Evaluation of the Edwards Aquifer

in Kinney and Uvalde Counties, Texas

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Prepared for:

Edwards Aquifer Authority

June 19, 2006

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ACKNOWLEGEMENTS

This work was funded by the Edwards Aquifer Authority. We thank Mr. Steve Johnson and Mr. Geary Schindel of the Edwards Aquifer Authority for their efforts in planning and executing the project. The Uvalde County Groundwater Conservation District and the Kinney County Groundwater Conservation District collaborated with the project through Memoranda of Understanding executed with the Edwards Aquifer Authority. We especially thank Mr. Vic Hildebran of the Uvalde County Water Conservation District for the many days assisting the project through field studies and gaining well access. The project would not have been possible without his assistance. We also thank Mr. Cary Spurgeon for extremely beneficial discussions of the hydrogeology of the study area. We thank Ms. Sky Lewey of the Nueces River Authority for assistance in local river and spring evaluation. We thank Dr. Tom Ewing for constructive discussions of seismic investigations of the deep geologic structure of the survey area. We thank Mr. Bill Mitchell and Mr. Rick Sample for their dedicated fieldwork that provided the data used in this analysis. We thank Mr. Bob Maclay for providing insight on the geology and hydrology of the Edwards Aquifer based on his many years of experience. Constructive reviews by Mr. Jim Winterle and Dr. Gary Walter improved this report. We thank Ms. Cheryl Patton for her assistance with report preparation. Lastly, we thank all the kind folks of Kinney and Uvalde counties who allowed us access to their properties and wells, without which this project could not have been possible.

EXECUTIVE SUMMARY

Uvalde County presently enjoys adequate groundwater resources to meet local municipal, domestic, ranching, and agricultural irrigation demands, and still its groundwater system provides significant levels of recharge to downstream users. It is estimated that 46% of the total average groundwater recharge of the San Antonio segment of the Edwards Aquifer can be attributed to Uvalde County (Edwards Aquifer Authority, 2005). Understanding the water resources of Uvalde County, including recharge and discharge, is central to the development of a representative conceptual model of groundwater flow. Although the water resources of Uvalde County derive primarily from the Edwards Aquifer, other aquifers, such as the Austin Chalk, Buda Limestone, the Trinity Aquifer and the fluvial Leona Formation, play important roles in the complex hydrogeologic regime of Uvalde County.

The objective of this investigation was to evaluate the groundwater systems in Uvalde County and develop an updated conceptual model that (i) incorporates existing and newly collected data on hydrology, geochemistry, and structural geology, and (ii) clearly defines the hydraulic and hydrogeologic relationship between the Uvalde pool and the San Antonio pool of the Edwards Aquifer. It is imperative to have an accurate, comprehensive understanding of this relationship to be able to effectively manage the water resources of the Edwards Aquifer in Uvalde County and, more generally, all water sources associated with the Edwards Aquifer in and beyond Uvalde County. The boundaries of the study area coincide with those of Kinney and Uvalde counties.

Refined or new conceptual models of the groundwater systems were developed for Kinney and Uvalde counties. Assessment of the stratigraphic and facies geology, structural geology, water chemistry, and hydrogeology provided the basis for the designation of a separate pool in the Edwards Aquifer in Kinney County which extends from a groundwater divide between Mud and Pinto creeks on the west to a zone of low permeability near the Kinney County/Uvalde County line on the east. All evidence suggests that recharge from the West Nueces River basin recharges the Kinney County pool, not the Uvalde pool of the Edwards Aquifer. This new conceptual model does not assert that there is no groundwater flow from the Kinney County pool to the Uvalde pool, only that there is limited or minimal flow.

Evaluations indicate that an average of 70,000 acre-ft annually recharges the Kinney County pool. Of this, approximately 6,000 acre-ft are annually removed by pumping and 20,000 acre-ft are discharged from Las Moras, Pinto, and Mud springs. This hypothesized conceptual model for the Kinney County pool contends that there is sufficient opportunity for discharge of the remaining 44,000 acre-ft, primarily through floodplains, nearby hydrostratigraphic units, and channels associated with rivers and creeks to the south of the Edwards Aquifer recharge zone.

The structure of the Knippa Gap was evaluated to help understand groundwater flow in Uvalde County. Geologic structural maps of the Edwards Aquifer provided an improved understanding of the principal components of groundwater flow through the Knippa Gap. Of greatest interest in this interpretation is the structure of the base of the Edwards Aquifer to the east of the City of Uvalde. There is a prominent ridge in the base of the Edwards Aquifer called the Uvalde Salient that reduces the saturated thickness of the Edwards Aquifer from 600 ft, to the east and west of the Uvalde Salient, to as little as 400 ft at the Uvalde Salient. The resulting topography of the base of the Edwards Aquifer is a series of prominent highpoints in the ridge that constrict groundwater flow through topographic saddles between the high points. This constriction results in a 4-mile wide high-capacity flow channel through central Uvalde County located immediately north of the City of Knippa. Cooks Fault forms its northern boundary and the structure of the Knippa Gap effectively forms its southern boundary. The chemistry of water in the channel is different from water south of the channel. Groundwater elevations suggest a groundwater trough coincident with the channel, which is an indication of high-transmissivity flow. Groundwater flow in the channel is essentially doubled by the addition of recharge from the Frio River-Dry Frio River basin at the Knippa

Gap. The combined effect of the structural constriction and focused recharge at the Knippa Gap cause a damming of groundwater upgradient and to the west of the Knippa Gap.

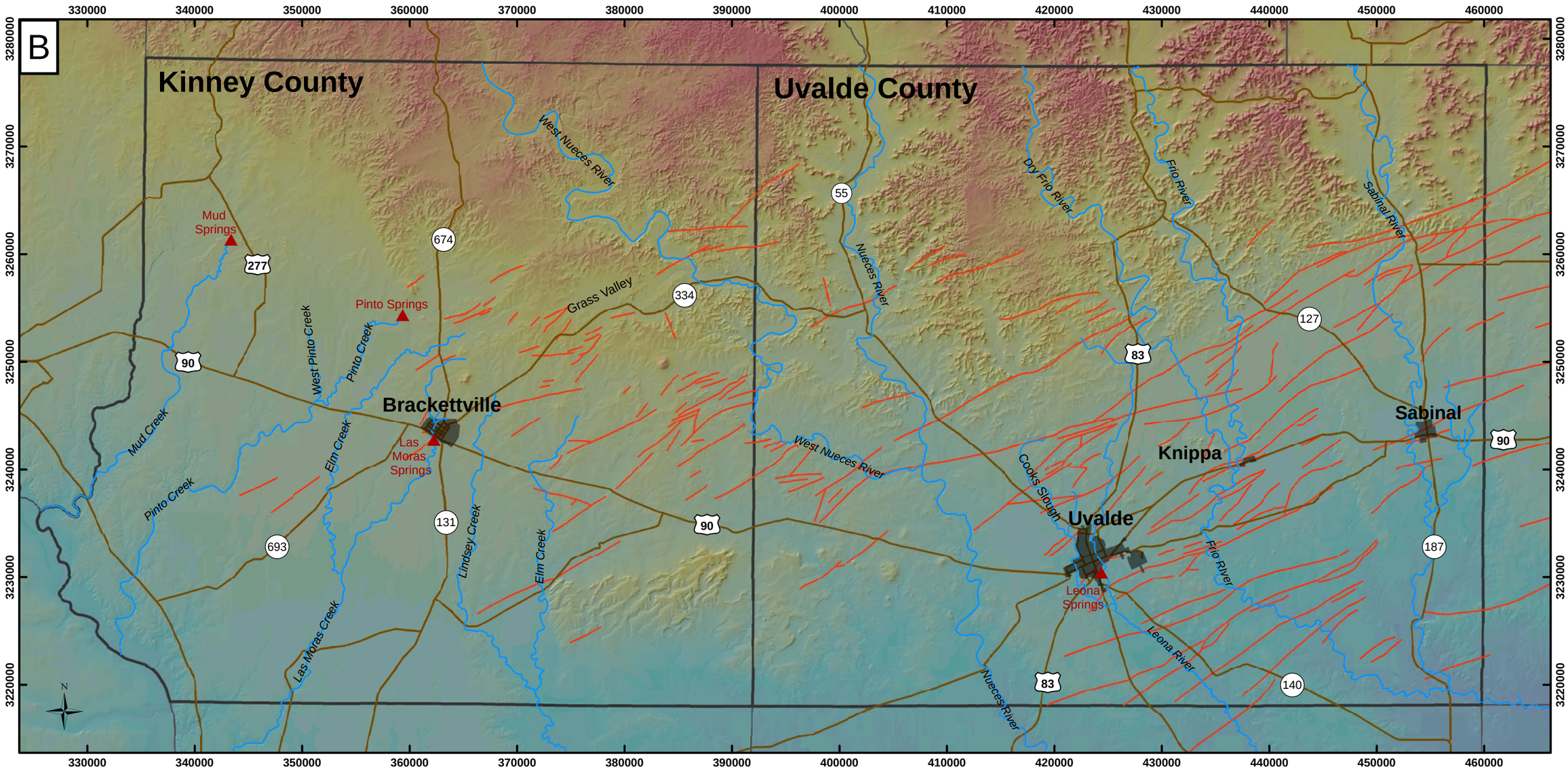
Recharge and discharge volumes of most of the Edwards Aquifer in Uvalde County are highly uncertain, although progress was made during this investigation to limit this uncertainty. Recharge from the West Nueces River is believed to recharge the Kinney County pool, not the Uvalde pool. Discharge from the Edwards Aquifer through floodplains, nearby hydrostratigraphic units, and channels associated with the Nueces, Leona, and Frio rivers is hypothesized by this investigation to significantly exceed previous estimates. These conceptual changes call for rethinking of the existing water balance calculation for Uvalde County which is based on the long-term average of 226,300 acre-ft/yr of recharge from the Nueces River-West Nueces River and the Frio River-Dry Frio River basins. Using reasonable assumptions and characterizations, it is calculated that approximately 270,000 acre-ft/yr flows through the high-capacity flow channel from the Uvalde pool to the San Antonio pool of the Edwards Aquifer. Although the assumptions inherent in this calculation make this estimate uncertain, it appears likely that total recharge in Uvalde County at least meets, if not exceeds, previous estimates. If the hypotheses provided in this report are valid, then recharge from the Nueces River and the Frio River-Dry Frio River basins, distributed recharge, and inflow from the Trinity and Austin Chalk aquifers, needs to be evaluated to improve estimates of the water balance of the Uvalde pool.

