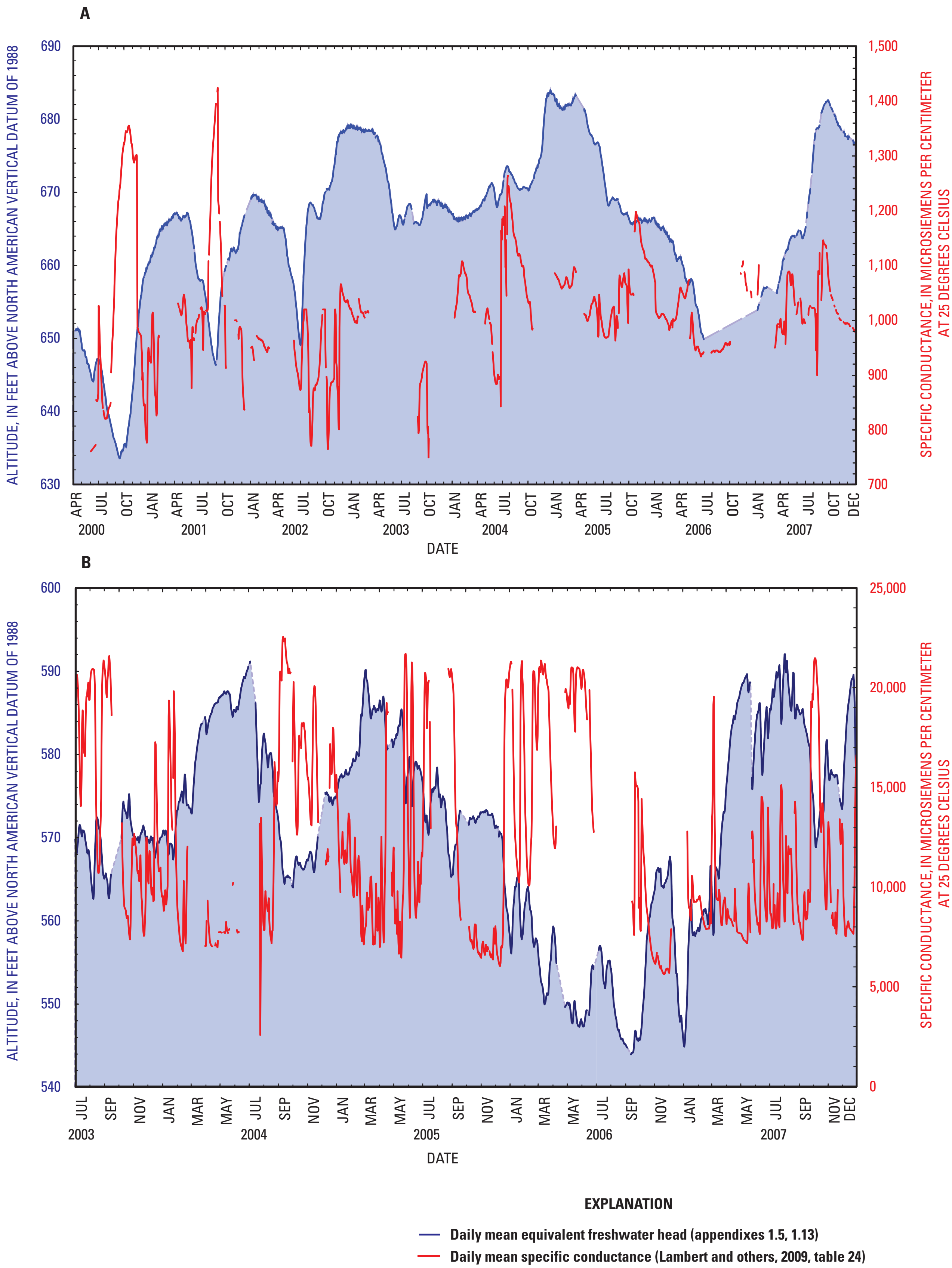


Figure 33. Specific conductance and equivalent freshwater head over time in wells (A) Tri-County 1 (2000–2007) and (B) Kyle 2 (2003–07).

