SwRI Project No. 20-14152

MEASURING FLOODPLAIN HYDRAULICS OF THE FRIO RIVER WHERE IT OVERLIES THE EDWARDS AQUIFER

Final Report

Prepared for

Edwards Aquifer Authority

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EXECUTIVE SUMMARY

The county of Uvalde hosts significant groundwater resources in a number of alluvial and consolidated rock aquifers. The most significant of these aquifers is the Edwards Aquifer which spans the central portion of the county from its western to eastern boundaries. Effective management of the Edwards Aquifer requires that the water budget be quantified. To calculate the water budget within acceptable limits, recharge and discharge of the aquifer must be adequately characterized. During the past decade, the Edwards Aquifer Authority has systematically reduced uncertainty in the calculation of the recharge and discharge of the Edwards Aquifer. Actions taken to advance this effort include defining the aquifer boundary conditions, identifying the aquifer permeability architecture, and quantifying recharge and discharge. The Edwards Aquifer Authority commissioned this investigation to characterize the hydraulic relationship between the Frio and Dry Frio River system and the Edwards Aquifer to better understand the hydrogeology of the Edwards Aquifer in Uvalde County and to reduce uncertainty in water budget calculations.

This report summarizes the results of the investigation of the hydraulic relationship between Frio and Dry Frio Rivers and the subsurface as it defines the recharge and discharge of the Edwards Aquifer. This project was performed by the Geosciences and Engineering Division of Southwest Research Institute® for the Edwards Aquifer Authority. Geologic structure, subsurface imaging, groundwater and surface water elevations, and water quality of the Frio and Dry Frio Rivers and environs were examined to evaluate the hydraulic relationship between the Frio and Dry Frio River system and the Edwards Aquifer. Of interest are four waterholes in the Frio River south of the confluence with the Dry Frio River. Surface water persists in all four waterholes even during periods of limited precipitation, such as late 2008 and early 2009. The source of water for the waterholes is not known. Two potential sources are either underflow via the Frio and Dry Frio River floodplains or springflow from depth. If the source is floodplain underflow, then surface water gauging of river flow in the Frio and Dry Frio Rivers would not accurately represent the true rate of recharge of the Edwards and related aquifers by recharge in the river channels.

Geophysical imaging of the subsurface of the floodplains of the Dry Frio River and the Frio River upstream and downstream of the confluence with the Dry Frio River did not detect evidence of significant subsurface flow through either paleo-channel deposits or preferential flow pathways developed in the bedrock. This evidence indicates that there are neither paleo-stream channel deposits nor preferential flowpaths available to convey significant floodplain underflow.

Examination of water quality analyses from the four Frio River waterholes and several nearby wells indicates multiple source(s) of water in the waterholes. The water compositions likely result from a mix of fresh water input from rainfall and river flow events, upward leakage of relatively saline water from the Edwards Aquifer or the Austin Chalk (or both), and loss of CO_2(g) and precipitation of calcite during equilibration with the atmosphere. Additional data, in particular analyses of stable isotopes for the waterholes and surrounding wells, would assist in constraining geochemical modeling that may identify the sources and evolution of the waterholes' chemistry.

Surface and groundwater elevations suggest that the Buda and Edwards Aquifers and the three southern waterholes are hydraulically connected. Black Waterhole North is perceived to be hydraulically connected to the Austin Chalk Aquifer, but neither the Austin Chalk Aquifer nor Black Waterhole North appear to be in hydraulic communication with the Edwards Aquifer. However, there are insufficient water elevation measurements to be conclusive.

In summary, the Frio and Dry Frio Rivers are interpreted to be hydraulically connected with the Edwards Aquifer in the Edwards Aquifer recharge zone. Both rivers exit the recharge zone about six miles north of the City of Knippa. There is no evidence of underflow in the Frio and Dry Frio River floodplains. This indicates that surface water flow gauging, if performed immediately before and after the rivers enter and exit the recharge zone, should accurately represent the amount of water recharged to the Edwards Aquifer. Supporting this conceptualization is that the source water for all four waterholes is interpreted to be from depth as springs and that there is no evidence of floodplain underflow.

1. INTRODUCTION

Uvalde County, Texas hosts significant groundwater resources in a number of alluvial and consolidated rock aquifers. The most significant of these aquifers is the Edwards Aquifer which spans the central portion of the county from its western to eastern boundaries. As much as 40 percent of the recharge of the San Antonio segment of the Edwards Aquifer has been attributed to recharge that occurs in Uvalde County (Hamilton et al., 2008). Sources of recharge to the Edwards Aquifer typically consist of precipitation on the recharge zone (i.e., autogenic recharge), surface water focused in river and stream beds (i.e., allogenic recharge), and as subsurface interformational flow from upstream aquifers. Discharge occurs by spring flow, pumping, and interformational flow to downstream aquifers. Effective management of the Edwards Aquifer requires that the water budget be adequately quantified. To calculate the water budget within acceptable limits, recharge and discharge of the aquifer must be adequately characterized.

During the past decade, the Edwards Aquifer Authority has systematically reduced uncertainty in the calculation of the recharge and discharge of the Edwards Aquifer. Actions taken to advance this effort include defining the aquifer boundary conditions, identifying the aquifer permeability architecture, and quantifying recharge and discharge. The Edwards Aquifer Authority commissioned this investigation to characterize the hydraulic relationship between the Frio and Dry Frio River system and the Edwards Aquifer to better understand the hydrogeology of the Edwards Aquifer in Uvalde County and to reduce uncertainty in water budget calculations (Figure 1).

This report summarizes the investigation of the hydraulic relationship between Frio and Dry Frio Rivers and the subsurface as it affects the recharge and discharge of the Edwards Aquifer. This project was performed by the Geosciences and Engineering Division of Southwest Research Institute® (SwRI®) for the Edwards Aquifer Authority. The project considered studies of the hydrogeology of Uvalde County performed in the last several years, with particular emphasis on investigations of the hydraulic significance of the Leona and Nueces Rivers and Elm and Turkey creeks with regard to regional and local aquifers (Green et al., 2006, 2008a,b). These recent studies were of interest because they provide direct evidence of the hydraulics and the hyporheic exchange of rivers, floodplain sediments, and subsurface flows of these rivers and streams as they cross the Edwards Aquifer.

1.1. Technical Approach

Interpretation of the hydraulic relationship between the Frio River and the Edwards Aquifer was performed by: (i) characterization of the morphology of the floodplain of the Frio and Dry Frio Rivers where they exit the Edwards Aquifer recharge zone, (ii) imaging the subsurface of this floodplain using a geophysical survey, (iii) characterization of the hydraulic properties of the floodplain and the Edwards Aquifer using existing information, a survey of local wells, and a hydrogeological assessment of any other relevant information that could contribute to the project, (iv) sampling and evaluation of water chemistry to discern potential water sources and flow regimes, and

(v) assessment of the volumetric surface water and groundwater flow in terms of floodplain hydraulics and discharge from the Edwards Aquifer.

1.2. Geological Setting

Uvalde County is served by several regional and local aquifer systems. Geologic structure, depositional environments of the geologic formations, and groundwater elevations define the presence, extents, and hydraulic relationships of these aquifer systems. Aquifers occur in formations from lower Cretaceous limestones (Trinity Aquifer) to Quaternary alluvium (Leona Formation). The Edwards Aquifer is the primary aquifer in Uvalde County. Significant secondary aquifers include the Trinity, Buda Limestone, Austin Chalk Formation, and Leona Formation. Incidental secondary aquifers, those whose extent are limited even on a local scale, include the Escondido Formation, Anacacho Limestone, and igneous rock units (Figure 2).

The Edwards Aquifer in Uvalde County is composed of Lower Cretaceous carbonate (mostly dolomitic limestone) strata (Figure 2). The Edwards Aquifer overlies the (Lower Cretaceous) Glen Rose Limestone, which comprises the lower confining unit of the Edwards Aquifer and is overlain by the (Upper Cretaceous) Del Rio Clay, the basal formation of the upper confining unit. The Buda Limestone and the Austin Chalk are secondary aquifers in Uvalde County that overlie the Edwards Aquifer. The Upper Cretaceous Anacacho Limestone and Escondido Formation overlie the Austin Chalk in southern Uvalde County. Upper Cretaceous and (or) Lower Tertiary igneous rocks intrude all stratigraphic units that compose the Edwards Aquifer, particularly in southern Uvalde County (Clark, 2003). Most wells in unconsolidated sediments in Uvalde County are in the gravels of the Leona Formation in the Leona River floodplain. A limited number of additional wells in unconsolidated sediments are found along other rivers and streams, such as the Nueces River and Indian Creek.

A facies change in the Edwards Group, the Balcones Fault Zone, the Uvalde Salient, and the prevalence and location of igneous intrusions are the principal geological features that characterize the structural and hydraulic relationships among these aquifers. The cumulative effect of these geologic features is to impede the eastward flow of groundwater in the Edwards Aquifer in central Uvalde County. This impediment is referred to as the Knippa Gap (Maclay and Land, 1988).

The Edwards Group transitions from the Maverick Basin in the western half of Uvalde County to the Devils River Trend in the eastern half. The facies transition occurs close to the trace of the Frio and Dry Frio Rivers. Maverick Basin rocks are divided into the basal nodular unit of the West Nueces Formation; the lower, middle, and upper units of the McKnight Formation; and the lower and upper units of the Salmon Peak Formation. The Devils River Trend is composed of a basal nodular unit and the overlying undifferentiated rocks of the Devils River Formation (Clark, 2003). The Salmon Peak Formation of the Maverick Basin and the upper part of the Devils River Formation comprise the most porous and permeable rocks in Uvalde County. The McKnight and West Nueces Formations of the Maverick Basin and the lower section of the Devils River

Formation are less permeable and are not typically found to be significant sources of groundwater (Maclay, 1995; Clark 2003).

1.3. Relationship between the Uvalde Salient and the Edwards Aquifer

The Balcones Fault Zone is manifested by a large number of faults in the vicinity of the City of Uvalde with relatively small down-to-the-southeast displacements, together with several faults antithetic to the main trend (i.e., down-to-the-northwest displacement). To the northeast of the City of Uvalde, a smaller number of faults, one with a throw of 200 feet, accomplish the same amount of total displacement. The geological formations and the systematic displacements associated with the Balcones Fault Zone are disrupted in central Uvalde County along a structural uplift referred to as the Uvalde Salient (Welder and Reeves, 1962; Rives, 1967; Clark and Small, 1997; Clark, 2003). This structural high has the general shape of a ridge that is widest near Cook's Fault to the north and narrows and plunges to the south (Figure 3)(Green et al., 2006). The north-south oriented Uvalde Salient is located immediately east of the City of Uvalde and is interpreted to have formed contemporaneously with magmatic intrusions and extrusions of late Cretaceous age (Clark and Small, 1997). Dates are based on an 40Ar/39Ar geochronologic study (Miggins and others, 2004) that showed at least two distinct phases of magmatic activity in Uvalde County. The first phase of intrusive activity occurred approximately 82–80 m.y. ago and a younger phase of intrusive rocks (phonolites) was emplaced 74–72 m.y. ago. The geologic structure was subsequently disrupted by the Miocene age Balcones Zone faulting (Abbott, 1974; Maclay and Land, 1988).

The effect of the Uvalde Salient on geology in Uvalde County is illustrated in Figure 4. The top of Figure 4 provides a generalized geologic schematic of Uvalde County in the absence of the uplift associated with the Uvalde Salient, but with uniform normal faulting and down-to-the-southeast displacements. The middle of Figure 4 presents a similar schematic, but with the effect of uplift on geologic structure caused by the Uvalde Salient. In this schematic, the Uvalde Salient has the effect of exposing the geologic units at and south of the Uvalde Salient that otherwise would have been buried in the subsurface. The bottom of Figure 4 provides a final image that superimposes locations of the faults of Balcones Fault Zone onto the previous schematic. The magnitude of fault displacement is displayed as the thickness of lines. As illustrated, the greatest fault displacement is centered over the Uvalde Salient. The actual geologic structure near the Uvalde Salient is more complicated than suggested in Figure 4; however, the general structural trend illustrated in this schematic is apparent in the complicated geologic setting of Uvalde County (Clark and Small, 1997; Clark, 2003; Green et al., 2006).