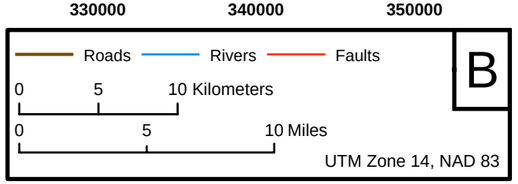
1 INTRODUCTION

The Edwards Aquifer is the primary source of water for many south-central Texas communities. It supplies residential water for 1.7 million people, provides water for agriculture, industry, and recreation, and it is the primary source of water for the city of San Antonio (Figure 1.1) (Sharp and Banner, 1997; Hovorka et al., 1998; Edwards Aquifer Authority, 2005). Uvalde County enjoys adequate groundwater resources to meet local municipal, domestic, ranching, and agricultural irrigation demands and still provide significant levels of recharge to downstream users. The importance and proper management of water resources in Uvalde County has important implications that extend across county boundaries. For example, it is estimated that 46% of the total average groundwater recharge of the San Antonio segment of the Edwards Aquifer can be attributed to flow from Uvalde County (Edwards Aquifer Authority, 2005). This estimate includes recharge from the Nueces River-West Nueces River, Frio-Dry Frio River, and the Sabinal River basins. Although the water resources of Uvalde County are dominated by the Edwards Aquifer, other aquifers, such as the Austin Chalk, Buda Limestone, Trinity Aquifer, and the fluvial Leona Formation, play important roles in the complex hydrogeologic regime of Uvalde County. Water resources cannot be effectively managed in the absence of an accurate, representative conceptual model of the groundwater flow regime. Development of a conceptual model of the groundwater flow regime of Uvalde County will require an understanding of the interactions among all local aquifers and, ultimately, the water balance in Uvalde County. Characterization of all significant sources of recharge and discharge in the study area is an integral part of calculating the water balance.

The Edwards Aquifer Authority has undertaken a number of studies to resolve questions regarding the character of the Edwards Aquifer so that its water resources can be optimally managed. Much of the management of the Edwards Aquifer is driven by policies imposed to manage the down-gradient portion of the Edwards Aquifer, including pumping demands in urban areas and flows at Comal and San Marcos springs. Understanding the down-gradient portion of the Edwards Aquifer cannot be reasonably achieved in the absence of an appropriate and defensible conceptual model for the western portion of the San Antonio segment of the Edwards Aquifer. This is particularly true given the large volume of recharge to the San Antonio segment of the Edwards Aquifer that originates in Uvalde County (Edwards Aquifer Authority, 2005). An understanding of the water regimes of Uvalde County is essential to forming a conceptual model of the western portion of the San Antonio segment of the Edwards Aquifer.

The Edwards Aquifer Authority commissioned this investigation to provide an improved conceptual model of the groundwater systems of Uvalde County through an analysis of structural geology, hydrology, and geochemistry of Kinney and Uvalde counties. Specifically, this study was designed to investigate the groundwater system of the Edwards Aquifer with respect to the principal sources of recharge and points of discharge in Uvalde County. This report presents the findings of this investigation.





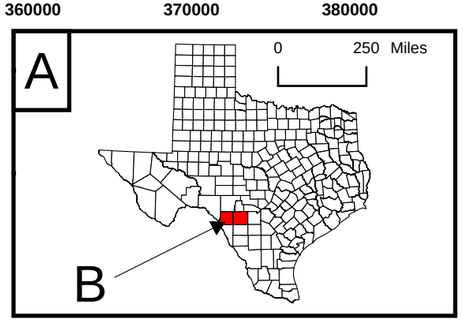


Figure 1.1: Location map of the study area.

2 OBJECTIVES AND PROJECT SCOPE

The objective of this investigation is to evaluate the water systems in Uvalde County, Texas and develop an updated conceptual model that (i) incorporates existing and newly collected data on hydrology, geochemistry, and structural geology, and (ii) clearly defines the hydraulic and hydrogeologic relationship between the Uvalde pool and the San Antonio pool of the Edwards Aquifer. An accurate, comprehensive understanding of this relationship is needed to effectively manage the water resources of the Edwards Aquifer in Uvalde County and, more generally, all water resources associated with the Edwards Aquifer in and beyond Uvalde County.

Although the water systems of Uvalde County were the focus of this study, the study area boundaries were expanded during the project to include areas where an understanding of hydrogeology was important to development of a conceptual flow model for Uvalde County. The originally proposed boundaries extended from the hypothesized groundwater divide near Brackettville in the west to middle Medina County in the east. A preliminary conceptualization of the hydrogeologic systems of Kinney and Uvalde counties at the onset of the project was that the eastern half of Kinney County was part of the Uvalde pool of the Edwards Aquifer. However, findings during this study suggested that much of Kinney County is in a groundwater pool mostly separate from the Uvalde pool of the Edwards Aquifer. Thus, the project boundaries were extended west to the Val Verde County line to enable evaluation of the Edwards Aquifer and the Edwards-Trinity Aquifer in Kinney County and support a clearer delineation of the Kinney County pool.

Similarly, the eastern boundary of the study was modified based on early evaluation of results. The originally proposed eastern boundary was moved from middle Medina County to the Medina County/Uvalde County line after early analyses of groundwater elevation measurements in the confined zone of the Edwards Aquifer indicated there was no significant groundwater flow from the northwestern corner of Medina County into Uvalde County. As a result, the boundaries of the revised study area coincided with those of Kinney and Uvalde counties (Figure 1.1).

The geologic setting and the groundwater flow systems in Uvalde County are complex. To adequately understand and conceptualize groundwater flow in the Edwards Aquifer in Uvalde County, it was necessary also to understand and conceptualize flow in the other aquifers in Uvalde County, insofar as they affect the Edwards Aquifer. Therefore, it was necessary to include the Buda Limestone, Austin Chalk, Trinity, Edwards-Trinity, and Leona Formation aquifers in the investigation. In addition, a limited number of water wells in Uvalde County draw from igneous intrusions and from the Anacacho Formation. Although igneous intrusions and the Anacacho Formation are not typically considered aquifers, they do serve locally as aquifers and play limited roles in the overall groundwater regime. These local aquifers have been included in the study to provide a comprehensive interpretation of the groundwater system of Uvalde County. The scope of this investigation was essentially limited to the subsurface, however, comprehensive assessment of the groundwater systems of Uvalde County could not be undertaken without also evaluating locations and quantities of surface recharge and discharge in the study area.