(toward the northeast). As explained at the beginning of the “Lateral Head Gradients at the Interface” section, lateral gradients were not computed for the Fish Hatchery transect because the assumption of a horizontal aquifer, necessary for computation of accurate equivalent heads, was judged not applicable for the Fish Hatchery transect. At the Kyle transect, the direction of potential lateral flow at the interface, like that in the vicinity of the East Uvalde transect, probably fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals; but the prevailing direction at the interface on average in the vicinity of the Kyle transect, based on the directions of the lateral gradient for coincident periods of head record during 2000–2007, likely is from the transition zone into the freshwater zone. Another factor that might contribute to potential flow on average from the transition zone into the freshwater zone in the vicinity of the Kyle transect is the physical setting—the substantial narrowing of the transition zone. If flow from a relatively large volume (flow area) of aquifer is funneled into a relatively small volume of aquifer, then the potential for water to discharge from the small volume could become relatively greater.

The data for this report support the hypothesis that the interface, conceptualized as a sloping surface as indicated in figures 5–8, is likely to remain stable laterally and vertically over time. The most direct evidence in support of that hypothesis is the conductivity data from interface wells TC2 and KY2 that show an essentially stable vertical interface position (depth in the borehole) over a range of hydrologic conditions. At well TC2, the interface position was essentially unchanged as equivalent freshwater heads differed by as much as about 25 feet among the times geophysical logs were run (fig. 15). At well KY2, the interface position varied over a range of roughly 50 feet as equivalent freshwater heads differed by as much as 35 feet; 50 feet of variation is considered “stable” relative to a regional scale of miles. At the Fish Hatchery transect, the interface (again assuming a sloping configuration) was contained between wells FH1 and FH2, spaced 1.8 miles apart, throughout the range of hydrologic conditions that occurred at the times geophysical logs were run, despite an upward gradient (indicated by upward borehole flow) on the saline-water side of the interface (well FH2) during each log run.

A stable interface over time does not necessarily mean no flow from the transition zone into the freshwater zone. Continuous specific conductance recorded by monitors installed at depths of 700–800 feet below land surface in wells TC1 and KY2 (Lambert and others, 2009, table 24) indicates variability over time (fig. 33). Although generally no clear relations between conductivity (or temperature or borehole flow) and equivalent freshwater head at the times geophysical logs were run could be identified, the graphs of specific conductance and equivalent freshwater head over time in wells TC1 (2000–2007) and KY2 (2003–07) show inverse relations. During the periods of record, specific conductance (microsiemens per centimeter at 25 °C) varied over a range of several hundred in freshwater well TC1 and several thousand in interface well KY2. (The conductance monitor was on the saline-water side of the interface in well KY2). Specific conductance generally increased when equivalent freshwater head decreased, indicating movement of more-saline water toward the freshwater zone, but then specific conductance generally decreased when heads rose again. The relation indicates that more-saline water that moved toward or entered the freshwater zone during dry conditions was diluted and “washed away” by freshwater flow when wet conditions returned. From a regional perspective considering the hypothesis of relatively low permeability in the transition zone relative to that in the freshwater zone, it follows that the relatively low-permeability rocks of the transition zone allow relatively little flow toward the freshwater zone, even if gradients toward the freshwater zone are relatively large and that the relatively high-permeability rocks of the freshwater zone allow relatively large flows that are easily capable of diluting and washing away any encroaching saline water, even if gradients in the freshwater zone are relatively small. Further, in the vicinity of the Kyle transect, any upward flow of freshwater from the Trinity aquifer, for which the potential is indicated by relatively strong upward borehole flows in well KY1 and to a lesser extent in well KY2, would tend to contribute to the dilution of any saline water leaking into the freshwater zone in that area.

No single line of evidence confirms the hypothesis that the interface in the San Antonio segment of the Edwards aquifer is relatively stable over time, and thus the potential for irreversible movement of saline water into the freshwater zone is small; but the cumulative evidence from the water-level (head) and borehole geophysical log data supports that hypothesis.