The Uvalde Salient is mostly located to the west of the transition of the Maverick Basin facies to the Devil's River Trend facies of the Edwards Aquifer (Figures 3 and 4). Thus, that portion of the Edwards Aquifer to the west of the Uvalde Salient is composed of the Salmon Peak, McKnight, and West Nueces Formations. Of these formations, only the upper Salmon Peak Formation is considered a significant aquifer (Maclay, 1995; Clark, 2003). There are portions of the Edwards Aquifer within the Uvalde Salient that have been sufficiently uplifted that the Salmon Peak has either been partially eroded, raised above the water table, or both, thereby significantly reducing the saturated thickness of the transmissive portion of the Edwards Aquifer and impeding the flow of groundwater from west to east across the Uvalde Salient. The transmissivity (i.e., the product of the hydraulic conductivity times its saturated thickness) of the Edwards Aquifer increases to the east of the Uvalde Salient mostly due to the lower elevation of the base of the Edwards Aquifer, which increases the saturated thickness of the permeable portion of the Devils River Formation (Green et al., 2006). As a result of this increased transmissivity, the hydraulic gradient to the east of the Uvalde Salient in the Devils River Formation is much less than the hydraulic gradient across the Uvalde Salient (Figure 5).

1.4. Igneous Intrusions

There are numerous igneous intrusions mapped in southern Uvalde County (Clark, 2003). The presence of additional igneous intrusions near Uvalde with no surface expression has been inferred using results of an aeromagnetic survey (Smith et al., 2002, 2008). Magnetic surveys are an effective tool to identify the location and extent of igneous intrusions in Uvalde County due to the strong magnetic signature of the intrusions relative to the weak magnetic signature of the Cretaceous limestone formations. For this reason, the map of the magnetic field intensity clearly illustrates the location and extent of the igneous intrusions regardless of whether a surface expression of an intrusion is evident (Figure 6). Although the aeromagnetic survey (Smith et al., 2002, 2008) did not cover all of southern and western Uvalde County, the magnetic map does include the northern half of the Uvalde Salient. As illustrated, there is a higher density of intrusions at the boundaries of the Uvalde Salient relative to the main body of the Salient. The highest density of igneous intrusions is immediately east of the Uvalde Salient and extends east to the city of Knippa. This high density of intrusions is coincident with an area of limited groundwater availability in both the Edwards and secondary aquifers.

1.5. Analysis of Subsurface Flow in the Frio River Floodplain

The Edwards Aquifer Authority publishes a document of annual recharge assessments made by the U.S. Geological Survey for the major watersheds in the Edwards Aquifer recharge zone. The Frio and Dry Frio Rivers traverse a long reach through the Edwards Aquifer recharge zone (Figure 1). Recharge of the Edwards Aquifer via the Frio River and Dry Frio River basin is estimated using loss/gain river flow measurements (Hamilton et al., 2008). The median annual recharge to the Edwards Aquifer for the period 1934 to 2007 is estimated to be 125,100 acre-ft for the Frio River and Dry Frio River basin. The recharge estimates published in Hamilton et al. (2008) assume that river gauge measurements accurately reflect the amount of recharge that enters the Edwards Aquifer along reaches of the Frio and Dry Frio Rivers that cross the recharge zone. The accuracy of this recharge calculation is also predicated on the assumption that little or no subsurface flow occurs in the Frio River and Dry Frio River floodplains where the rivers exit the recharge zone. Assessments of other rivers and streams in Uvalde County indicate subsurface flood plain flow may be significant (Green et al, 2006, 2008a,b).

The potential for subsurface flow in the Frio River floodplain is suggested by the presence of perennial waterholes in the Frio River south of the Edwards Aquifer recharge zone. Uncertainty in estimates of recharge in the Frio and Dry Frio Rivers can be reduced by determining whether the waterholes are expressions of subsurface flow in the Frio and Dry Frio River floodplains or points of discharge from depth (i.e., springs).

The confluence of the Frio and Dry Frio Rivers is about seven miles south of the Edwards Aquifer recharge zone near the city of Knippa. From there, the Frio River continues to the south for an additional five miles then trends to the southeast where the river exits Uvalde County. There are four prominent waterholes in the Frio River located within five miles south of the confluence of the Frio and Dry Frio Rivers. The most northern waterhole is identified as the Black Waterhole on the U.S. Geological Survey Knippa Quadrangle 7-1/2 minute topographic map. In a publication by Clark and Small (1997), the next waterhole to the south is also identified as the Black Waterhole. They are referred to here as Black Waterhole North and Black Waterhole South to avoid confusion. Cypress Waterhole and Toadstool Waterhole are located farther south (Figure 10).

Surface water flow measurements made by the US Geological Survey are available for the Frio River at Concan (Figure 7), the Dry Frio River near Reagan Wells (Figure 8), and the Frio River below the confluence with the Dry Frio River (Figure 9). Except during significant precipitation events, there is no surface flow in either the Frio or Dry Frio Rivers through most of the recharge and confined zones of the Edwards Aquifer. Regardless, the four waterholes, which are all located within the confined zone of the Edwards Aquifer, maintain water even during extended periods of minimal or no precipitation. An investigation was undertaken to ascertain whether the waterholes are indications of subsurface flow or expressions of spring discharge from depth. Principal components to the investigation were geophysical surveys to image the subsurface beneath the Frio and Dry Frio riverbeds, comparison of hydraulic heads, and the chemical analysis of water sampled from the waterholes.

1.6. Subsurface Imaging

Electrical resistivity surveys were performed along three transects across the Frio and Dry Frio Rivers to discern the possible presence of high porosity zones characterized by high resistivity that could serve as groundwater flow pathways (Figure 10). Previous work in the region has shown that highly permeable groundwater flow pathways in paleo-channels, characterized by high resistivity, are present in fluvial floodplains (Green et al., 2008b). Two of the transects were located on the Frio River and the Dry Frio River approximately four miles south of the Edwards Aquifer recharge zone. The third transect was located on the Frio River approximately three miles south of the confluence of the Dry Frio River near Black Waterhole South. The two transects on the Frio River are referred to as Frio River – north of Knippa, and Frio River – Black Waterhole South. All three transects were located within the Edwards Aquifer confined zone and south of the recharge zone. The transects were oriented perpendicular to the river channels.

The geophysical surveys were conducted using a Syscal ProSwitch electrical resistivity system (Iris Instruments, Orleans, France). The survey system consisted of linear arrays of 72 electrodes spaced 16.4-ft apart. A dipole-dipole electrode configuration array was used. The depth of investigation was approximately 130 ft. Measurements along transects requiring more than 72 electrodes were collected using a "roll-along" survey method to provide continuous coverage. The measured resistivity data were inverted to provide an interpretation of the subsurface (Loke, 2004).

The resistivity results are graphically illustrated as vertical profiles in Figures 11. Results are presented in units of ohm-meters (ohm-m), a measure of the electrical resistivity of the geologic section to an induced current. Modeled electrical resistivity values in the shallow subsurface range from less than 10 to greater than 400 ohm-m for the two northern transects, and less than 50 ohm-m for the transect at Black Waterhole South.

Most of the two northern transects indicate continuous zones of relatively high resistivity (i.e., green to red colors) at or near the ground surface overlying more electrically conductive formations (i.e., blue colors) (Figure 11). The relatively high resistivity layer in the two northern transects is interpreted to be the Austin Chalk. The underlying conductive layer is interpreted to be the Eagle Ford Shale. The depth of the transition between the Austin Chalk and the Eagle Ford Shale is 80 to 100 ft on the west side of the Dry Frio River and slightly less on the east side. This transition occurs at a similar depth at the northern Frio River transect. The Austin Chalk thins in the bed of the Dry Frio River in the interval 600 to 850 ft and may be absent in the Frio River to the north of Knippa in the interval 650 to 900 ft as indicated by the low resistivity (i.e., less than 250 and 75 ohm-m, respectively) in Figure 11.

The entire subsurface at the southern Frio River transect is comprised of significantly less resistive rocks (Figure 11). These rocks are interpreted to be the Anacacho Limestone consistent with the mapped geology (Barnes, 1983). The Anacacho Limestone is characterized as a massive mudstone to packstone with thick sequences of bentonitic clays and no solution cavity development (Clark and Small, 1997). The thickness of the Anacacho Limestone in Uvalde County is estimated to be 470 ft. This description is consistent with the results of the resistivity survey.

In summary, there is no indication in the geophysical survey results of electrical resistivities higher than the adjoining media that would indicate subsurface channels of high permeability. The riverbeds at the two Frio River transects have electrical resistivity structures similar with media outside of the floodplains. This observation is interpreted as the absence of floodplain paleo-stream channel deposits capable of high capacity flow. In particular, the riverbed at the northern Frio River transect is interpreted to be underlain by the Eagle Ford Formation and the riverbed at the southern Frio River is interpreted to be underlain by the Anacacho Limestone. The Dry Frio River survey results suggest the Austin Chalk continues across the entire transect. The lack of zones with more electrically resistive material in the riverbeds at all three transects is interpreted to be evidence that there is an absence of hydraulically permeable media different from the host rocks capable of conveying significant water through the subsurface in the riverbeds.

1.7. Groundwater and Surface Water Elevations

Water elevations were measured at surface water and well locations to ascertain the hydraulic relationship among aquifers and surface water bodies along the Frio and Dry

Frio Rivers. Water elevations were measured at the two Black Waterholes, Toadstool Waterhole, and a small pool immediately south of the Cypress Waterhole (as it is identified on the U.S. Geological Survey Garner Field 7-1/2 minute quadrangle map)(Figure 1). Key among these data is the elevation of surface water in the waterholes relative to water elevations in nearby wells. This relationship may provide evidence regarding whether the waterholes are in hydraulic communication with groundwater or are simply expressions of surface and subsurface flow through the river channels.

Different geological units are exposed at the four waterholes. The Anacacho Limestone, igneous intrusions, and Tertiary and Quaternary gravels are exposed at the two Black Waterholes; the Austin Chalk is exposed at the Cypress Waterhole; and the Buda Limestone is exposed at the Toadstool Waterhole (Clark and Small, 1997). With the exception of Black Waterhole South, the waterholes are located proximal to mapped faults (Clark and Small, 1997; Green et al., 2006). Most are normal faults, however Cypress Waterhole is located in the upthrown block just south of a large reverse fault called the Agape Fault (Clark and Small, 1997).

Surface and groundwater elevations at the waterholes and nearby wells measured in July 2008 provide evidence of the hydraulic relationship of the waterholes with the local aquifers. Groundwater elevations were measured at nearby wells during a synoptic water elevation survey conducted by SwRI for the Uvalde County Underground Water Conservation District. Surface water elevations were measured at the four waterholes as part of this project. These water elevations are plotted in Figure 12. Water elevations at the three southern waterholes [i.e., 858.42 ft mean sea level (msl) at Black Waterhole South; 842 ft msl at Cypress Waterhole; 819.07 ft msl at Toadstool Waterhole] are consistent with groundwater elevations at two nearby wells in the Buda Aquifer (i.e., 837.51 ft msl at UV161; 824.88 ft msl at UV162) supporting the supposition that the Buda Aquifer and the three southern waterholes are in hydraulic communication. Comparison of these water elevations with the four Edwards Aquifers wells near the Pat Johnson ranch (well numbers 6951602, 6951606, 6952403, and 6952404) suggest that the Edwards Aquifer is also potentially in hydraulic connection with the Buda Aquifer and the three southern waterholes, however this correlation is tenuous due to the large hydraulic gradient relative to the distance from the Edwards Aquifer wells to the Buda Aquifer wells and the waterholes. No Austin Chalk Aquifer wells were found near the three southern waterholes for comparison. Because the Austin Chalk Aquifer has been extensively drilled for water supply wells in this region, this absence of wells is interpreted to indicate that the Austin Chalk Aquifer does not extend to this area.