3 PREVIOUS INVESTIGATIONS

Previous studies provide the foundation for the investigation of the aquifers in the study area. Foremost are a series of county studies commissioned by the Texas Water Commission in cooperation with the United States Geological Survey. These studies include investigations of Kinney (Sayre, 1936; Sayre and Bennett, 1942; Bennett and Sayre, 1962) and Uvalde (Welder and Reeves, 1962), and Medina (Holt, 1956, 1959) counties. These seminal reports provide comprehensive summaries of the understanding at the time of their publication. Recent studies by Maclay and Small (1986), Maclay and Land (1988), Maclay (1995), and Groschen (1996) provide assessments of the San Antonio segment of the Edwards Aquifer.

Early estimates of focused and distributed recharge to the Edwards Aquifer were predicated on an approach originally developed by Lowry (1955), advanced by Petitt and George (1956), and refined by Garza (1962, 1966). This approach was further refined by Puente (1975, 1976, 1978). The Puente approach was used for the next 25 years to estimate recharge of the Edwards Aquifer. The recharge analysis developed by Puente (1975, 1976, 1978) was modified in recent Edwards Aquifer recharge studies conducted by HDR Engineering (2002) and LBG-Guyton (2005).

Rose (1972) and Hovorka et al. (1993, 1996) provided descriptions of the depositional environment of Edwards Aquifer strata in the study area, particularly in terms of how the depositional environment affects the hydraulic properties of the Edwards Aquifer. Some hypotheses suggested that the relatively high density of igneous intrusions in the study area (Rose, 1972; Ewing, 2004) may affect the groundwater flow regime. Significant analyses of the hydraulic properties have been performed (Small and Maclay, 1982; Mace, 2000; Mace and Hovorka, 2000; Hovorka, et al., 1998) leading to a geostatistical assessment of the transmissivity of the San Antonio segment of the Edwards Aquifer by Painter et al. (2002). The prospect for conduit development in the Edwards Aquifer, including Uvalde County and part of Kinney County, was recently investigated by Worthington (2004) and Hovorka et al. (2004).

Rose (1972) provided a regional synthesis of the stratigraphy of the Edwards Aquifer in southern Texas. Analysis by Small (1986) provided the geological structural framework of the Edwards Aquifer. Recent studies by Clark and Small (1997) and Clark (2003) provided improved understanding of the structural geology in Uvalde County.

Piezometric contour maps for the study area illustrate the general groundwater flow patterns within the San Antonio segment of the Edwards Aquifer. Water is recharged from river basins located in the Edwards Aquifer contributing and recharge zones to the north. After entering the subsurface, the direction of flow is generally from west to east through the confined zone. Bennett and Sayre (1962) provided maps of groundwater elevation contours for Kinney County for the periods 1930–1940, January 1952, and August 1956. Welder and Reeves (1962) presented a similar map for Uvalde County for December 1957. The groundwater contour map by Maclay and Land (1988) for the winter of 1973 is commonly cited as representative elevations for “normal precipitation” periods in the San Antonio segment of the Edwards Aquifer. The Maclay and Land (1988) study, however, is terminated to the west near Brackettville, which at that time was perceived as a groundwater divide and the western boundary of the San Antonio segment of the Edwards Aquifer. Regional maps of the piezometric surface were provided by Bush et al. (1992) and Kuniansky and Holligan (1994). Several smaller-scale studies located a groundwater divide in the Edwards Aquifer near Brackettville in Kinney County (Sayre and Bennett, 1942; Bennett and Sayre, 1962; Bush et al., 1992; Hovorka et al. 1993; LBG-Guyton, 1995; Maclay, 1995; Groschen, 1996; Khorzad, 2003; and Snyder, 2004). Most numerical models of the San Antonio segment of the Edwards Aquifer specified a groundwater divide that aligns with Brackettville as the western boundary (Klemt et al., 1979; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992; Lindgren et al., 2004),

with the exception of regional Edwards-Trinity Aquifer models by Kuniansky and Holligan (1994) and Anaya and Jones (2004).

Groundwater flow modeling studies that account for long-term aquifer recharge and discharge balancing provide valuable insight into the reasonableness and realism of groundwater flow conceptual models. Lindgren et al. (2004) provided a thorough review of these models and their uses. The general premises of the models are mostly consistent. Recharge is specified in the recharge zone as focused recharge in river basins and as distributed subsurface recharge in the inter-stream areas of the contributing and recharge zones. New recharge models for the Nueces River-West Nueces River, the Frio River-Dry Frio River, and the Sabinal River basins by HDR Engineering (2002) and LBG-Guyton (2005) have improved upon previous approaches to estimate recharge originally developed by Lowry (1955), advanced by Petitt and George (1956), refined by Garza (1962, 1966), and further refined by Puente (1975, 1976, 1978).

The southern boundary of the Edwards Aquifer in the study area has been characterized as a no-flow boundary with the exception of discharge occurring from springs (e.g., Mud, Pinto, Las Moras, and Leona). Previous discharge rates through Leona Springs and the Leona River floodplain (summarized in Lindgren et al., 2004; Edwards Aquifer Authority, 2005) were recently refined in investigations by Green et al. (2003) and Green (2004) based on geophysical data and aquifer test results.

Holt (1956, 1959) first identified a groundwater flowpath in north Medina County whose direction of flow from the surface recharge (Edwards Aquifer outcrop belt) first tracks to the southwest, past the western end of the Medina Lake Fault, then turns to the southeast and eventually to the northeast parallel to the main trend of the Balcones Fault zone to the points of ultimate discharge at Comal and San Marcos springs. Evaluations by Maclay and Land (1988) and Maclay (1995) corroborated Holt's (1956, 1959) conceptualization of groundwater flow in the central portion of the San Antonio segment of the Edwards Aquifer. Maclay and Land (1988) interpreted this flowpath to extend into Uvalde County. Clark and Journey (2005) recently suggested that the south-central flow unit in the confined zone does not extend into Uvalde County.

Hydrochemical information for groundwater in Kinney, Uvalde, and Medina counties has generally been disseminated in two ways: (1) through brief descriptions of water quality analyses assembled and presented as part of the Texas Water Commission studies of Kinney County (Bennett and Sayre, 1962), Uvalde County (Welder and Reeves, 1962), and Medina County (Holt, 1956), and (2) as part of compilations and analyses of hydrochemical data for the entire San Antonio segment of the Edwards Aquifer (e.g., Pearson and Rettman, 1976; Maclay, et al., 1980; and Groschen, 1996).

Within the area of interest for this study, Kinney, Uvalde, and far western Medina County, Bennett and Sayre (1962), Welder and Reeves (1962), and Holt (1956) provided brief descriptions of water quality pertinent to potential uses for irrigation and human consumption and included tables of chemical analyses for samples collected by the U.S. Geological Survey primarily in the late 1930's and 1940's for Kinney County and Medina County, and the late 1950's for Uvalde County. Bennett and Sayre (1962) included a brief description of water quality for each water-bearing formation within Kinney County, while Holt (1956) did the same for Medina County. Most of the analyses in the Texas Water Commission reports included measurements of major constituents but did not include measurements of pH (especially for Kinney County), which precludes their effective use in subsequent hydrochemical modeling. Bennett and Sayre (1962) and Welder and Reeves (1962) noted the general decrease in water quality of Edwards wells to the south and southwest within Kinney and Uvalde counties. They associated the presence of sulfate and hydrogen sulfide in wells of higher total dissolved solids (TDS > 1000 ppm) and attributed the occurrence of hydrogen sulfide to the reduction of sulfate from anhydrite by hydrocarbons. Bennett and Sayre (1962) and Welder and Reeves (1962) delineated an approximate boundary of the saline-water line (water free from hydrogen sulfide to the north of this line) along a trend similar to the track of

U.S. Highway 90 in Kinney County and continuing across the southern portion of Uvalde County. Wells to the south of this boundary are high in TDS (>1000 ppm), sulfate, and chloride. This saline-water zone is also known as the bad-water zone and is primarily defined as the zone of high TDS (>1000 ppm) within the Edwards Aquifer. The saline-water line in Kinney and Uvalde counties was additionally constrained by subsequent investigations (e.g., Harden, 1968; Maclay et al., 1980). Chemical analyses results published in the Texas Water Commission county water resources reports have been incorporated as much as possible into the Texas Water Development Board groundwater database (Texas Water Development Board, 2005). However, there are many wells that do not appear in the Texas Water Development Board groundwater database but do have chemical analytical results listed in the county groundwater bulletins. These wells were never assigned a state well number under the numbering system used today (Texas Water Development Board, 2005). The Texas Water Development Board is working to identify and incorporate data from these wells, but currently the data are excluded from the database.