Summary

The freshwater zone of the San Antonio segment of the Edwards aquifer in south-central Texas (hereinafter, the Edwards aquifer) is bounded to the south and southeast by a zone of transition from freshwater to saline water (hereinafter, the transition zone). Freshwater is defined here as that containing less than 1,000 mg/L dissolved solids concentration; slightly saline water, that containing 1,000 to 3,000 mg/L dissolved solids concentration; moderately saline water, that containing 3,000 to 10,000 mg/L dissolved solids concentration; and very saline water, that containing 10,000 to 35,000 mg/L dissolved solids concentration. The freshwater/saline-water interface (hereinafter, the interface) is the 1,000-mg/L dissolved solids concentration threshold. The transition zone is defined here as the region of the aquifer with dissolved solids concentrations ranging from 1,000 to 10,000 mg/L.

This report presents the findings of a study, done by the U.S. Geological Survey in cooperation with the San Antonio Water System, to obtain lithologic properties (rock properties associated with known stratigraphic units) and physicochemical properties (fluid conductivity and temperature) and to analyze the hydraulics of flow in and near 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; and on the basis of findings, assesses the potential for irreversible movement of saline water into the freshwater zone of the Edwards aquifer. Monitoring wells from which data were collected for this report are in and near the transition zone in Uvalde County (East Uvalde [EU] transect, four wells), in Comal and Guadalupe Counties (Tri-County [TC] transect, five wells), and in Hays County (Fish Hatchery [FH] transect, two wells; and Kyle [KY] transect, four wells). 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]).

Water-level data were collected to obtain head distribution over time as an indicator of hydrologic conditions. Daily mean water levels from continuously measured hydraulic heads in monitoring wells of the transects were converted to equivalent freshwater heads so that accurate lateral head gradients between the transition zone and the freshwater zone could be computed.

Geophysical log data were collected using conventional methods (caliper, gamma, resistivity, induction, fluid conductivity, and fluid temperature) and advanced methods (borehole televiewer imaging tools and electromagnetic and heat-pulse vertical flowmeters). These tools were used to obtain lithologic properties from which stratigraphic units of the aquifer could be identified (the tops of the stratigraphic units penetrated were picked from drillers' logs but were refined by the geophysical logs) and to obtain vertical flow (magnitude and direction under ambient conditions) relative to the stratigraphic units in each well. The directions of vertical flow indicated the directions of vertical gradients at each well.

The natural gamma logs for East Uvalde freshwater wells EU1 and EU2, completed in the reefal facies of the Devils River Trend depositional province, indicate carbonate rocks with a lack of contrast in the upper sections of the boreholes and increasing clayey material in the lower sections of the boreholes. In contrast, the gamma logs for saline-water wells EU3 and EU4 show greater variation in lithology down the boreholes than that in either wells EU1 or EU2, indicating that more clayey intervals corresponding to the McKnight Formation and the West Nueces Formation of the Maverick Basin depositional province are interbedded with carbonate rocks. The natural gamma logs for Tri-County freshwater well TC1, interface well TC2, and saline-water wells TC3 and TC4 indicate that Edwards aquifer rocks 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. The natural gamma logs for Fish Hatchery freshwater well FH1 and saline-water well FH2 (both wells completed in rocks of the San Marcos Platform depositional province) indicate that the borehole sections are composed of fairly clean limestone interbedded with clayey lenses. For well FH2 (deeper of the two), 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. The natural gamma logs for Kyle transect freshwater well KY1, interface well KY2, and saline-water wells KY3 and KY4 indicate that the wells are open to clean limestone with some clayey intervals in the cyclic and marine members and the leached and collapsed members in the upper part of the Edwards aquifer, and in the dolomitic and basal nodular members in the lower part of the Edwards aquifer. Wells KY1, KY2, and KY3 also are open to the Glen Rose Limestone (Trinity aquifer) at the base of the wells. The gamma logs for these wells indicate that the Glen Rose Limestone has greater clay content than the formations of the overlying Edwards aquifer.