The northernmost waterhole, Black Waterhole North, has a different hydraulic relationship compared with the three southern waterholes. A Buda Aquifer well (UV174) located about 1.5 miles west of Black Waterhole North has a significantly lower water level elevation (i.e., 847.1 ft msl) relative to Black Waterhole North (887.5 ft msl) even though it is upgradient from the waterhole. The water elevation of Black Waterhole North is, however, consistent with the elevation (891.6 ft msl) observed at an Austin Chalk Aquifer well (UV144) located about 2 miles to the northeast. Lastly, the groundwater elevation of 819.6 ft msl at an Edwards Aquifer well (UV088), located midway between

Black Waterhole North and the Austin Chalk Aquifer well at 891.6 ft msl (UV144) to the northeast, is similar to the groundwater elevation observed of 847.1 ft msl at the Buda Aquifer well (UV174) located to the west supporting the premise that the Buda and Edwards Aquifers are in hydraulic communication in this area. Note that the water level in UV088 was measured in January 2006 and not measured during this field study. These relationships are interpreted as evidence that Austin Chalk Aquifer is not in hydraulic communication with the Edwards and Buda Aquifers in the Knippa area.

Hydraulic communication among the Edwards Aquifer and the secondary aquifers of Uvalde County (i.e., most notably the Buda and Austin Chalk Aquifers) has been investigated by SwRI in a separate project for the Uvalde County Underground Water Conservation District. Preliminary results for this assessment indicate that the Buda and Austin Aquifers are not continuous through the Frio and Dry Frio River area and that segments of these aquifers, particularly near and east of Knippa, are not in hydraulic communication with the Edwards Aquifer. This lack of communication is manifested by the significantly higher groundwater elevations observed in Austin Chalk wells to the east of Knippa relative to groundwater elevations in the Edwards Aquifer in the same area. If this conceptualization is valid, then the relatively high water elevation measured at Black Waterhole North indicates the source of its water is the Austin Chalk Aquifer and not the Edwards Aquifer.

1.8. Water Chemistry

Water samples were collected from the two Black Waterholes, Toadstool Waterhole, and the small pool immediately south of the Cypress Waterhole (Figure 13). Misidentification of the location of the actual Cypress Waterhole led to sampling of the small pool just downstream of the Cypress Waterhole.

Samples were collected and analyzed using standard water quality analysis methods. Specific conductivity, pH, temperature, oxidation-reduction potential, and dissolved oxygen were measured in the field using a Hydrolab® Minisonde 4A multiprobe. Alkalinity was measured in the field by titration. Water samples collected for subsequent analysis of major ions and other constituents were placed in high-density polyethylene or amber glass containers. Samples to be analyzed for cations and metals were filtered (0.45-μm) and acidified using trace metal-grade HNO_3. Samples to be analyzed for anions were also filtered. Following collection, all samples were placed on ice in coolers in the field and were subsequently maintained at 4° C upon return to the laboratory and prior to analysis. Cations and metals were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) and anions were analyzed using ion chromatography (IC) or by ion-selective electrode (ISE)(fluoride only). Water quality analytical results are summarized in Table 1 and included in Appendix A

One immediate observation is that the measured specific conductivity [also total dissolved solids (TDS) content] increases in the waterholes from north to south (TDS values: Black Waterhole North 140 mg/L; Black Waterhole South 348 mg/L; pool near Cypress Waterhole 401 mg/L; Toadstool waterhole 556 mg/L). Because this reach of the Frio River is located along the eastern flank of the Uvalde Salient, an area of intense faulting that overlies the transition of fresh to saline water in the Edwards Aquifer, one possible explanation for the TDS increase is groundwater from the Edwards Aquifer leaking upward into the waterholes. Other possible interpretations of the increased TDS content include evaporative concentration of dissolved constituents, upward leakage of groundwater from other formations, such as the Austin Chalk, or some combination of upward leakage and evaporation.

A Piper plot of water quality results from the waterholes (Figure 14) reveals the waterholes have Ca-HCO_3 (Black Waterhole North) or Ca-Mixed Anion (all others) compositions. Only the Black Waterhole North composition is similar to compositions of fresh Edwards Aquifer well waters and water samples collected from upstream in the Frio and Dry Frio Rivers at Reagan Wells and Concan, respectively. In fact, the waterholes show similarities to more saline (TDS > 1000 mg/L) Edwards Aquifer and Austin Chalk Aquifer well waters nearby (Figures 13 and 14). The constituent compositions of water from the waterholes suggest they may be a result of mixing of fresh Edwards Aquifer groundwater and/or river water, and saline Edwards Aquifer or Austin Chalk Aquifer waters (Figure 14). However, exchange of CO_2(g) between the waters and atmosphere is also occurring. As CO_2(g) is lost from solution in the waterholes, pH increases and calcite may precipitate. Low concentrations of Ca and HCO_3 as measured in the waterholes, suggest calcite precipitation occurs. Notably, however, three of the four waterholes are not in equilibrium with atmospheric CO_2(g), and they have modeled CO_2(g) concentrations similar to the river samples and freshwater wells closer to the recharge zone (Figure 15). Only water from Black Waterhole North approaches atmospheric CO_2(g) concentration. This suggests that these waterholes are replenished with CO_2(g)-laden water, which could be supplied by carbonate aquifer waters or by soil-CO_2(g)-enriched runoff.

Comparison of Na and Cl concentrations (Figure 16) and SO_4 concentrations (Figure 17) again provide evidence for evaporation and/or mixing with saline waters. It is worthy to note that the saline waters that fall on the Na–Cl and SO_4 mixing lines are located nearest to the waterholes and along the eastern edge of the Uvalde Salient (Figure 13). Using the data available, geochemical modeling is insufficient to distinguish between evaporation-dominated or mixing-dominated hypotheses for the observed constituent concentrations in the waterholes. Although trends in Na and Cl (Figure 16) suggest mixing as the driver for changes in waterhole chemistries, Ca and SO_4 data (Figure 17) suggest equally plausible final concentrations can result from fresh carbonate water evaporation followed by calcite precipitation and CO_2(g) loss and mixing with saline waters followed by calcite precipitation and loss of CO_2(g). Moreover, the similar groundwater composition of the wells in the area, prevents identification of Edwards Aquifer water or Austin Chalk Aquifer water as a sole source for the waterholes using only these water quality data as evidence. Additional data, such as stable isotope compositions of the wells and waterholes, may help to identify the most favorable hypothesis for the evolution of the waterholes compositions.

2. CONCLUSIONS

Effective management of the Edwards Aquifer requires that its water budget be accurately known. Central to calculation of the water budget of the Edwards Aquifer are recharge and discharge distributions and rates. Current estimates of recharge of the Edwards Aquifer by the Frio and Dry Frio Rivers (i.e., annual medium of 125,100 acre-ft) is predicated on the assumption that subsurface flow in the Frio and Dry Frio River floodplain is negligible and that recharge from these rivers is accurately measured using river flow gauges. This investigation was undertaken to understand the hydraulic importance of the Frio and Dry Frio Rivers to the Edwards Aquifer and to ascertain whether this conceptualization of recharge by these rivers is valid.

Geologic structure, subsurface imagining, groundwater and surface water elevations, and water quality of the Frio and Dry Frio Rivers and environs were examined to evaluate the hydraulic relationship between the Frio and Dry Frio River system and the Edwards Aquifer. The Frio and Dry Frio Rivers are located at the juxtaposition of the Uvalde Salient, within the midst of a field of volcanic intrusions, and the Edwards Aquifer facies transition from the Maverick Basin to the Devil's River Trend. The Frio and Dry Frio Rivers traverse the longest reach of the Edwards Aquifer recharge zone of rivers that recharge the Edwards Aquifer allowing ample opportunity for surface water to recharge the subsurface.

Of interest are four waterholes in the Frio River south of the confluence with the Dry Frio River. Surface water persists in all four waterholes even during periods of limited precipitation, such as late 2008 and early 2009 while this investigation was underway. The source water for the waterholes is not known. Two potential sources are either underflow via the Frio and Dry Frio River floodplains or springflow from depth. If the source water is floodplain underflow, then surface water gauging of river flow in the Frio and Dry Frio Rivers would not accurately represent the true rate of recharge of the Edwards and related aquifers by recharge in the river channels. Knowing the source water for the waterholes is therefore of critical importance to understanding the hydraulic relationship of the Frio and Dry Frio Rivers to the Edwards and related aquifers.

Geophysical imaging of the subsurface of the floodplains of the Dry Frio River and the Frio River upstream and downstream of the confluence with the Dry Frio River did not detect evidence of paleo-channel deposits or preferential flow pathways developed in the bedrock. This evidence indicates that there are neither paleo-stream channel deposits nor preferential flowpaths available to convey significant floodplain underflow.

Surface and groundwater elevations indicate that the Buda and Edwards Aquifers and the three southern waterholes are hydraulically connected. Black Waterhole North is perceived to be hydraulically connected to the Austin Chalk Aquifer and that neither the Austin Chalk Aquifer nor Black Waterhole North is in hydraulic communication with the Edwards Aquifer, however there are insufficient water elevation measurements to be conclusive.

Examination of water quality analyses from the four Frio River waterholes and several nearby wells indicates identifying the source(s) of water in the waterholes is quite complex. The water compositions likely result from a mix of fresh water input from rainfall and river flow events, upward leakage of relatively saline water from the Edwards Aquifer or the Austin Chalk (or both), and loss of CO_2(g) and precipitation of calcite during equilibration with the atmosphere. One strong indicator of upward leakage as a source of input to the waterholes is their persistence over time. All of the waterholes had substantial water at the time of sampling during the fall of 2008, which followed a particularly dry summer season. Additional data, in particular analyses of stable isotopes for the waterholes and surrounding wells, may assist in constraining geochemical modeling that may identify the sources and evolution of the waterholes' chemistry.

In summary, the Frio and Dry Frio Rivers are assumed (Hamilton et al., 2008) to be hydraulically connected with the Edwards Aquifer in the Edwards Aquifer recharge zone. Both rivers exit the recharge zone about six miles north of the City of Knippa. There is no evidence of underflow in the Frio and Dry Frio River floodplains. This indicates that surface water flow gauging, if performed immediately before and after the rivers enter and exit the recharge zone, should accurately represent the amount of water recharged to the Edwards Aquifer. Supporting this conceptualization is that the source water for all four waterholes is interpreted to be from depth as springs and that there is no indication of floodplain underflow.

3. REFERENCES

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4. DISCLAIMER

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Table 1. Summary of Water Quality Analytical Results for Frio River Waterholes

Parameter	Units	Black Waterhole North	Black Waterhole South	South of Cypress Waterhole	Toadstool Waterhole
Temperature	°C	29.47	28.09	31.96	31.2
pH		8.23	7.52	7.95	7.68
ORP	mV	630	470	409	391
SpC	uS/cm	252.6	598.7	675.3	900
TDS	mg/L	140.2	348	401	556
Alkalinity	mg/L as CaCO3	67.3	88	123.4	99.3
F	mg/L	0.17	0.14	0.12	0.12
Cl	mg/L	22	98	60	130
SO4	mg/L	14.5	43	76	95
NO3	mg/L	0.27	N/A	13.55	6.46
Ba	mg/L	0.05	0.107	0.0871	0.0952
B	mg/L	0.07	0.190	0.103	0.111
Ca	mg/L	20.25	51.2	70.4	77.6
K	mg/L	2.49	3.48	2.71	2.69
Mg	mg/L	8.30	21.3	19.1	23.8
Na	mg/L	11.05	25.6	22.7	38.0
Si	mg/L	9.45	9.51	8.07	7.32
Sr	mg/L	0.17	0.545	0.540	0.592

Table 2. Locations of surface water gauging stations on the Frio and Dry Frio Rivers in Uvalde County

Agency	Site Number	Site Name	Period of Record		
			Begin Date	End Date	Count
USGS	08195000	Frio Rv at Concan, TX	1923-09-18	2008-12-04	803
USGS	08196000	Dry Frio Rv nr Reagan Wells, TX	1952-08-21	2008-12-04	537
USGS	08197500	Frio Rv bl Dry Frio Rv nr Uvalde, TX	1953-09-18	2008-12-02	297