Pearson and Rettman (1976) compiled chemical analyses from 92 wells in the Edwards Aquifer for the Edwards Underground Water District. Wells were sampled in the early 1970's and approximately 20 of the 92 samples were collected within the region of interest for this project (Kinney, Uvalde, and far western Medina Counties). Based on distributions of chemical species and calculated saturation indices for several mineral types, Pearson and Rettman (1976) grouped Edwards Aquifer waters into five chemical types: recharge, main fresh-water, varied, and two types of transitional and saline waters. Most wells sampled in Uvalde County were placed in the varied group, which contained water characteristics of both the main fresh-water and transitional groups. Those wells in central Uvalde County included in the main fresh-water group of Pearson and Rettman (1976) occur in a fast-flow zone identified by structural and hydrologic analyses in this study.

Maclay et al. (1980) summarized hydrochemical data collected in the 1970's [including data listed by Pearson and Rettman (1976)] for Edwards Aquifer wells in the San Antonio segment (ranging from Kinney County in the west to Hays County in the east) of the Edwards Aquifer. The summary included many wells located in Kinney and Uvalde counties (23 of 123 wells sampled are located in the area of interest), and surveyed a wide variety of chemical constituents including stable isotopes and tritium. Unfortunately, few if any, stable isotope and tritium data were collected in Kinney County and the western portions of Uvalde County. The Maclay et al. (1980) summary also provided calculations of mineral saturation indices. Using the hydrochemical data, Maclay et al. (1980) delineated multiple hydrochemical facies for water in the Edwards Aquifer and identified six aquifer zones based on water type. In particular, Maclay et al. (1980) identified increases in magnesium and sulfate as being indicative of zones of slower circulation within the fresh-water zone. Waters high in TDS, sulfate, and chloride concentrations were identified as occurring in zones of very slow groundwater circulation. Quality control of the collected chemical data was very good and most of the data are useful for hydrochemical modeling. Data summarized in this report as well as those in the Pearson and Rettman (1976) report, are incorporated into the Texas Water Development Board groundwater database.

Groschen (1996) analyzed hydrochemical trends for two selected flowpaths within the Edwards Aquifer. One of these flowpaths, called the western Medina flowpath by Groschen (1996), includes data from the eastern edge of the study area (western Medina County and eastern Uvalde County). For this flowpath, Groschen (1996) noted hydrochemical trends for several parameters as water flowed from the recharge area in Medina County toward Comal Springs. Among these trends, calcium and alkalinity showed decreasing concentrations along the flowpath, whereas magnesium increased in concentration. Specific conductance along the flowpath was found to be relatively constant. Although these trends are consistent with dedolomitization, a process involving the chemical replacement of dolomite with calcite, the concentration of sulfate along the flowpath suggested that dissolution of sulfate minerals was not driving the dedolomitization process, and data were insufficient to confirm that dedolomitization occurs. In general, Groschen (1996) found that the water chemistry data were not sufficient to confirm any particular

flowpath. Groschen (1996) also observed no significant change in water chemistry for wells along the western Medina flowpath over the period 1968 to 1990. Results of limited stable isotope analyses indicated fresh water in eastern Uvalde County and western Medina County is of meteoric origin. In their study, Maclay et al. (1980) also noted that the chemical composition of water within the aquifer did not change significantly over the time period analyzed (1970–1978).

Hydrochemical studies of the saline-water zone of the Edwards Aquifer in Kinney and Uvalde counties have also provided useful information for assessing hydrochemical trends for the groundwater flow systems in the study area. Groschen and Buszka (1997) found that the saline-water zone was compartmentalized and could be generally categorized into two distinct hydrochemical regimes, one in which some fresh water mixing occurs and a stagnant zone that has no fresh-water input. The two wells in the study region that are cited in the Groschen and Buszka (1997) report are located in the fresh-water/saline-water-transition zone, which includes some mixing with water from the fresh-water zone. This is consistent with the varied and transitional group designations of Pearson and Rettman (1976) and the calcium-magnesium-sulfate water type identified by Maclay et al. (1980) for wells in southern Uvalde County. Interestingly, the Uvalde County well sampled in the Groschen and Buszka (1997) report (well YP-69-59-101) was sampled again in 1992 (as reported in the Texas Water Development Board database) and produced remarkably less saline water (TDS change from 1800 to 870 ppm). The Groschen and Buszka (1997) saline-water hydrochemical report provides limited data to identify sources of strontium and other constituents in the water samples. Based on the information in the report, it appears that sources of strontium and fluoride are carbonate rocks and not igneous intrusions.

Clement and Sharp (1988) and Oetting et al. (1996) also reported on water types within the saline-water zone of the Edwards Aquifer. They noted that the water type of the saline-water zone in south and southwestern Kinney County is distinctly different than the water type observed in the saline-water zone of southern Uvalde County. Notably, the Kinney County saline waters are high in sulfate and low in chloride and sodium, whereas the Uvalde County saline waters are high in chloride and sodium as well as sulfate. Clement and Sharp (1988) suggested that chloride was flushed from the aquifer rocks and thus was found in low concentrations in groundwater from the Kinney County saline-water zone. Maclay (1995) noted that, while rocks in the saline-water zone are generally more porous, the pores are not well connected. It seems likely that the high sulfate in the Kinney County samples is due to the much greater content of gypsum and anhydrite in the Maverick Basin rocks of Kinney County, and the low chloride is due to the low connectivity of primary porosity in those rocks. That is, rather than being flushed, the chloride in primary pore spaces is not yet accessible. Rocks of the eastern Maverick Basin and the Devils River Trend in the Edwards Aquifer saline-water zone of Uvalde County originally had fewer sulfate minerals and have undergone greater dissolution and dedolomitization. Thus, more chloride is available to enter solution and less sulfate is derived from remaining gypsum and anhydrite. Oetting et al. (1996) concluded that the increased amount of chloride in the saline-water zone of Uvalde County was a result of mixing of fresh water with deep Edwards Aquifer brines and leakage of high chloride waters upward from underlying stratigraphic units. Oetting et al. (1996) noted that the saline-water zone of southern Kinney County occurs in rocks that are isolated from underlying aquifers due to the absence of significant faulting and igneous intrusions, and thus, this portion of the saline-water zone does not have a source for high chlorides.

The USGS conducted an aeromagnetic survey that included part of Uvalde County (Smith et al., 2002). Survey results illustrated the extent, size, and density of igneous intrusions, some of which do not have a surface topographic expression. The aeromagnetic survey results are consistent with interpretations by Rose (1972) and Ewing (2004) of igneous activity in Kinney and Uvalde counties. The aeromagnetic survey (Smith et al., 2002), however, revealed a higher density of igneous intrusions in Uvalde County than had previously been mapped based on surface geology and borehole data.

4 DATA COLLECTION AND ANALYSIS

An assessment of the existing literature on geologic structure, water chemistry, and hydrogeology of the study area was performed at the onset of the project. Subsequent to the assessment of existing information, additional data were collected to support in-depth analysis of the water resources of Uvalde County. Field investigations of the geologic structure were performed and information was collected from existing and newly completed wells to improve the resolution of structural interpretations. Specifically, the following sources of information were utilized: Bureau of Economic Geology Edwards Aquifer well database (Collins and Hovorka, 1997), Texas Water Development Board online well database for Uvalde County, Holt (1956), wells provided by Ewing (2005), Welder and Reeves (1962), and Uvalde County Underground Water Conservation District well records. In addition, an interpretation of seismic data (Ewing, 2005) was incorporated into the fault and structure contour map of the Uvalde Salient. Fault interpretations used to develop the fault framework presented in this report include the following maps: Holt (1956), Collins and Hovorka (1997), and Clark (2003). The San Antonio (Barnes, 1983) and Del Rio (Barnes, 1977) 1º×2º geological atlas maps were used along with mapping of Holt (1956) to constrain the outcrop extent of Edwards Aquifer geologic units. Well and map data were used to construct gridded surfaces of the top and base of the Edwards Aquifer. These surfaces included fault interpretations taken from the sources listed above. Combining these structural surfaces with digital elevation data, a three-dimensional characterization of the Edwards Aquifer outcrop and subsurface in Kinney and Uvalde counties was generated. Multiple iterations were performed to obtain a model that provided a reasonable match with existing geological maps, and honored the well and seismic data interpretations. During this process, newly acquired well data were added to the database and some well data found to be erroneous were excluded from the database used for structural analysis.