Fluid conductivities recorded in East Uvalde transect wells EU1 and EU2 indicate freshwater down the entire lengths of the boreholes. Fluid conductivities recorded in well EU3 indicate saline water in the borehole. Well EU4 contained saline water during four of six log runs, but for one of the runs, salinity was entirely in the freshwater range and for another was in the fresh and slightly saline ranges. The seven conductivity logs for Tri-County transect well TC1 indicate freshwater. On the basis of fluid conductivity, well TC2 intersected the interface at or slightly above the contact between the Kirschberg evaporite member and the dolomitic member. Above that contact, freshwater was in the borehole during all log runs, and below it, saline water was in the borehole. Neither borehole flow nor changes in head between the times the logs were run affected the position of the interface, which is essentially the same on all logs. The fluid conductivity logs for wells TC3 and TC4 indicate saline water along the entire lengths of the boreholes for all log runs; the ranges of values reflected among the logs varied widely (slightly saline to very saline). The fluid conductivity logs run in Fish Hatchery well FH1 all indicate freshwater in the borehole. The fluid conductivity logs for well FH2 indicate saline water, ranging from slightly saline to very saline. Fluid conductivity logs for Kyle transect well KY1 indicate freshwater throughout the borehole during all log runs. Fresher water near the bottom of the borehole is indicated on each of the logs. This fresher water appears to be in the Glen Rose Limestone (Trinity aquifer). Well KY2 is the second of two wells of this report that intersects the interface. Fluid conductivity logs show that the interface intersected the borehole in the Kirschberg evaporite member and upper part of the dolomitic member. The range in salinity of water between the upper and lower sections of the KY2 borehole indicated by most of the logs is large—from fresh to very saline. Unlike in interface well TC2, the position of the interface in the KY2 borehole changed about 50 feet over time. Although the position of the interface bears some relation to head at the time the logs were run, the conductivity values below the interface do not. Fluid conductivity logs run in wells KY3 and KY4 indicate that water in the boreholes at the times of the log runs was moderately to very saline. No identifiable relation between conductivity values from logs in monitoring wells in all transects and heads in the wells at the times the logs were run is evident; and no identifiable relation between conductivity values and vertical flow in the boreholes concurrent with the times the logs were run is evident.

The temperature logs for wells of the East Uvalde transect indicate temperatures ranged from about 20 °C (well EU2) to about 40 °C (well EU4); for the Tri-County transect, about 21 °C (well TC1) to about 39 °C (well TC4); for the Fish Hatchery transect, about 18 °C (well FH1) to about 32 °C (well FH2); and for the Kyle transect, about 20 °C (well KY1) to about 30 °C (well KY4). Temperatures increased with depth in all the logs.

The directions of the lateral equivalent freshwater head gradient at the interface in the East Uvalde transect for 19 coincident periods of head record for 2000–2007 indicate a nearly even split between into the freshwater zone (nine) and out of the freshwater zone (10). The directions of the lateral gradient at the interface are affected to a greater or lesser degree by hydrologic conditions (antecedent and concurrent recharge) and relatively greater and smaller withdrawals. The direction of the equivalent freshwater head gradient and thus the potential lateral flow at the interface in the vicinity of the East Uvalde transect fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals. Whether the prevailing direction on average is into or out of the freshwater zone is not clearly indicated.

The directions of the lateral head gradient at the interface in the Tri-County transect were mixed (head higher at the interface than on either side) in 25 of 30 coincident periods of record for 2000–2007, into the freshwater zone in one period, and uncertain in four periods. Why equivalent freshwater heads generally were higher at the interface than on either side of it cannot be explained with available data. There does not appear to have been a prevailing direction of the lateral gradient at the interface in the vicinity of the Tri-County transect.

The directions of lateral head gradient at the interface in the Kyle transect for 42 coincident periods of record for 2000–2007 were into the freshwater zone for about one-half the periods (22), mixed for one-third of the periods (14), out of the freshwater zone for three periods, and uncertain for three. The direction of the lateral gradient at the interface in the vicinity of the Kyle transect, like that in the vicinity of the East Uvalde transect, probably fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals; but the prevailing direction on average of the lateral gradient and thus potential lateral flow at the interface in the vicinity of the Kyle transect likely is from the transition zone into the freshwater zone.

The direction of vertical flow in all four East Uvalde transect wells with measurable flow was mostly upward, and magnitude of flow generally was greater when equivalent freshwater heads were high than when they were low. Equivalent freshwater heads at the times of each of the four flow logs, whether relatively high or relatively low, were higher on the saline-water side of the interface than on the freshwater side. The hypothesis regarding the vertical gradient in the vicinity of the East Uvalde transect, and thus the potential for vertical flow near an interface conceptualized as a surface sloping upward in the direction of the dip of the stratigraphic units, is that the potential for vertical flow fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals.