APPENDIX A

Location			**Black Waterhole North**		**Black Waterhole South**	**South of Cypress Waterhole**	**Toadstool Waterhole**
GED Sample Name		Frio 1/ GED 13	Frio 1/ GED 18 Duplicate	Frio 1 Average	Frio 2/ GED 14	Frio 4/ GED 16	Frio 3/ GED 15
Parameter	Sample Date	12-Sep-08	12-Sep-08		12-Sep-08	12-Sep-08	12-Sep-08
Temperature	°C	29.47	N/A		28.09	31.96	31.2
pH		8.23	N/A		7.52	7.95	7.68
ORP	mV	630	N/A		470	409	391
SpC	uS/cm	252.6	N/A		598.7	675.3	900
TDS	mg/L	140.2	N/A		348	401	556
DO	mg/L	5.01	N/A		4.66	N/A	6.11
DO%		68	N/A		61.9	N/A	85.9
BP	mmHg	731	N/A		732.1	729.2	730.5
Alkalinity	mg/L as CaCO3	67.3	N/A		88	123.4	99.3
F	mg/L	0.16	0.17	0.17	0.14	0.12	0.12
Cl	mg/L	21	23	22	98	60	130
SO4	mg/L	15	14	14.5	43	76	95
NO2	as N mg/L	< 0.06	< 0.06		< 0.06	< 0.06	< 0.06
NO3	as N mg/L	0.06	0.06	0.06	N/A	3.06	1.46
NO3	mg/L	0.27	0.27	0.27	N/A	13.55	6.46
Ag	mg/L	< 0.005	< 0.005		< 0.005	< 0.005	< 0.005
Al	mg/L	0.01	< 0.01		< 0.01	< 0.01	< 0.01
As	mg/L	< 0.008	< 0.008		< 0.008	< 0.008	< 0.008
Ba	mg/L	0.0465	0.0469	0.05	0.107	0.0871	0.0952
Be	mg/L	< 0.0001	< 0.0001		< 0.0001	< 0.0001	< 0.0001
B	mg/L	0.068	0.068	0.07	0.190	0.103	0.111
Bi	mg/L	< 0.03	< 0.03		< 0.03	< 0.03	< 0.03
Ca	mg/L	20.2	20.3	20.25	51.2	70.4	77.6
Cd	mg/L	< 0.002	< 0.002		< 0.002	< 0.002	< 0.002
Co	mg/L	< 0.003	< 0.003		< 0.003	< 0.003	< 0.003
Cr	mg/L	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001
Cu	mg/L	< 0.001	< 0.001		< 0.001	< 0.001	0.001
Fe	mg/L	0.01	< 0.01		< 0.01	< 0.01	< 0.01
K	mg/L	2.47	2.50	2.49	3.48	2.71	2.69
Li	mg/L	< 0.002	< 0.002		< 0.002	< 0.002	< 0.002
Mg	mg/L	8.27	8.33	8.30	21.3	19.1	23.8
Mn	mg/L	< 0.001	< 0.001		< 0.001	0.002	< 0.001
Mo	mg/L	< 0.005	< 0.005		< 0.005	< 0.005	< 0.005
Na	mg/L	11.0	11.1	11.05	25.6	22.7	38.0
Ni	mg/L	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01
P	mg/L	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01
Pb	mg/L	< 0.005	< 0.005		< 0.005	< 0.005	0.007
Sb	mg/L	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01
Se	mg/L	< 0.02	< 0.02		< 0.02	< 0.02	< 0.02
Si	mg/L	9.42	9.47	9.45	9.51	8.07	7.32

Location		Black Waterhole North			Black Waterhole South	South of Cypress Waterhole	Toadstool Waterhole
GED Sample Name		Frio 1/ GED 13	Frio 1/ GED 18 Duplicate	Frio 1 Average	Frio 2/ GED 14	Frio 4/ GED 16	Frio 3/ GED 15
Parameter	Sample Date	12-Sep-08	12-Sep-08		12-Sep-08	12-Sep-08	12-Sep-08
Sn	mg/L	< 0.03	< 0.03		< 0.03	< 0.03	< 0.03
Sr	mg/L	0.164	0.166	0.17	0.545	0.540	0.592
Ti	mg/L	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001
Tl	mg/L	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01
U	mg/L	< 0.3	< 0.3		< 0.3	< 0.3	< 0.3
V	mg/L	0.007	0.006	0.007	0.006	0.003	0.003
W	mg/L	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01
Y	mg/L	< 0.0004	< 0.0004		< 0.0004	< 0.0004	< 0.0004
Zn	mg/L	< 0.01	< 0.01		< 0.01	< 0.01	< 0.01

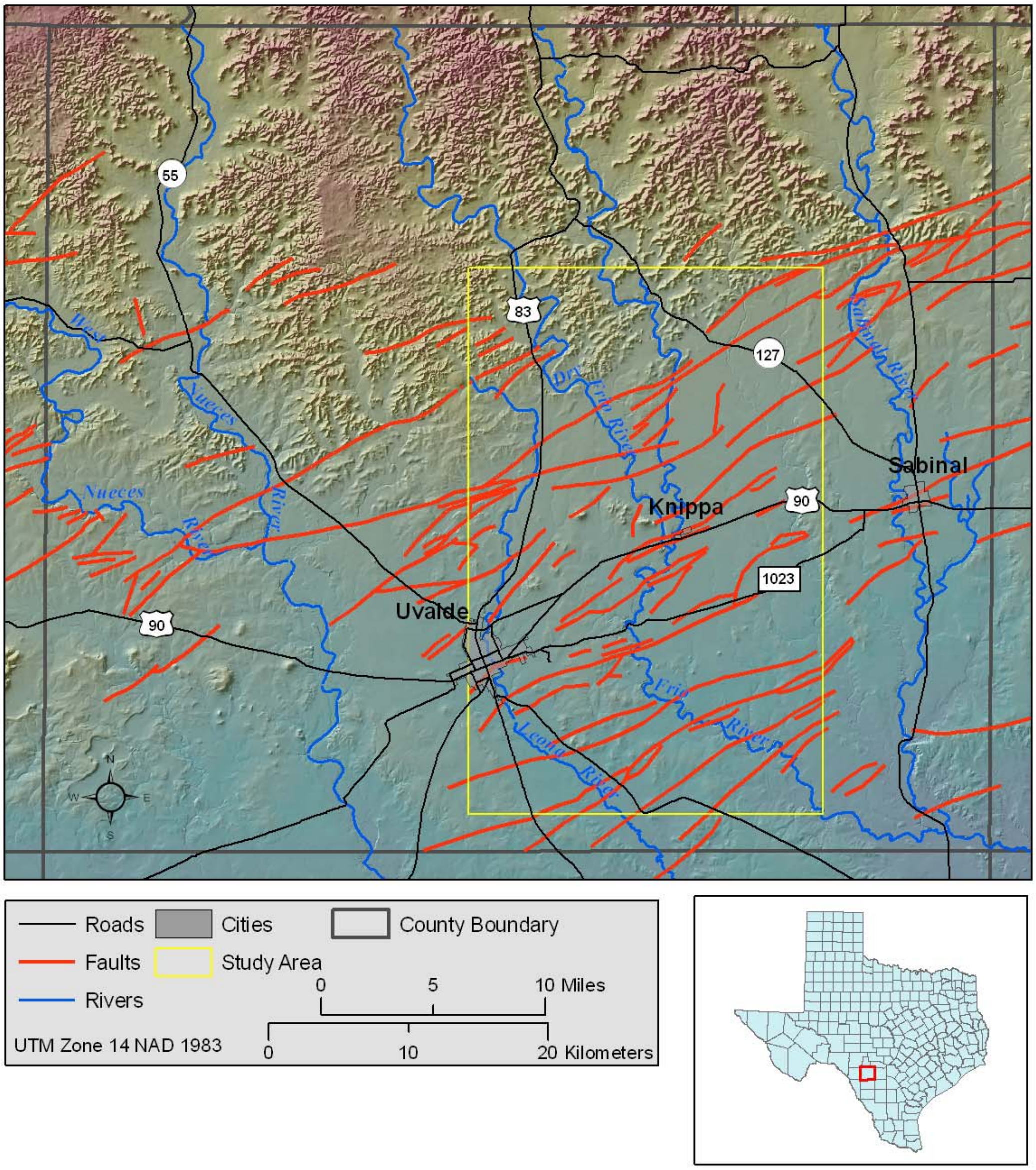

Figure 1. Map of Uvalde County. The study is focused on the area denoted by the yellow box.

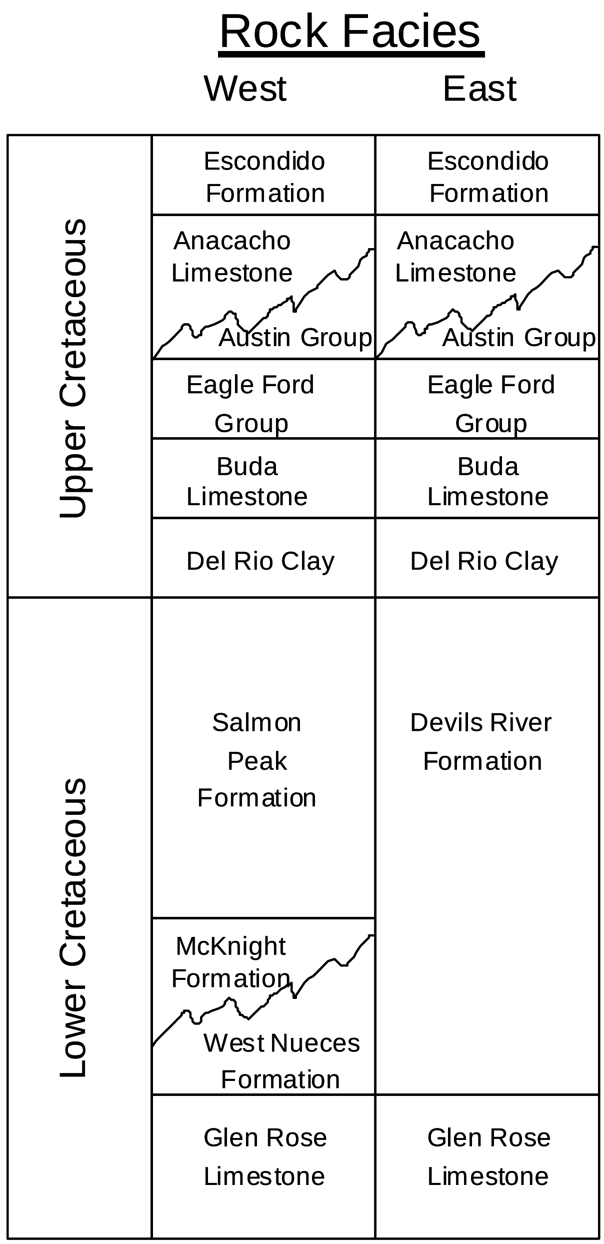

Figure 2. Generalized stratigraphic column for Uvalde County, Texas (adapted from Groschen and Buszka, 1997)