Water chemistry data were compiled from existing sources to assist in the identification of waters according to their chemical characteristics. Historical data were derived from the Texas Water Development Board groundwater database (Texas Water Development Board, 2005), which was downloaded in Microsoft Access format. Initially, the downloaded database contained data through 2003, but a newer version of the database, which contained data through mid-2004, was acquired during the project. These data were augmented with results of water sample analyses that were collected by the Edwards Aquifer Authority, but not yet incorporated into the Texas Water Development Board groundwater database, and by strontium data collected by the Edwards Underground Water District (Waugh, personal communication) but not included in the 2004 version of the Texas Water Development Board groundwater database. Numerous published reports (e.g., Livingston, 1947; Holt, 1956; Petitt and George, 1956; Bennett and Sayre, 1962; Welder and Reeves, 1962; Pearson and Rettman, 1976; Maclay et al., 1980; Groschen, 1996; and Edwards Aquifer Authority hydrological status reports through 2004) were reviewed to determine if any additional hydrochemical data could be added to the groundwater database. With the exception of wells not assigned numbers in the current state well numbering system, most hydrochemical data contained in the reports appeared to have been incorporated into the database. Eleven additional samples were added from the reports by comparing and correlating the historical well numbers and sample dates from the published data with those listed in the groundwater database. Southwest Research Institute staff also assisted Edwards Aquifer Authority staff in the identification of optimal locations from which to sample water in support of this project, although results of these analyses are not yet available.

Once the groundwater database was acquired, data for all wells within the region of interest for this study were extracted and assembled into spreadsheet format. Initially, data were extracted for Edwards Aquifer wells with available water quality analyses located in Uvalde County, eastern Kinney County, and western Medina County. As the study progressed, additional data were extracted to include wells located in the western part of Kinney County and to include wells completed in all aquifers within the study region. The water quality data were selected for analysis in this study because they contain information

regarding the concentration of major chemical constituents of the groundwater that are most important for hydrochemical modeling. The number of wells in Kinney and Uvalde counties with infrequent constituent data (e.g., trace elements and isotopes) was not sufficient to be useful in the analyses for this study; thus, the infrequent constituent data were not included. The data were then sorted into separate spreadsheets by aquifer code (Nordstrom and Quincy, 1999). For the Edwards Aquifer wells in the study area, this extraction produced data for 667 samples from 266 wells. Water well data, such as location and depth, were extracted from a separate portion of the database and associated with the water quality data based on state well number.

The water quality data for each sample entry were then exported into PHREECi version 2.8 (Parkhurst and Appello, 1999) and mineral saturation indices for common minerals occurring in the Edwards Aquifer rocks (e.g., calcite, dolomite, gypsum, etc.) were calculated. The hydrochemical calculations assumed chemical equilibrium in the groundwater and utilized the reported total alkalinity (as given in the Texas Water Development Board database) to constrain the bicarbonate content of each sample. Bicarbonate concentrations included in the Texas Water Development Board database were not used in the hydrochemical calculations because they appear to have been calculated from the total alkalinity using a standard conversion factor that did not account for varying amounts of dissolved CO_2 (not measured directly by alkalinity), which may be an important contributor to total bicarbonate, especially in waters with pH below 7. For those samples in the database that did not have a measured pH value, a pH of 7 was assumed in the calculations. This assumption has a potentially important impact on calculated saturation indices for calcite and other carbonate minerals; subsequent trend analyses utilizing the saturation index of calcite did not include these samples. As defined in PHREEQCi (Parkhurst and Appello, 1999), the saturation index represents the relative saturation of a mineral in a particular solution. Saturation index values greater than zero (positive) indicate that a solution is saturated with respect to a given mineral, while values less than zero (negative) indicate undersaturation. Note that saturation as represented by a positive saturation index does not necessarily mean that a given mineral will precipitate as these reactions are often limited by other factors such as kinetics. Moreover, the calculated saturation index is often quite dependent on pH. For instance, loss of CO_2(g) from solution during sampling can produce an artificially elevated pH measurement, resulting in conditions that are saturated with respect to calcite, even though the water in the subsurface is actually undersaturated with respect to calcite. The effect of pH uncertainty is addressed in Groschen (1996).

Once completed, information calculated using PHREEQCi was combined with the original water chemistry data, and the data were processed to select a single representative sample for each well in the data set. Well samples with a limited number of available parameters and well samples with measured water chemistry indicating charge imbalance (> 5% charge balance error) were excluded from the selection process. Of the remaining samples, wells with only a single measurement were included, and wells with multiple samples were reviewed to select a representative sample. The representative sample approach was used rather than an averaging of sample data to eliminate potential artifacts of averaging, such as induced charge imbalance or changes in calculated saturation indices for minerals. In general, representative samples selected were (i) close to average values for a set of samples from a given well, (ii) contained a full suite of parameters, including strontium and fluoride, and (iii) were collected more recently. The representative sample set for each aquifer code was then extracted into a new spreadsheet. Statistical and graphical analyses utilized this representative subset. More than 260 wells were included in the Edwards Aquifer set (aquifer codes 11 and 13); 44 wells were included in the Glen Rose aquifer set (aquifer code 28); 89 wells were included in the Carrizo-Wilcox Aquifer set (aquifer code 10); and 111 wells were included in the aquifer code 22 set, which combines waters sampled from the Austin Chalk, Leona Gravel, Uvalde Gravel, Eagle Ford Shale, and Anacacho Limestone. In Kinney and Uvalde counties the majority of these samples are from the Austin Chalk or the Leona/Uvalde Gravels. For this study, detailed analysis focused on the Edwards Aquifer samples with some minor analysis of the Austin Chalk and Leona/Uvalde/alluvial samples.

The representative sample chemistry data were analyzed graphically using geographic information system software (ArcGIS ver. 9, ESRI). Data to construct contour maps of chemical constituents and other aquifer features were processed geostatistically using the default ordinary kriging method found in ArcGIS without introduction of anisotropy. A principal components analysis was also conducted for the Edwards Aquifer representative sample set to evaluate whether a grouping of variables could assist in analyzing the hydrochemical information contained in the data. principal components analysis calculations were performed using raw data and standardized data (normalized to the standard distribution for each variable). The principal components analysis and other statistical calculations were performed using SYSTAT Ver. 11 (Systat Software, 2004).

The greatest expenditure of effort by project staff was focused on data collection and analysis as part of the synoptic water-level surveys. Results from these surveys provided new data to constrain the piezometric surface contour map of the study area. Approximately 300 wells in Kinney and Uvalde counties were inspected during the execution of the project. Most inspected wells were not included in the synoptic survey. The reasons why wells were not included in the study varied and included the following:

1. The wellbore could not be accessed by water-elevation measurement instruments.
2. Pumps were running at the time of inspection.
3. Water levels in the wells were not detectable (i.e., either the water level was too deep or debris was encountered in the well bore).
4. The wells were already included in the existing Edwards Aquifer Authority synoptic water-level survey well inventory.

As a result of field inspections, a total of 121 wells, 35 wells in Kinney County and 86 wells in Uvalde County, were added to the synoptic water-level survey well inventory. These wells were combined with the 1 Kinney County well and the 34 Uvalde County wells in the existing Edwards Aquifer Authority synoptic water-level survey so that a total of 36 Kinney County wells and 120 Uvalde County wells were considered in this investigation. The wells added during this project were concentrated in areas critical to the accurate interpretation of the water systems of Uvalde County and were sufficient to support the analyses performed in this investigation. All new Kinney County wells added to the well inventory were Edwards Aquifer wells. Uvalde County wells added to the well inventory represented all major formations, with the exception of the Glen Rose Formation. Table 1 summarizes wells in formations other than the Edwards Aquifer. All wells in the pre-existing Edwards Aquifer Authority well inventory are Edwards Aquifer wells. Data for the newly acquired wells are summarized in Appendix A. The locations of wells used in the synoptic water-level elevation survey during this investigation are illustrated in Figure 4.1.

Table 1. Formations of non-Edwards Aquifer wells added to well inventory. Wells not listed here are in the Edwards Aquifer.

Well Identifier	Formation
UV014	Austin Chalk or Edwards Aquifer
UV015	Austin Chalk
UV044	Leona Formation
UV059	Austin Chalk
UV060	Austin Chalk or Edwards Aquifer
UV071	Austin Chalk or Serpentine
UV073	Serpentine
UV083	Austin Chalk
UV085	Austin Chalk
UV086	Austin Chalk
UV087	Anacacho Formation
UV089	Leona Formation
UV093	Buda Formation or Edwards Aquifer
UV103	Buda
UV105	Austin Chalk
UV113	Austin Chalk
UV118	Austin Chalk

The elevations of all wells added to the synoptic water-level elevation survey well inventory were surveyed by Raba-Kistner, Inc. The elevation survey was conducted in accordance with accepted survey guidelines and professional standards described in Appendix B. Synoptic water-level elevation survey results are included in Appendix A. Results from the elevation survey are included in Appendices B.