At all four times the flow logs were run in Tri-County transect wells, which encompassed a range of hydrologic conditions from wet to dry for the period of record (2000–2007), the interface was essentially in the same position in well TC2, below the regional dense member about at the contact between the grainstone member and the Kirschberg evaporite member; some combination of head gradient and permeability (each with lateral and vertical components) was functioning to keep the interface stable as heads changed. A downward gradient on the freshwater side of the interface and an upward gradient on the saline-water side are evidence of opposing potentials that appear to have stabilized the position of the interface over the range of hydrologic conditions that occurred at the times the logs were run.

Vertical flows in the borehole of Fish Hatchery transect well FH2 were upward whether hydrologic conditions were wet or dry. There appears to have been an upward gradient on the saline-water side of the interface under a wide range of hydrologic conditions. This upward gradient, coupled with the assumption of a sloping interface, implies a vertical gradient from the transition zone into freshwater zone. This potential for vertical movement of saline water into the freshwater zone (vertical movement of the interface) apparently was opposed by the potential (head) on the freshwater side of the interface that kept the interface beneath the bottom of well FH1 over the range of hydrologic conditions during which the logs were run.

The five flow logs for Kyle transect freshwater well KY1 all indicate upward flow ranging from less than 0.1 to nearly 4 gallons per minute that originates from the Glen Rose Limestone, the uppermost unit of the Trinity aquifer; and one log for well KY2 shows upward flow of 0.3–0.4 gallon per minute entering the borehole from the Trinity aquifer. These flow data constitute evidence of the potential for flow from the Trinity aquifer into the Edwards aquifer in the vicinity of the Kyle transect.

Subsurface temperature data were used to indicate zones of negligible groundwater flow (temperature [thermal] gradients greater than or equal to the conductive thermal gradient) and zones of active groundwater flow (temperature gradients less than the conductive thermal gradient or the absence of a temperature gradient). The findings regarding relative groundwater flow based on temperature indicate that flow on average is more active, or vigorous, on the freshwater side of the interface than on the saline-water side.

The freshwater zone and transition zone of the Edwards aquifer are connected by stratigraphy, structure, and hydraulics. A hydraulic connection between the transition zone and the freshwater zone is indicated by similar patterns in the hydrographs of the 15 transect monitoring wells in and near the transition zone and three county index wells in the freshwater zone during 1999–2007.

The data for this report in part support a conceptualization of regional flow in and near the transition zone in which water enters the transition zone from the freshwater zone in the western part of the Edwards aquifer, flows toward the northeast, and discharges to the freshwater zone in the eastern part of the aquifer. The probable fluctuating head gradient over time at the interface in the East Uvalde transect, or a gradient on average from the freshwater zone into the transition zone as previous studies have implied, could result in a net inflow of freshwater into the transition zone in the vicinity of the East Uvalde transect. Head data do not indicate a potential for lateral flow at the interface in the vicinity of the Tri-County transect, which is consistent with flow in the transition zone primarily parallel to the interface (toward the northeast). The head gradient at the interface in the Kyle transect also probably fluctuates between into and out of the freshwater zone, depending on recharge and withdrawals, but the prevailing direction at the interface on average likely is from the transition zone into the freshwater zone.

The data for this report support the hypothesis that the interface is likely to remain stable laterally and vertically over time. The most direct evidence in support of that hypothesis is the conductivity data from interface wells TC2 and KY2 that show an essentially stable vertical interface position (depth in the borehole) over a range of hydrologic conditions. Continuous specific conductance and concurrent head data show that when more-saline water moved toward or entered the freshwater zone during dry conditions, it was diluted and "washed away" by freshwater flow when wet conditions returned. The hypothesis is that relatively low-permeability rocks of the transition zone allow relatively little flow toward the freshwater zone, even if gradients toward the freshwater zone are relatively large and that relatively high-permeability rocks of the freshwater zone allow relatively large flows that are easily capable of diluting and washing away any encroaching saline water, even if gradients in the freshwater zone are relatively small. No single line of evidence confirms the hypothesis that the interface in the San Antonio segment of the Edwards aquifer is relatively stable over time, and thus the potential for irreversible movement of saline water into the freshwater zone is small; but the cumulative evidence from the water-level (head) and borehole geophysical log data supports that hypothesis.

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