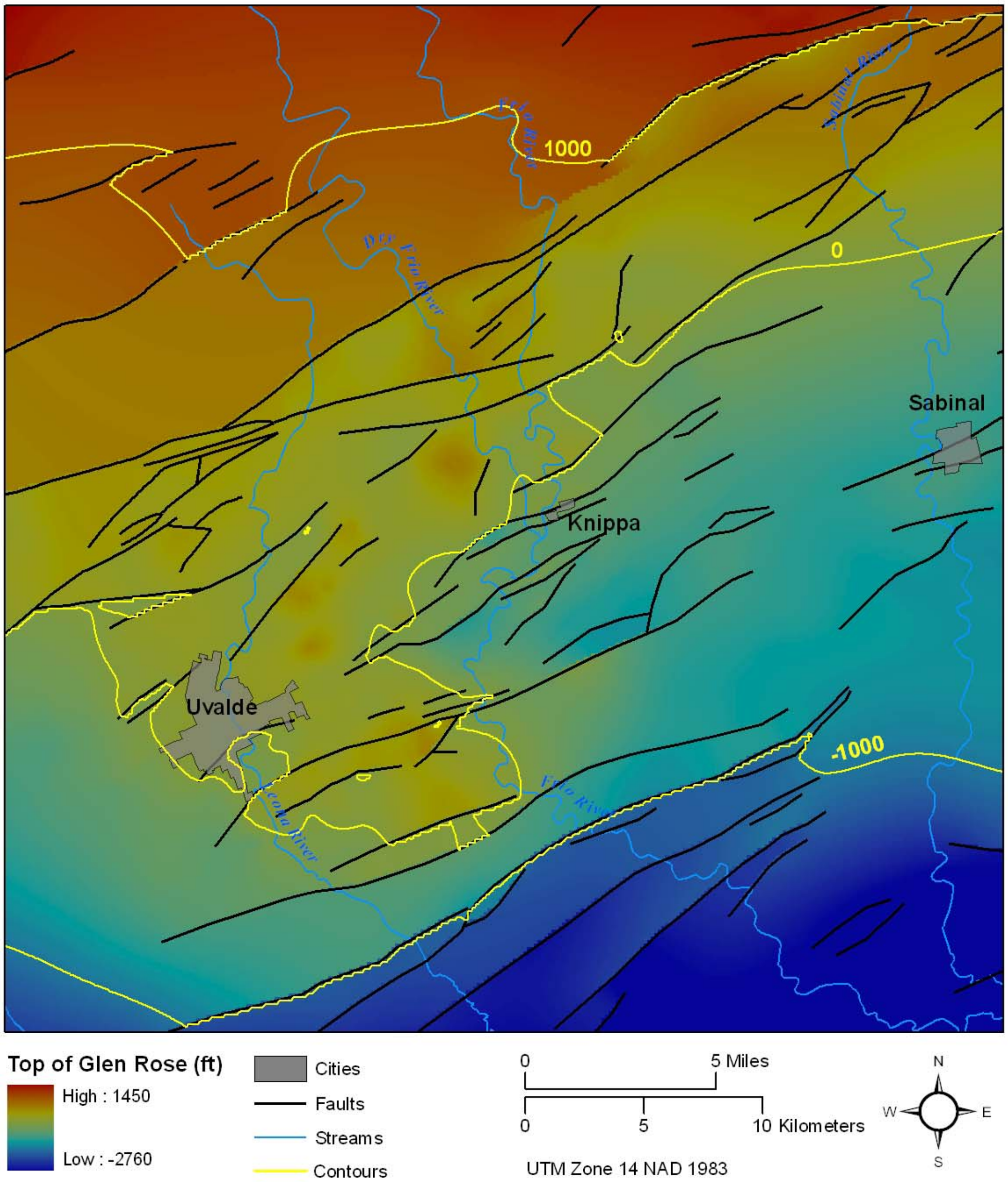

Figure 3. Geologic structure map showing faults and the elevation of the top of the Glen Rose Limestone in southwestern Uvalde County. The Uvalde salient is highlighted by the 0-ft contour of the Glen Rose surface.

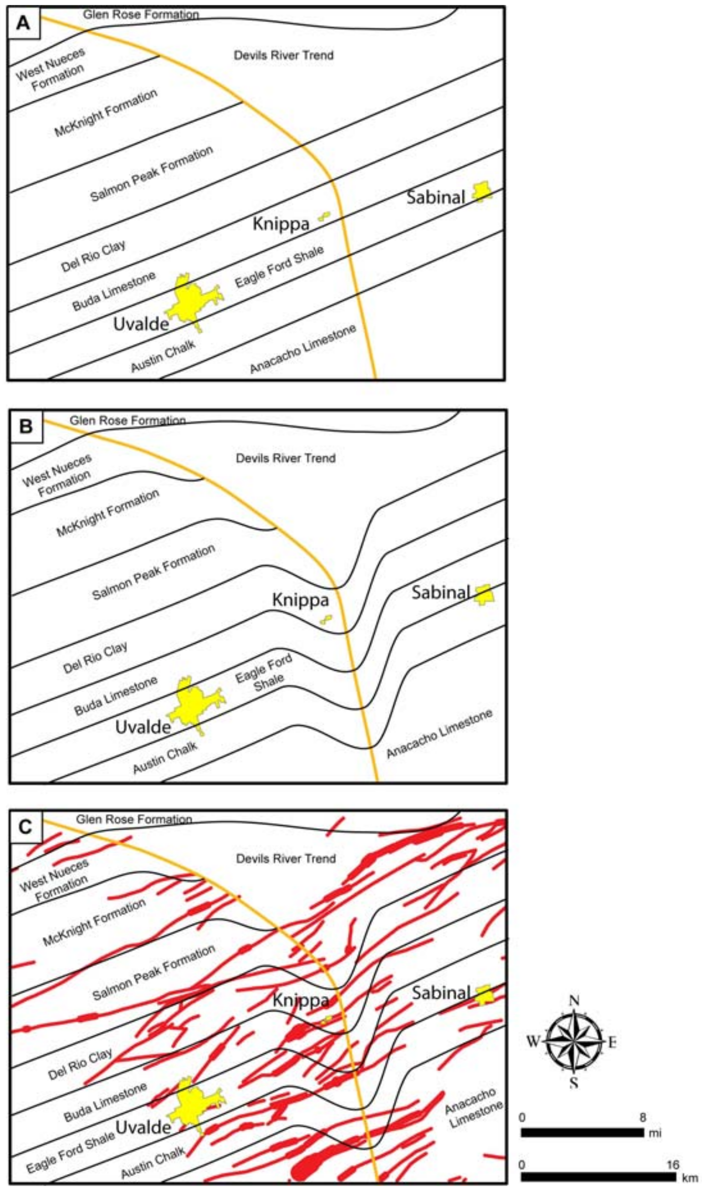

Figure 4. Schematic of the evolution of the Uvalde Salient. (A) illustrates the effect of down-to-the-southeast Balcones Zone faulting in the absence of the Uvalde Salient. (B) illustrates the effect of uplifting of the basement rocks on the exposure of Cretaceous-age formations resulting from the development of the Uvalde Salient. (C) includes fault traces to illustrate the high density of faulting associated with the Uvalde Salient. The orange line denotes the facies transition of the Edwards Aquifer from Maverick Basin on the left to the Devils River Trend to the east.

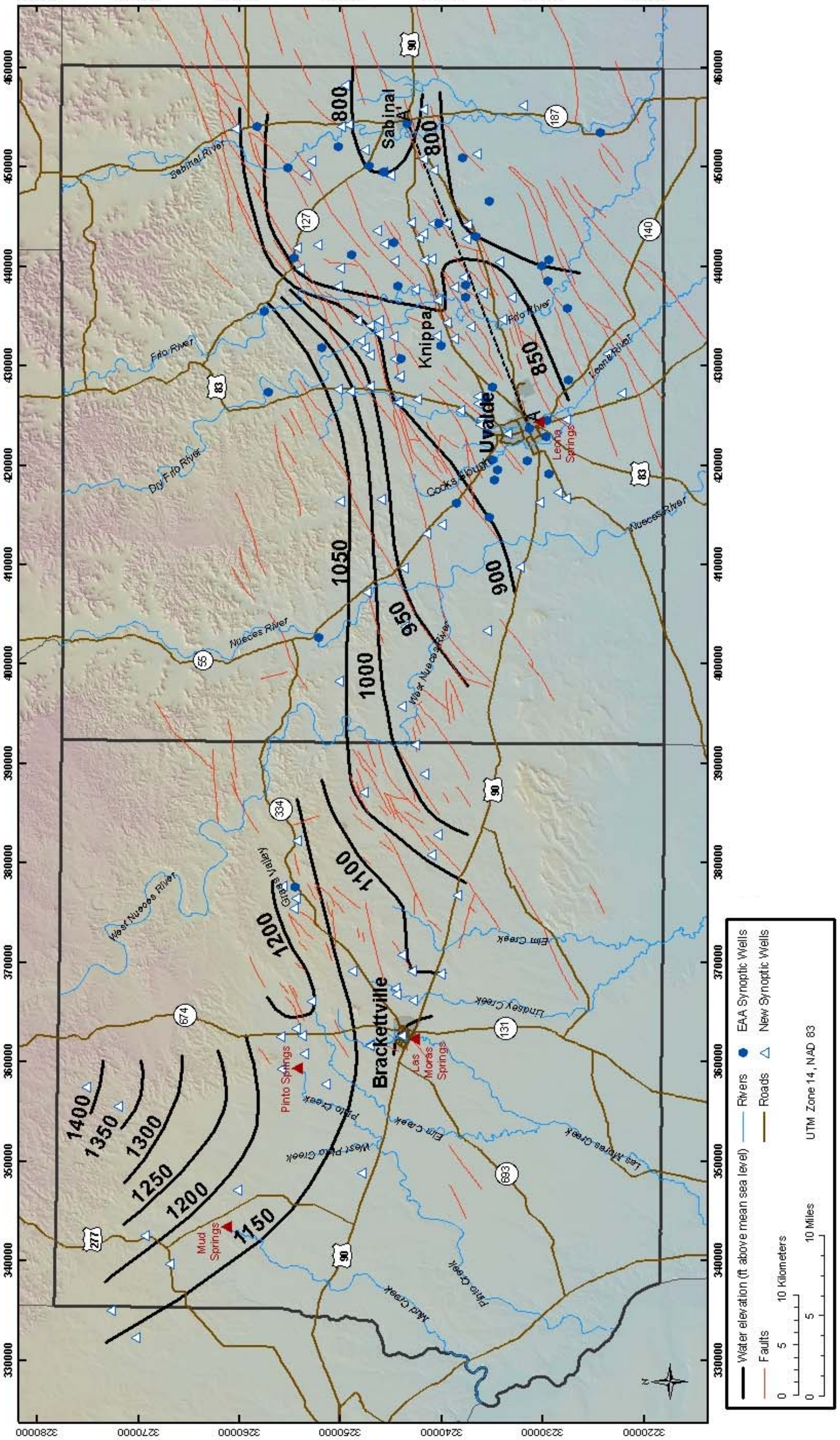

Figure 5. Potentiometric surface of the Edwards Aquifer for January-February 2006 (Green et al., 2006).