Three synoptic surveys were undertaken as part of the investigation. The dates of the synoptic surveys were July 2005, October-November 2005, and January-February 2006. Additional depth-to-water measurements were taken at the time the wells were first inspected. These additional measurements provided added opportunities to evaluate trends in groundwater elevation changes. In general, groundwater elevations were lowest during the January-February 2006 synoptic survey. Groundwater elevations during the October-November 2005 synoptic survey were generally higher than the July 2005 synoptic survey, although a number of wells indicated the opposite. A contour map of groundwater elevations from the January-February 2006 synoptic survey is illustrated in Figure 4.2. Only one groundwater elevation from the January-February 2006 was anomalous, UV088, which is located in the City of Knippa. The 795.8 ft above sea level (asl) groundwater elevation at UV088 is approximately 20 ft lower than neighboring Edwards Aquifer wells. Groundwater elevations at UV088 taken during the two earlier synoptic surveys, however, were similar to elevations taken at the neighboring Edwards Aquifer wells. A possible reason for the anomalously low January-February synoptic reading is that the pump at UV088 or another nearby well was running immediately prior to the measurement or that a pump in a nearby well running at the time of the measurement. All other groundwater-level measurements taken during the January-February synoptic survey were internally consistent.

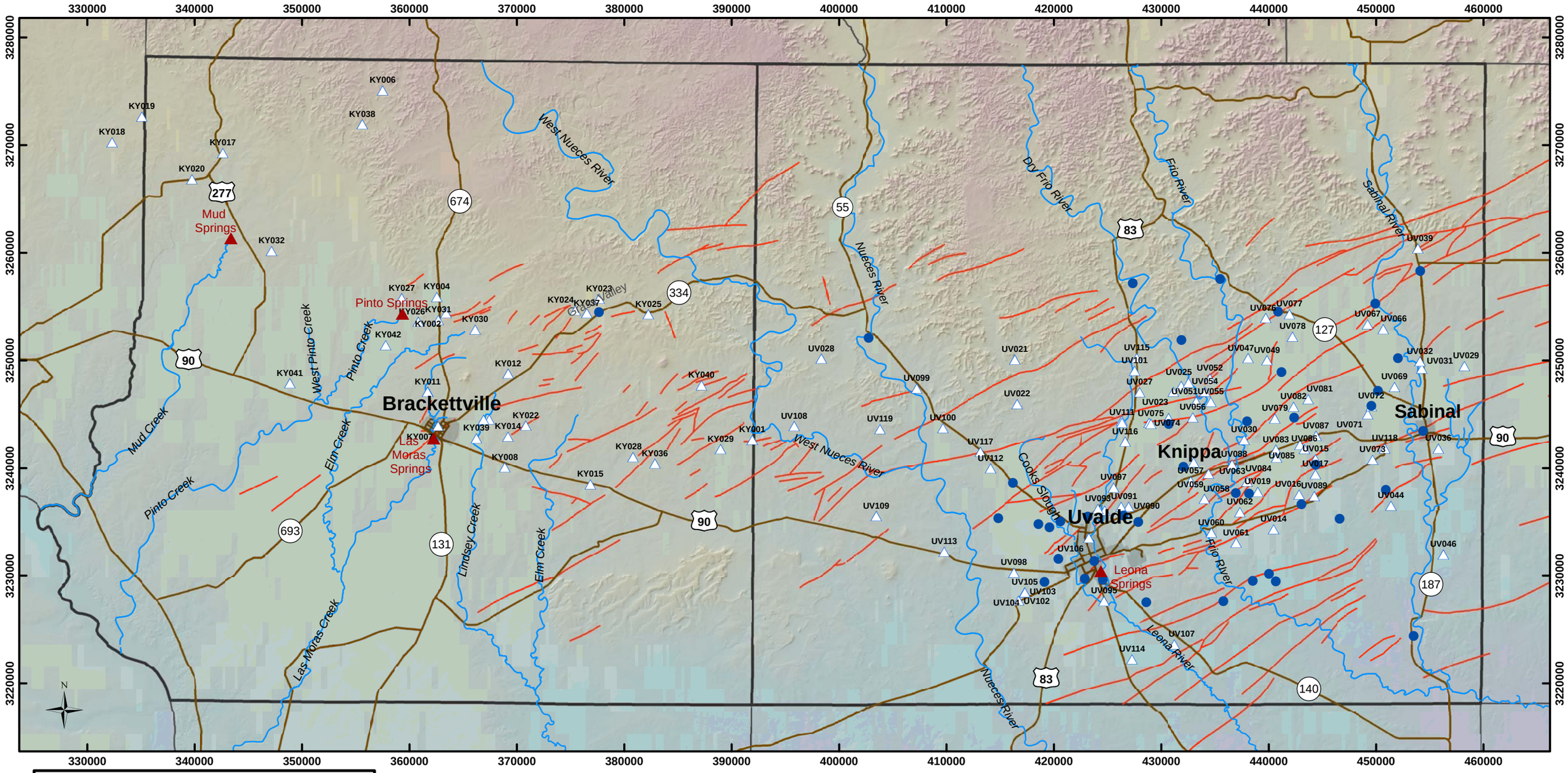


Figure 4.1: Map of locations of wells included in the synoptic water-level elevation survey.

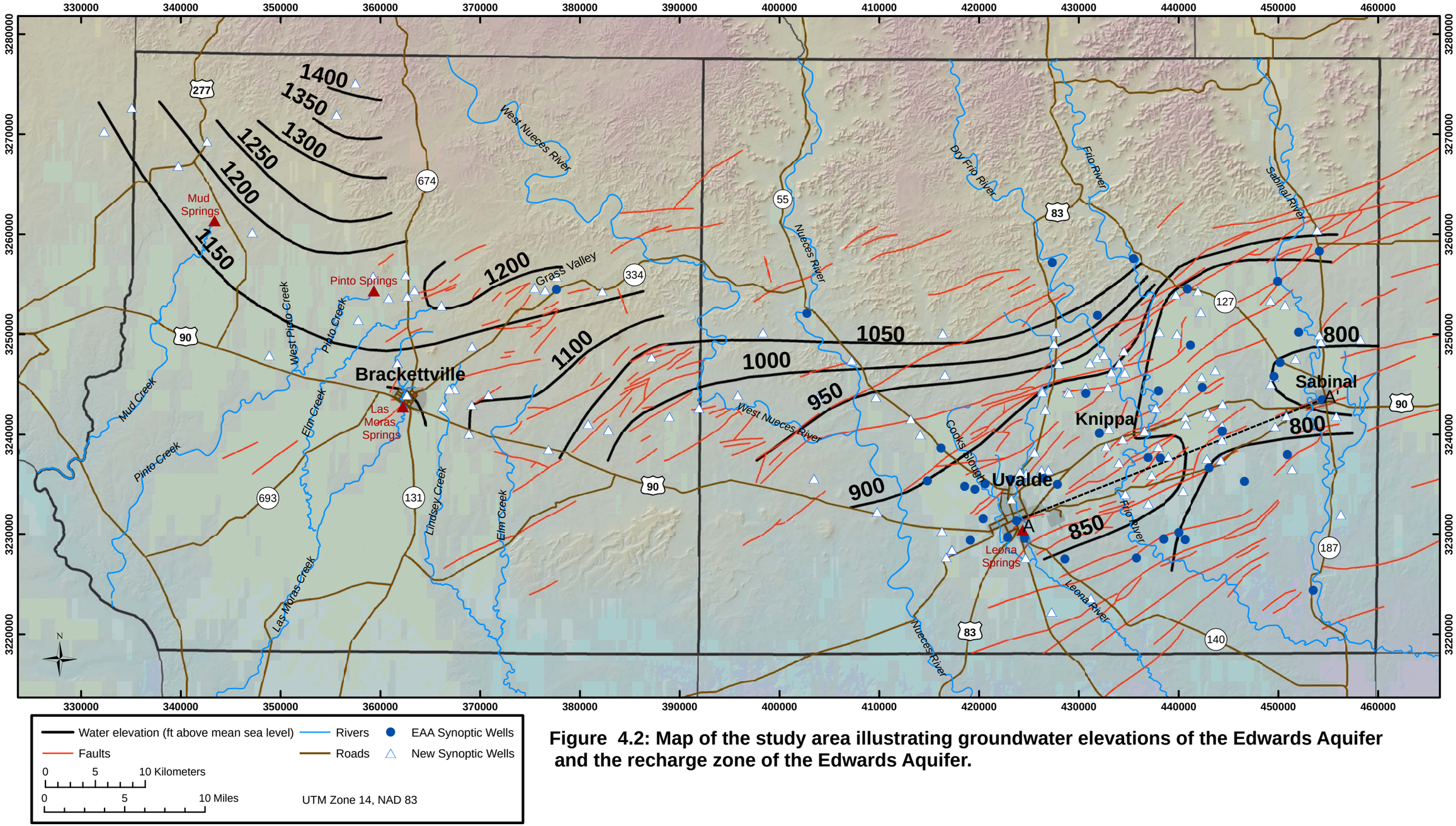


Figure 4.2: Map of the study area illustrating groundwater elevations of the Edwards Aquifer and the recharge zone of the Edwards Aquifer.