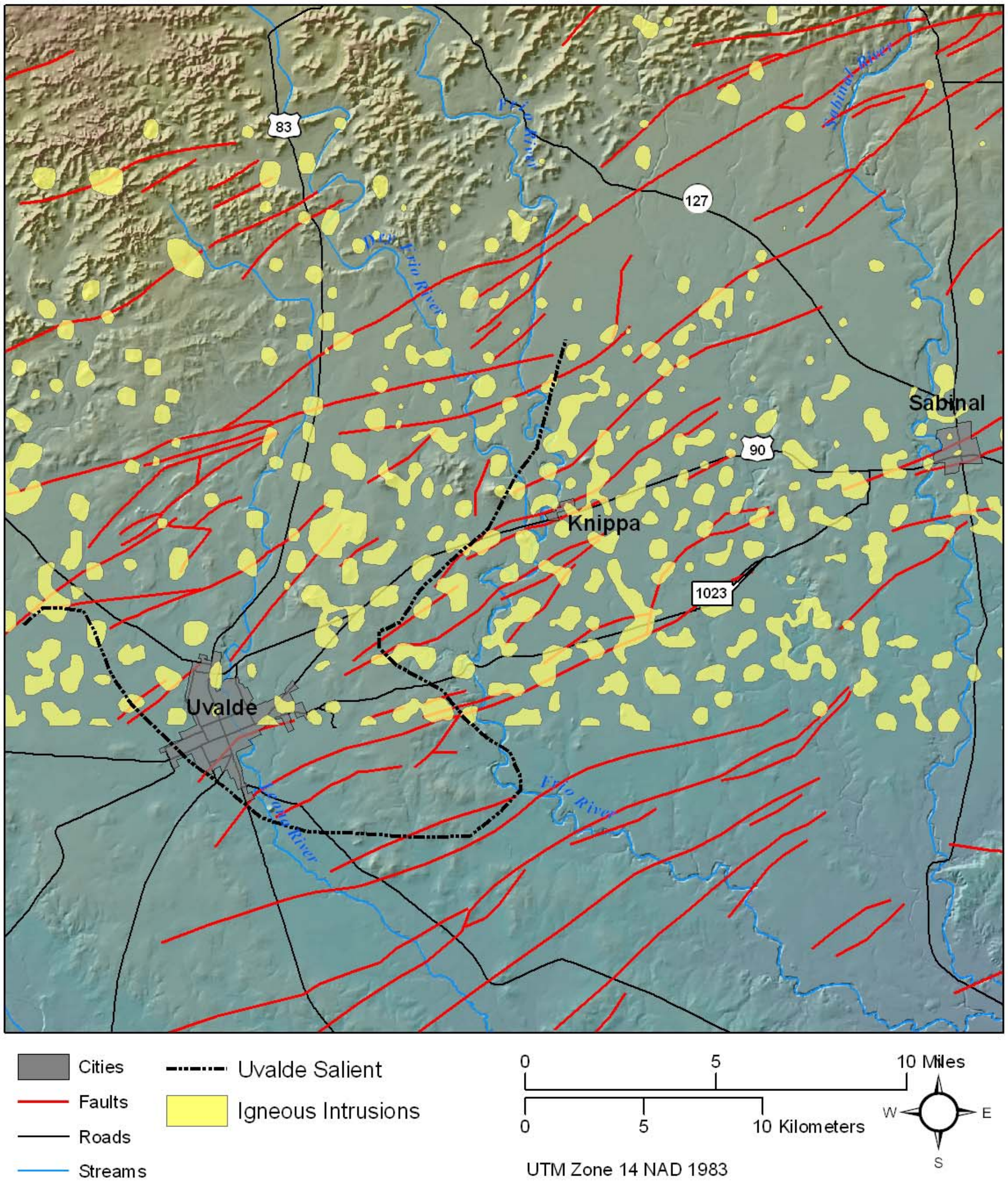

Figure 6. Locations of igneous intrusions in southwestern Uvalde County as inferred from aeromagnetic survey data of Smith, et al. (2008). The 0 ft elevation of the top of the Glen Rose Formation is used to mark the location of the Uvalde Salient.

Uvalde County, Texas
Hydrologic Unit Code 12110106
Latitude 29°29’18”, Longitude 99°42’16” NAD27
Drainage area 389 square miles
Contributing drainage area 389 square miles
Gage datum 1,203.71 feet above sea level NGVD29

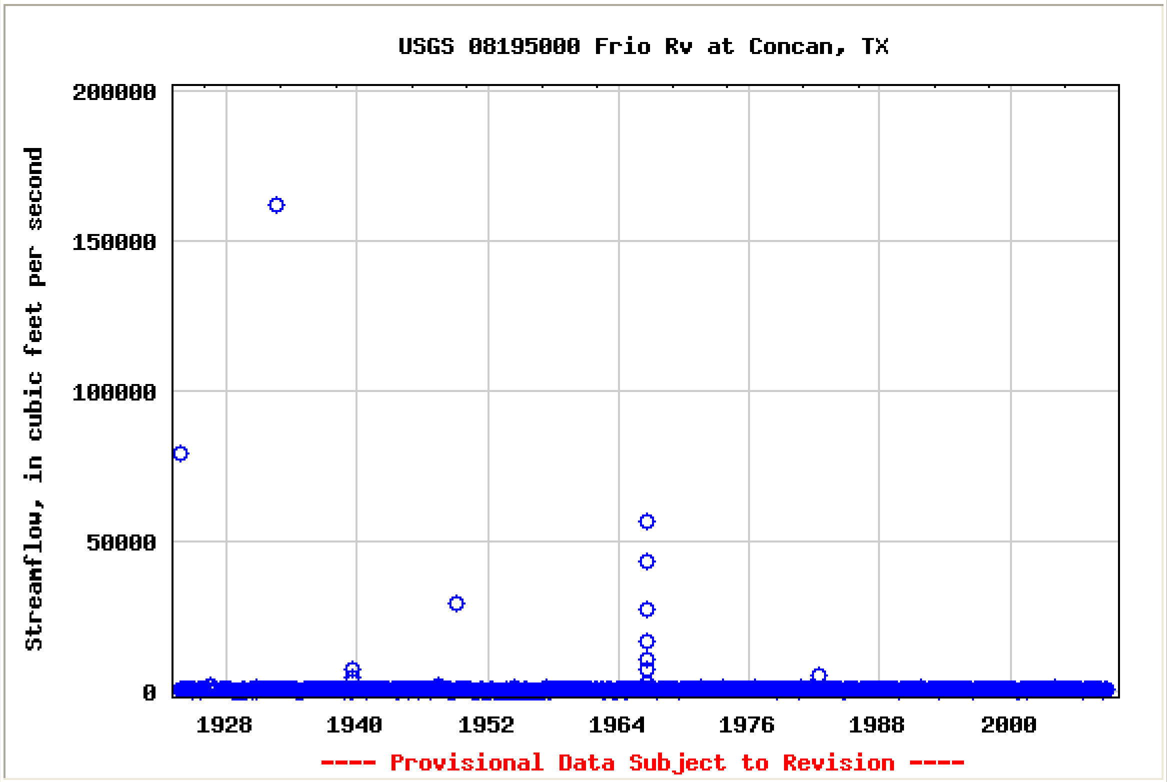

Figure 7. Surface water flow measured on the Frio River at Concan, Texas. [Date of data retrieval: January 7, 2009 http://waterdata.usgs.gov/nwis/measurements?site_no=08195000&agency_cd=USGS&format=gif]

Uvalde County, Texas
Hydrologic Unit Code 12110106
Latitude 29°30'16", Longitude 99°46'52" NAD27
Drainage area 126 square miles
Contributing drainage area 126 square miles
Gage datum 1,335.20 feet above sea level NGVD29

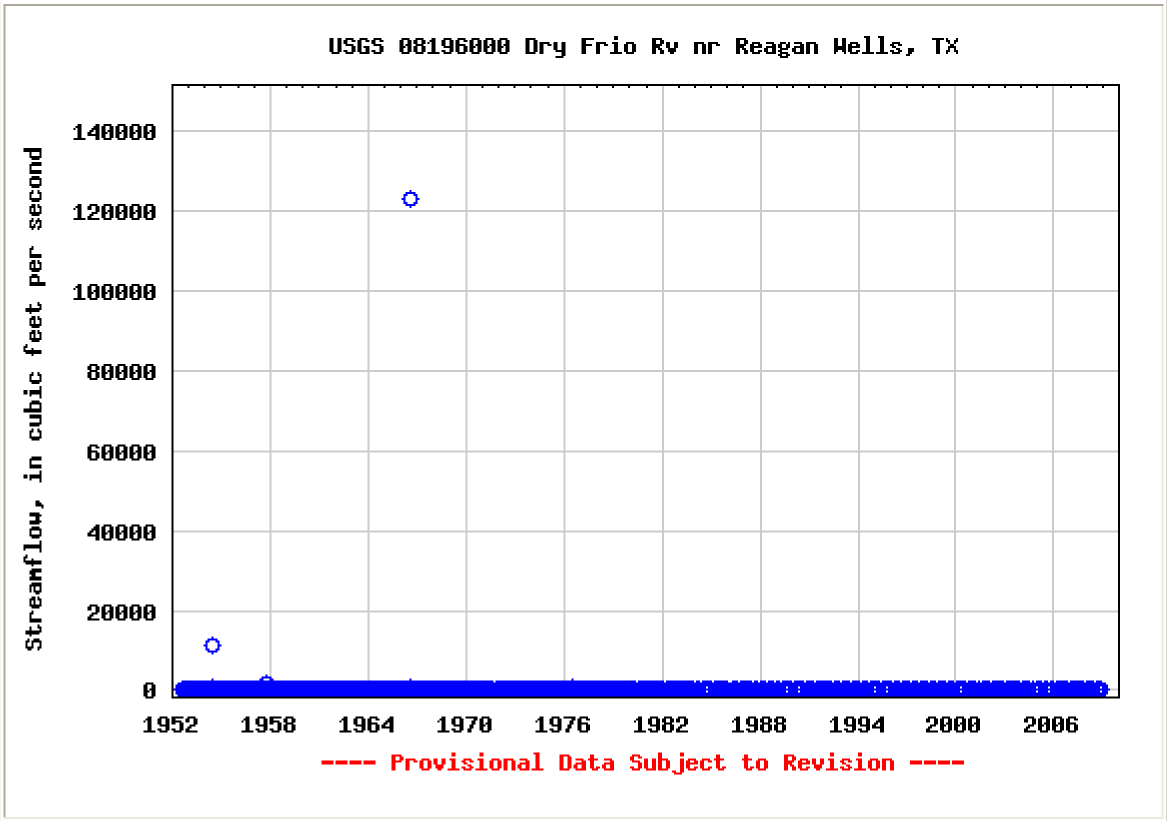

Figure 8. Surface water flow measured on the Dry Frio River near Reagan Wells, Texas. [Date of data retrieval: January 7, 2009 http://waterdata.usgs.gov/nwis/measurements?site_no=08196000&agency_cd=USGS&format=gif]

Uvalde County, Texas
Hydrologic Unit Code 12110106
Latitude 29°14'44", Longitude 99°40'27" NAD27
Drainage area 631 square miles
Contributing drainage area 631 square miles
Gage datum 882.47 feet above sea level NGVD29

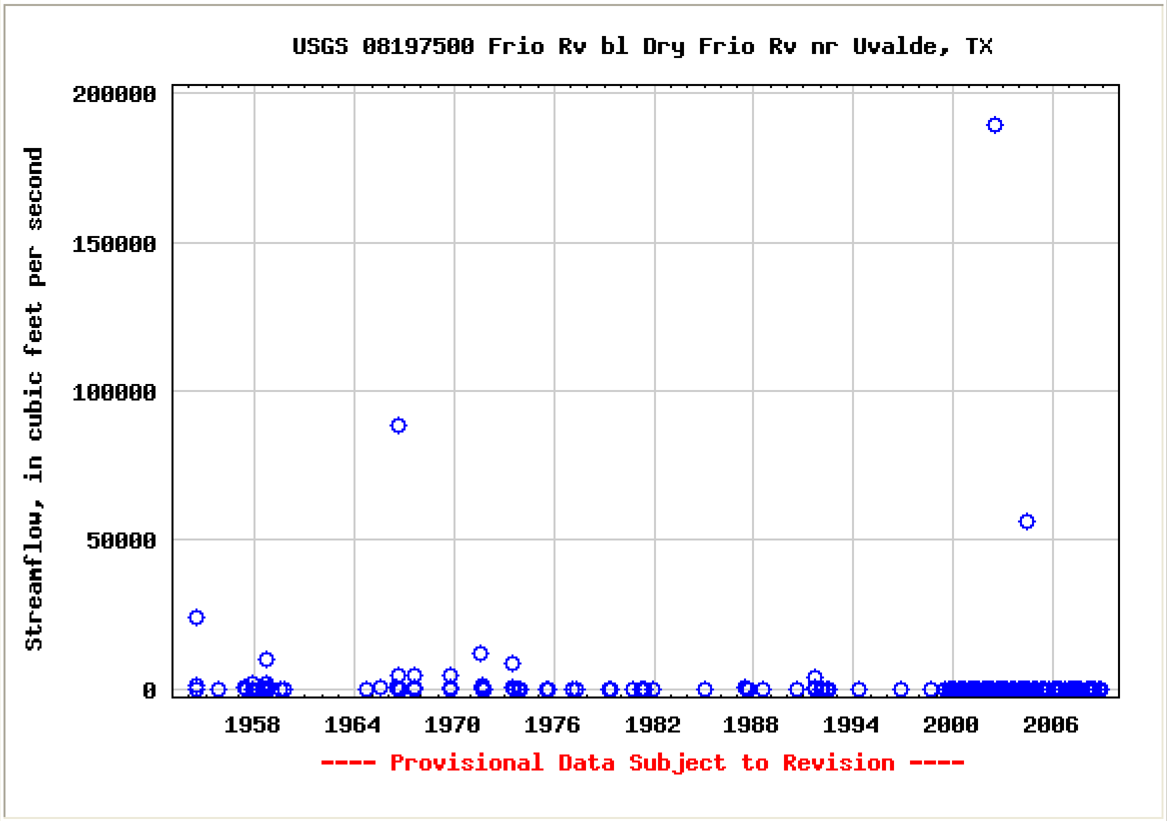

Figure 9. Surface water flow measured on the Dry Frio River below the Fry Frio River near Uvalde, Texas. [Date of data retrieval: January 7, 2009 http://waterdata.usgs.gov/nwis/measurements?site_no=08197500&agency_cd=USGS&format=gif]

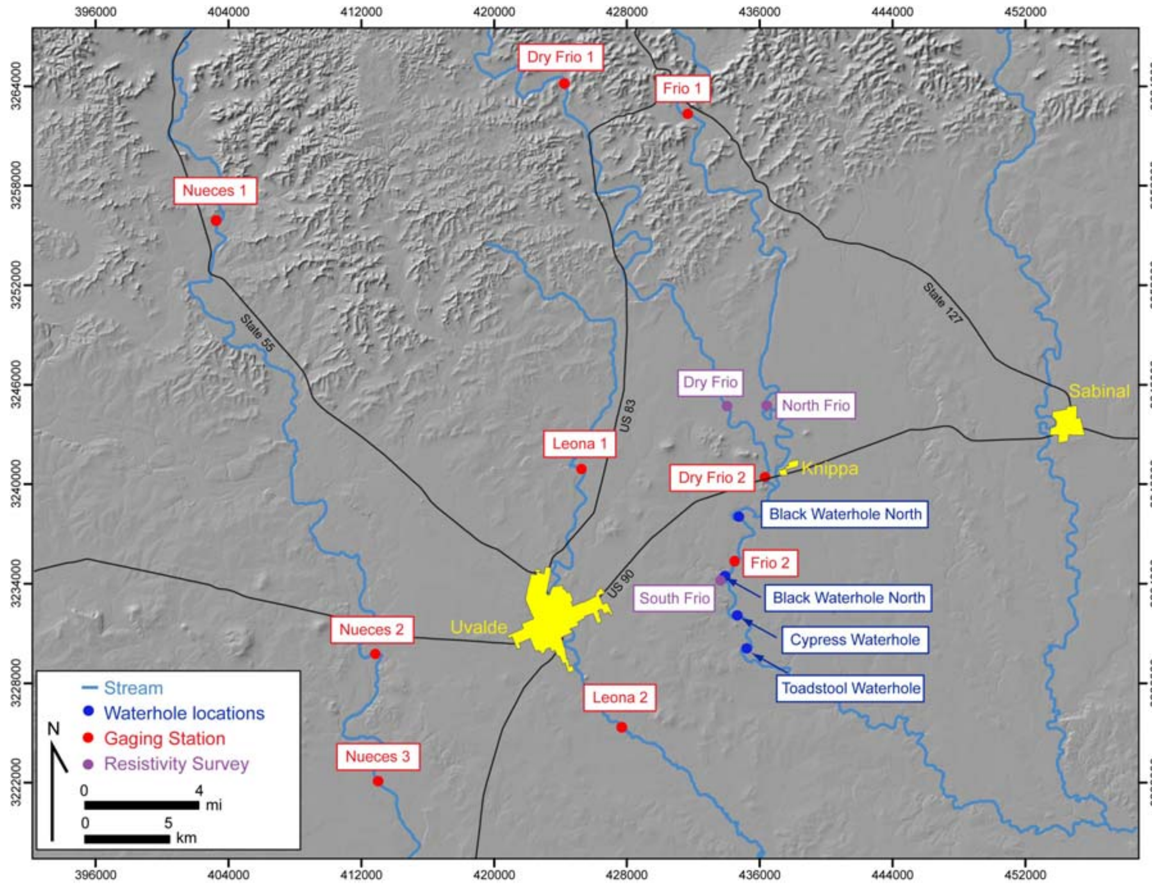

Figure 10. Locations of the waterholes (blue print) and the electrical resistivity survey transects (purple print)

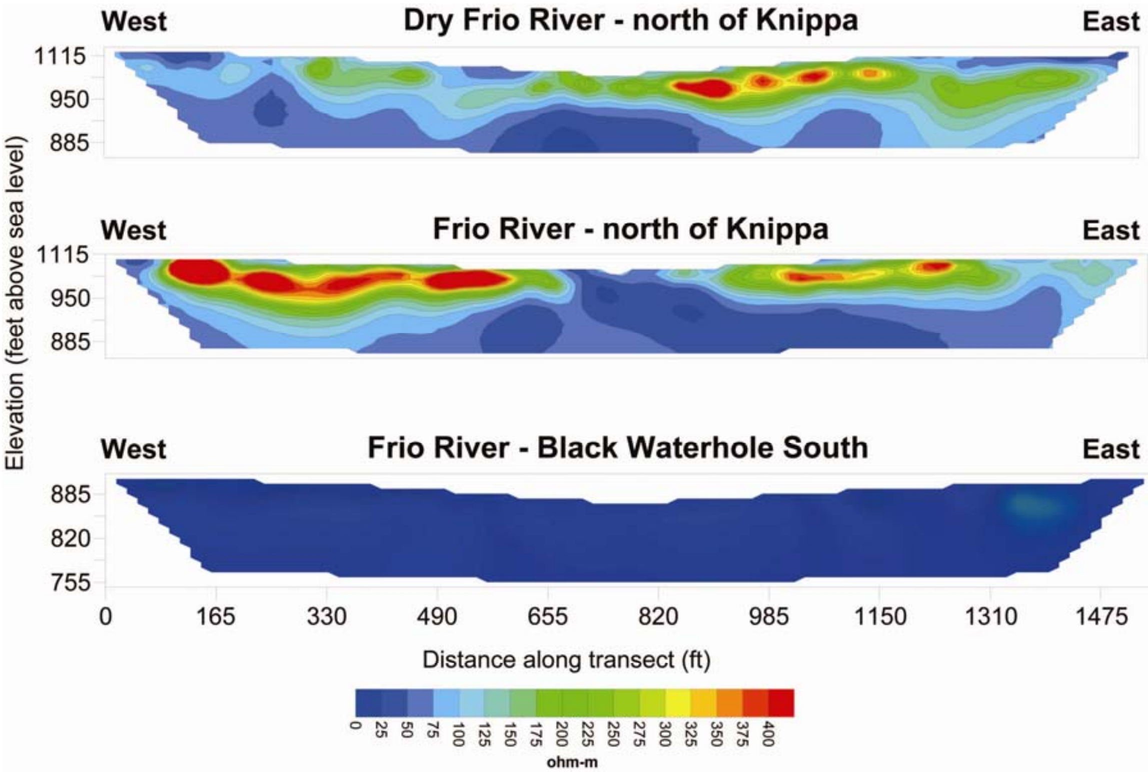

Figure 11. Electrical resistivity transects for the Dry Frio River north of Knippa, Frio River north of Knippa, and the Frio River at Black Water South

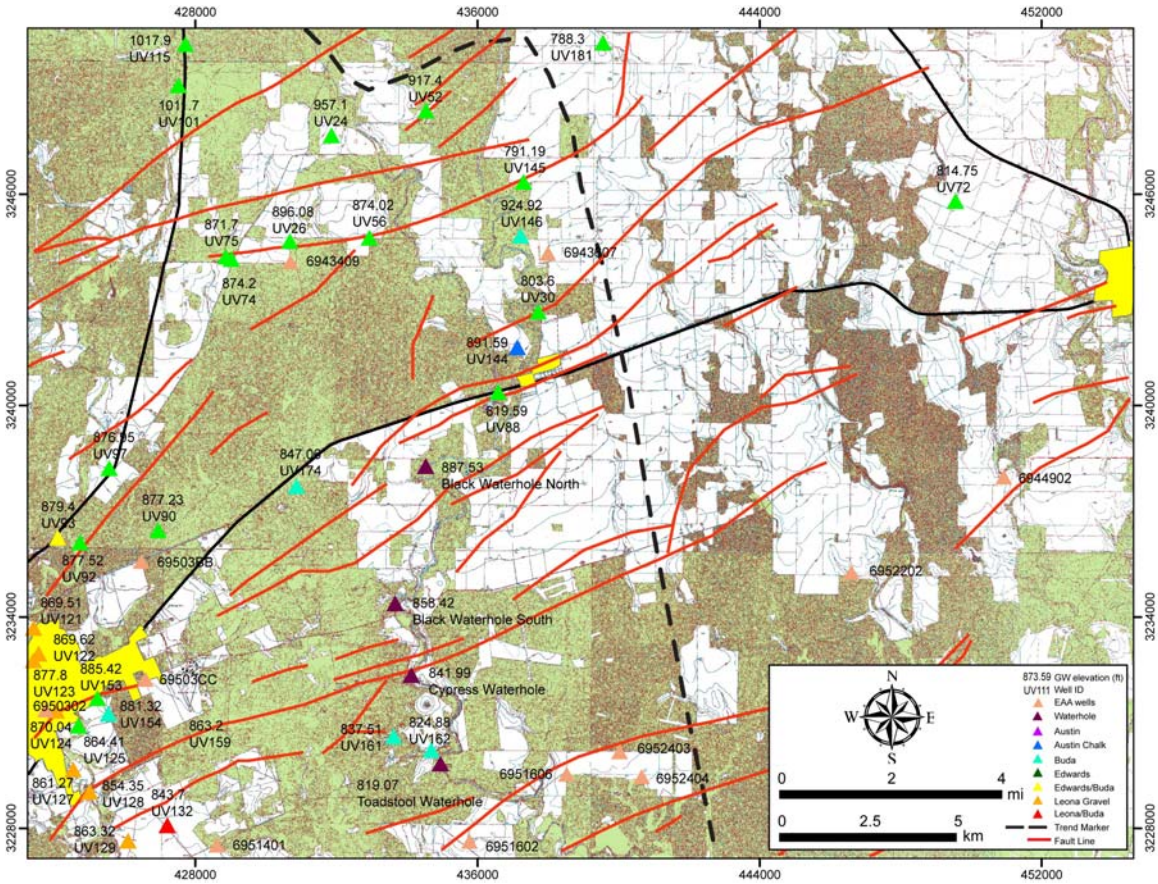

Figure 12. Locations of surface water and groundwater elevations. Water elevations are in ft msl. The dashed black line denotes the approximate transition of the Edwards Aquifer from the Maverick Basin on the left to the Devils River Trend on the right.