5 GEOLOGIC SETTING

The geologic setting of Kinney and Uvalde counties is complex. A systematic examination of the physiography and climate, geologic structure, and hydrogeology provided the basis for interpreting the water resources of the study area.

5.1 Physiography and Climate

The study area is located across the Balcones Fault Zone, which marks the transition between the Edwards Plateau region and the South Texas Plains (Rose, 1972). The climate in the study area is described as semi-arid with an average annual rainfall of 20.85 in/yr in Kinney County and 23.22 in/yr in Uvalde County (LBG-Guyton, 2005). To the north, the more massive and resistant carbonate members of the Edwards Group form the uplands of the Edwards Plateau. To the south, the Interior Inner Lowlands Belt of the South Texas Plains extends toward the Gulf of Mexico. The Interior Inner Lowlands Belt is mostly covered with younger alluvial materials that originate from the erosion of the Edwards Plateau with occasional outcrops of Upper Cretaceous formations. The Interior Lowlands Belt is characterized by black soils that extend discontinuously through southern Kinney and Uvalde counties.

Several drainage basins cross the area (Figure 5.1.1). The southern portion of Kinney County lies in the Rio Grande River drainage basin. The northern portion of Kinney County and the western portion of Uvalde County lie in the Nueces River-West Nueces River drainage basin (Fig. 5.1.1). The central portion of Uvalde County lies in the Frio River-Dry Frio River basin. The eastern portion of Uvalde County lies in the Sabinal River drainage basin. A small portion of northeast Uvalde County is in an un-named basin located between the Sabinal River and Medina River basins. Major streams in the Rio Grande drainage basin in Kinney County are Sycamore, Mud, Elm (W), Pinto, and Las Moras. Major streams in the Nueces River-West Nueces River drainage basin are Elm (E), Live Oak, Lindsey, Indian, and Turkey. [Note, there are two Elm Creeks in Kinney County designated here as Elm (W) to the west and Elm (E) to the east.] The Leona River is within the Nueces River drainage basin and Blanco Creek is within the Sabinal River drainage basin. With the exception of Live Oak and Indian creeks, these rivers and streams flow across the Interior Inner Lowlands Belt, although some headwaters are found in the Edwards Plateau. Indian Creek and Live Oak Creek, however, are located entirely on the Edwards Plateau within the Nueces River drainage basin.

The rivers and some of the larger streams on the Edwards Plateau in eastern Kinney County and Uvalde County have cut their floodplains through the Edwards Group rocks and have channel flows that are in the Glen Rose Formation. Because of the low permeability of the Glen Rose Formation relative to the Edwards Aquifer, water is frequently found to issue from the base of the Edwards Aquifer into river and stream beds overlying the Glen Rose Formation. Accordingly, water that recharges through exposed Edwards Group rocks in this area frequently reappears as discharge in river and stream beds (Bennett and Sayre, 1962). This water forms much of the baseflow that sustains flow in larger rivers and streams during periods of limited precipitation.

No streams to the west of the West Nueces River in Kinney County have eroded to the Glen Rose Formation. The West Nueces River has cut through the Edwards Aquifer along selected stretches (Bennett and Sayre, 1962). At locations within the West Nueces River that have the Edwards Group units as their base, water enters the Edwards Aquifer and is lost from the river. During periods of limited precipitation, surface water is only observed along reaches of the West Nueces River that have the Glen Rose Formation as their base.

The capacity of streams and rivers to transport water as either surface or ground water is a function of the floodplain. The floodplains of the rivers and streams within the study area are highly variable. The

floodplains differ both among the rivers and streams, and also differ spatially along different reaches of individual water courses. River and stream channels with limited capacity to transport surface water may in fact transport significant quantities of water through the subsurface via well-developed paleo-stream channels. The hydraulics of flow through floodplains and nearby hydrostratigraphic units is discussed in Section 6. With the exception of the Leona River (Green et al., 2004; Green, 2003), however, flow capacities of the stream and river floodplains in the study area have not been evaluated.

5.2 Geologic Structure

Geologic units of Cretaceous to Holocene age underlie the study area. Of particular interest in this study are those units that have the greatest influence on groundwater recharge, discharge, and flow. Significant aquifers include the Cretaceous Edwards-Trinity, Trinity, Edwards, Austin Chalk, Buda Limestone, and the Quaternary Leona Formation. Localized groundwater is occasionally found in igneous intrusions and the Anacacho Formation. The Edwards Aquifer is directly overlain by the Del Rio Clay and underlain by the Glen Rose Formation, both of which act as confining layers to the Edwards Aquifer in the study area. The stratigraphic column is illustrated in Figure 5.2.1 (Hovorka et al., 1996). The Edwards Aquifer or Group is represented by two regionally distinct facies in the study area. To the west, in the Maverick Basin, it consists of (from youngest to oldest) the Salmon Peak, McKnight, and West Nueces Formations. To the east, as part of the Devil's River Trend, the Edwards Aquifer comprises a single formation, the Devil's River Formation (Rose, 1972; Smith et al., 2000). The Trinity Aquifer consists of three parts: (i) the upper part consists of the Upper Member of the Glen Rose Formation, (ii) the middle part consists of the Lower Member of the Glen Rose Formation and the Cow Creek Limestone, which are separated by the Hensell Sand or Bexar Shale, and (iii) the lower part consists of the Hosston Formation and overlying Sligo Formation, and is separated from the Cow Creek Limestone by the intervening Hammett Shale (Mace et al., 2000).

The Edwards and Trinity aquifers are complex karst limestone aquifer systems that have permeability architectures that include a combination of host rock permeability, fractures and fault zones, and dissolution features (Maclay et al., 1981; Maclay and Small, 1983; Edwards Aquifer Authority, 2005). Although the strata that make up the Edwards Aquifer are younger and stratigraphically overlie the strata that comprise the Trinity Aquifer (Figure 5.2.1), displacement along faults of the Balcones fault system has placed the Edwards Aquifer laterally against (side-by-side with) the Trinity Aquifer in parts of the study area. The location and amount of fault juxtaposition are sensitive to the location, geometry, and displacement on faults (Ferrill et al., 2005). Along faults that define the structural interface between the Edwards and Trinity Aquifers, caves and some fault zones provide conduits for groundwater flow and potential pathways for interaquifer communication. The occurrence of and degree to which interaquifer communication occurs is not well defined, although various hydrologic and hydrochemical studies have attempted to place constraints on the amount of water that the Trinity Aquifer contributes to the Edwards Aquifer (e.g., LBG-Guyton Associates, 1995).

Rocks of both the Edwards and Trinity aquifers crop out in the Edwards Plateau region, and their southern and eastern outcrop boundary is within the Balcones Fault System, a zone of Tertiary age, down to the southeast, normal faulting (Foley, 1926; Maclay and Small, 1983, 1984; Stein and Ozuna, 1996; Clark, 2000; Collins, 2000). South and east of the Balcones Fault System, the Edwards Aquifer is confined beneath younger sedimentary rocks. Recharge of the aquifer occurs primarily by streamflow loss and infiltration in porous parts of the unconfined Edwards Aquifer recharge zone, responding to rainfall in the recharge zone and upslope catchment area. Water in the unconfined aquifer moves down hydraulic gradient following, in many places, tortuous flowpaths controlled by the Balcones Fault System. Natural discharge sites for the aquifer includes springs associated with the Balcones Fault System.