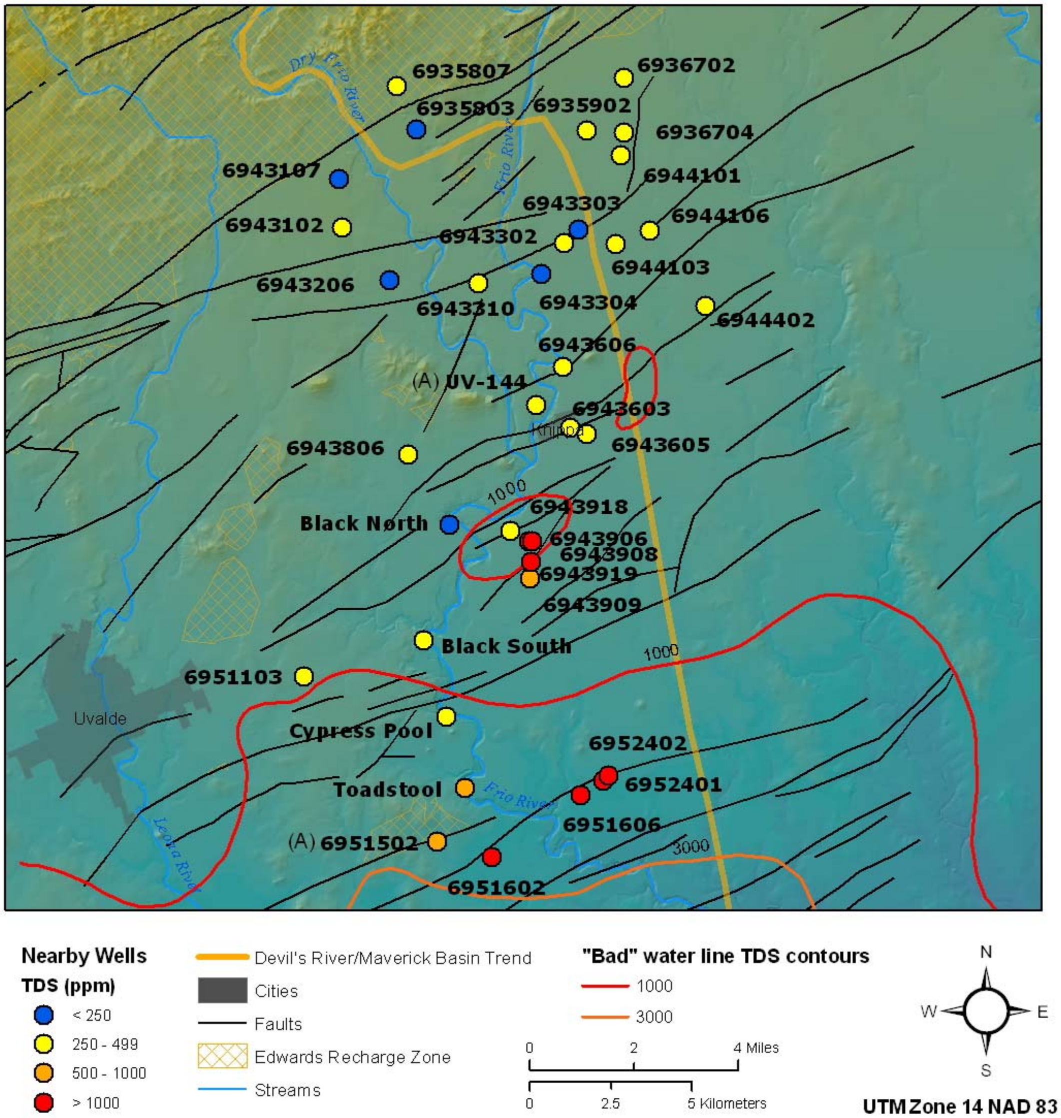

Figure 13. Locations of sampled Frio River waterholes and nearby Edwards and Austin Chalk [denoted by (A)] wells used in water chemistry comparisons. Measured total dissolved solids (TDS) content of the waterholes and wells is shown in the figure with historical Edwards Aquifer “bad-water” line TDS contours.

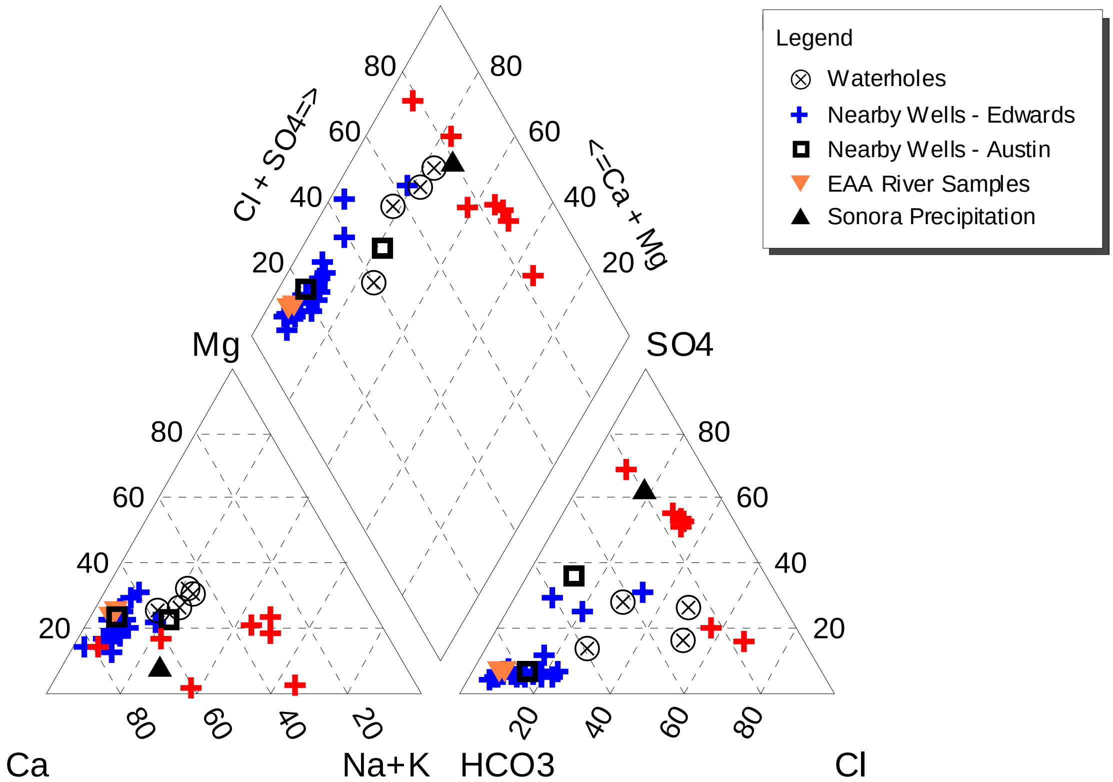

Figure 14. Piper diagram (Piper, 1944) illustrating water chemistry data from the four Frio waterholes, nearby wells, Frio and Dry Frio River samples, and precipitation. Edwards Aquifer wells with total dissolved solids content above 1000 mg/L are shown in red.

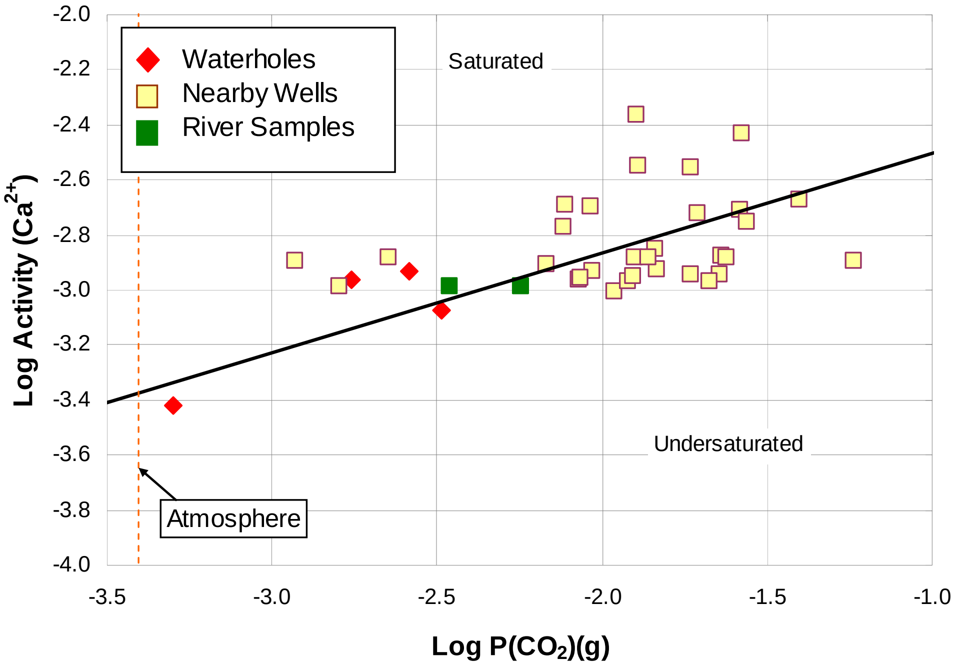

Figure 15. Plot of model calculated partial pressures of CO_2(g) versus Ca^{2+} activities in Frio waterholes, river samples, and nearby wells. Calcite saturation line and regions of calcite solubility are also shown. Partial pressure of CO_2(g) for waters in equilibrium with atmosphere is indicated by the dashed line.

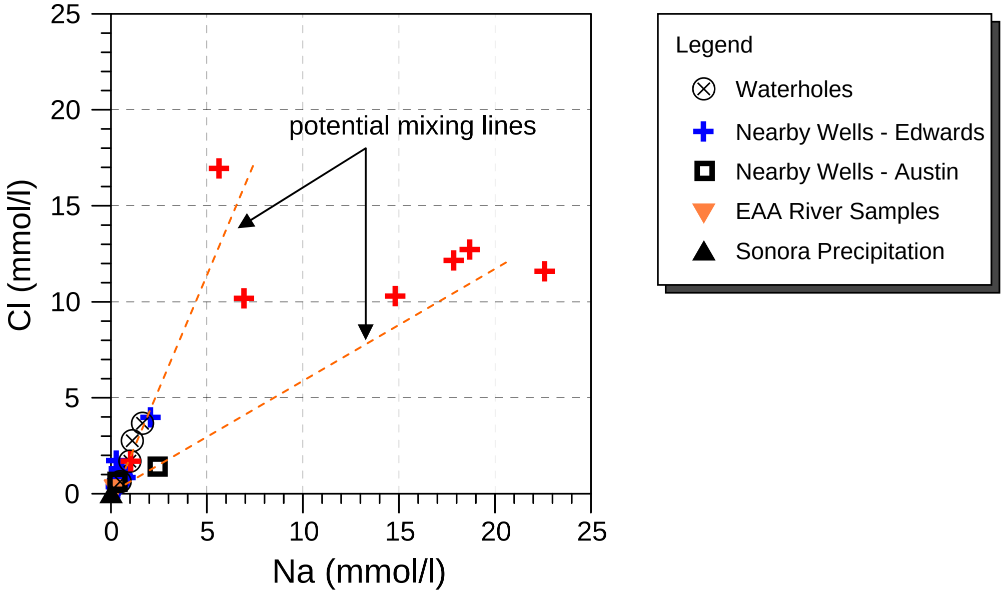

Figure 16. Plot of measured sodium (Na) and chloride (Cl) concentrations for Frio waterholes, river samples, and nearby wells. Potential mixing lines are shown. Waterhole samples chemistries generally lie on a mixing line between average Frio/Dry Frio River water compositions and more saline wells located to the east of the waterholes (but within the same large fault block). Edwards wells with TDS > 1000 mg/L are shown in red.

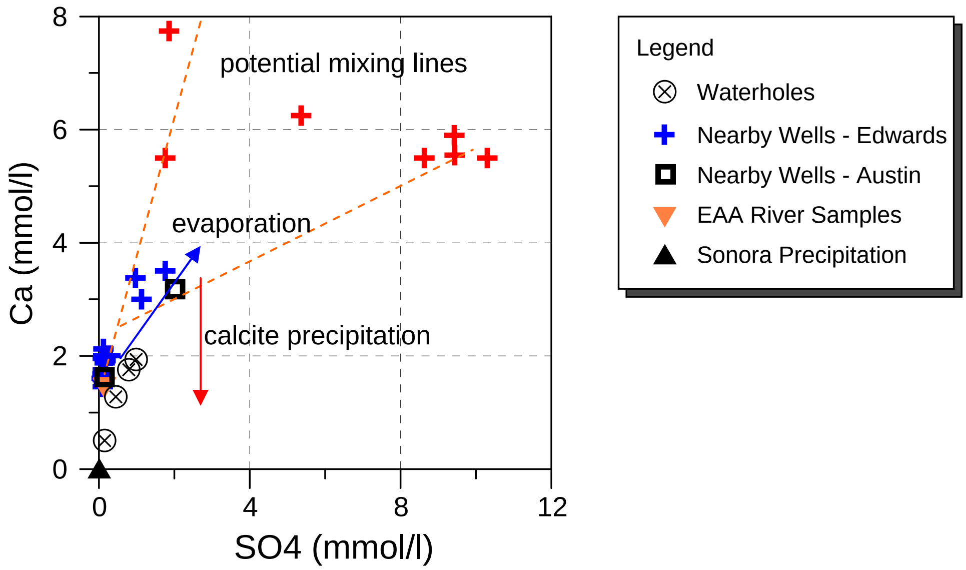

Figure 17. Plot of calcium (Ca) and sulfate (SO4) concentrations in Frio waterhole, river, and nearby well water samples. Potential mixing lines are shown by the orange dashed lines. Chemical trends resulting from evaporation and calcite precipitation are shown by the blue and red arrows, respectively. Edwards wells with TDS > 1000 mg/L are shown in red. Frio waterhole chemistries could be explained by mixing of Frio River waters and Edwards saline wells followed by calcite precipitation. Alternatively, waterhole water chemistries could result from evaporation of river waters followed by calcite precipitation.