The Balcones Fault System is a broad *en echelon* system of mostly south-dipping normal faults that formed during the middle to late Tertiary (Murray, 1961; Young, 1972). The arc-shaped zone trends east-northeast and spans much of central Texas. The structure of the study area is illustrated using maps of the main structural features (Figure 5.2.2), the top of the Edwards Aquifer (Figure 5.2.3), base of the Edwards Aquifer (Figure 5.2.4), and the saturated thickness of the Edwards Aquifer (Figure 5.2.5). The 16- to 19 mi-wide Balcones Fault System has a maximum total displacement of about 1200 ft (Weeks, 1945), and defines the transition from structurally stable flat-lying rocks of the Texas craton to gently coastward-dipping sediments of the subsiding Gulf of Mexico. Offset of carbonate strata across the Balcones Fault System resulted in a broad, weathered escarpment of vegetated limestone hills rising from the predominantly clastic coastal plains to the uplands of the Texas Craton. Within the fault system, the dip of bedding varies from gentle coastward to nearly horizontal, with occasional localized dip of hanging wall beds northward into some faults, and parallel to fault strike in relay ramp structures (Collins and Hovorka, 1997). Faulting has been interpreted as being rooted in the deeply buried foreland-basin sediments of the Ouachita orogeny (Murray, 1956).

It was recognized in the late 19th century that the Cretaceous limestones of the Balcones escarpment are a key economic factor in south central Texas, owing to their ability to recharge and store underground water in what was then an artesian basin underlying the north-western margin of the Rio Grande; or coastal plain (Hill, 1890; Hill and Vaughan, 1896; Muir, 1911). Geologists at that time also understood the importance of faulting within the aquifer. Robert Hill concluded in the first annual report of the Geological Survey of Texas: “The ascertainment, utilization, and improvement of these [water conditions], instead of being a matter entirely of rainfall, as is usually supposed, is more a question of structural conditions of the rocks which underlie the region” (Hill, 1890, page 138). Testimony to the importance of faults and fractures as flow conduits was also given by Muir (1911), who, in discussing the line of springs along the Balcones Fault Zone, had this to say: “The water of these springs does not drain from the sides of hills or bluffs, but rises up through fissures and fault joints to form large pools, often small lakes.” Muir also posited the idea that faults and fissures may divert flow and not simply affect cross-fault flow (Muir, 1911), an idea echoed later by Arnow (1963). Livingston et al. (1936) outlined many of the concepts that continue to frame conceptualization of the Cretaceous carbonate aquifers in south Texas. They emphasized the importance of faults and fractures as likely conduits for rapid subsurface flow within the Edwards Group limestones; they documented the contribution of river flow loss to recharge in the faulted and fractured Balcones Fault Zone; they recognized the importance of fault juxtaposition of stratigraphic units with differing permeability; and they documented recharge features within the Glen Rose Formation (Livingston, 1936).

The ability of faults to act as both conduits and barriers to flow within the Edwards Aquifer has been acknowledged by virtually all workers over the last century; however, since the 1950’s the concept of barrier faults that partition the aquifer has become increasingly popular (e.g., Holt, 1956, 1959; Maclay and Small, 1983; Maclay, 1989). It has also been noted that a fault that acts as a barrier to cross-fault flow may also serve to accentuate along-fault flow (Sharp and Banner, 1997; Ferrill et al., 2000; 2004). Faults are acknowledged to exert fundamental control on the groundwater flowpaths within the Edwards Aquifer in the following ways:

1. As both horizontal and vertical flow conduits because fault zones are often preferentially dissolved.
2. As barriers to flow, especially where displacement is sufficient to juxtapose the Glen Rose Formation (generally regarded as having lower permeability) in the upthrown block with Edwards limestones in the downthrown block; or Edwards limestones in the upthrown block with Del Rio Formation (mostly clay) in the downthrown block.
3. As both barriers and conduits depending on the nature of the fault.

Kinney and Uvalde counties lie at the far western limit of the Balcones Fault Zone (Figure 5.2.2), across what is generally considered to be the outcrop extent of the Edwards Aquifer. For most of its length, the Edwards Aquifer follows the trend and is dominated by the faults of the Balcones Fault Zone. The Balcones Fault Zone is characterized by relay ramps bounded by overlapping faults, alternating with segments in which a single large-displacement fault dominates (Collins and Hovorka, 1997; Ferrill et al., 2005). In western Uvalde County and through Kinney County, the outcrop strike of the Edwards Aquifer changes from approximately 080° to 110°. This change represents the western limit of the Balcones Fault Zone, and the influence of the Maverick Basin to the west. Fundamentally, this geometry reflects the underlying structure of the Ouachita orogen (Flawn et al., 1961; Thomas, 1977).

In the vicinity of the City of Uvalde, the Balcones Fault Zone is represented by a large number of faults with relatively small down-to-the-southeast displacements, together with several faults antithetic to the main trend (i.e., down-to-the-northwest displacement)(Figure 5.2.6). 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. This displacement effectively creates a structural high in the area of Uvalde, sometimes called the Uvalde Salient (Clark, 2003) (Figures 5.2.3-5.2.4). The effect of faulting and the Uvalde Salient on groundwater elevation is illustrated in a vertical cross section of the hydrogeology (Figure 5.2.7) from the City of Uvalde to the City of Sabinal (Figure 4.2). These structural features effectively dam groundwater to the west of the Uvalde Salient.

5.3 Hydrochemistry

The data used in this study to characterize the hydrochemistry of the Kinney County and Uvalde County region were collected from several sources over a large time span (including records from the 1930's to 2004). The data for each aquifer, as well as the electronic version of the Texas Water Development Board groundwater database (October 2004), are provided in Excel format on the CD included with this report. Although there is some information in the literature to indicate that slight water chemistry changes may occur over time in wells located in the fresh-water/saline-water mixing zone (e.g., Harden, 1968), other reports suggest that little change in water chemistry occurs over time in the Edwards Aquifer fresh-water zone. For example, Groschen (1996) observed no significant change in water chemistry for wells along the proposed western Medina County flowpath over the period 1968 to 1990, and Maclay et al. (1980) noted that the chemical composition of water within the aquifer did not change significantly over the time period (1970–1978) analyzed in their study. It was assumed, therefore, that the data for the many wells analyzed in this study could be compared directly even though they were collected over a long time frame.

Inspection of the hydrochemical data for Edwards Aquifer wells reveals and corroborates spatial trends observed in several previous investigations. Bennett and Sayre (1962) and Welder and Reeves (1962) noted the general decrease in water quality of Edwards wells to the south and southwest within Kinney County and to the south in Uvalde County. The occurrence of degraded water quality, as indicated by increased TDS values to the south of U.S. Highway 90 in Kinney County and south of the City of Uvalde in Uvalde County, is apparent from the data (Figure 5.3.1) and coincides well with the historical placement of the saline-water line in this region. Wells to the south of this boundary are high in TDS (>1000 ppm) and sulfate and, as a result, most water wells south of U.S. Highway 90 in Kinney County are completed in the Austin Chalk (Figure 5.3.1). From the data in the Bennett and Sayre (1962) report, the Austin Chalk fresh waters have a slightly higher average TDS content and significantly higher chloride content than Edwards Aquifer fresh waters in Kinney County; the data shown in Figure 5.3.1 are consistent with this observation. Also notable in Figure 5.3.1 are wells (YP-69-36-301 and TD-69-31-801) in northern Uvalde and Medina counties that are identified (by the Texas Water Development Board groundwater database) as completed in Edwards Aquifer rocks but that have high TDS relative to other Edwards Aquifer wells nearby. When combined with data for the concentration of

sulfate (Figure 5.3.2) in these wells, they (along with well TD-69-30-601) appear to be drawing water from the Trinity Aquifer and not the Edwards Aquifer. The characteristically higher sulfate and chloride content of Trinity Aquifer water is observed in these wells.

Using regional hydrochemical data, Maclay et al. (1980) delineated multiple hydrochemical facies for water in the Edwards Aquifer and identified six aquifer zones. In particular, Maclay et al. (1980) identified increases in magnesium and sulfate as being indicative of slower zones of circulation in the fresh-water zone. High TDS, sulfate, and chloride waters were identified as occurring in zones of very slow groundwater circulation. Figures 5.3.1–5.3.3 illustrate the increased concentration of these constituents in the saline-water zones of Kinney and Uvalde counties. Maclay et al. (1980) stated that sulfate minerals originally distributed throughout the rocks of the Edwards Aquifer fresh-water zone have been mostly dissolved by circulating water, but some lenses of sulfate minerals (e.g., gypsum and anhydrite) occur in zones where flow is restricted. Moreover, Maclay et al. (1980) noted that, in the saline-water zone where groundwater circulation is very slow, substantial amounts of dolomite and sulfate minerals (including strontium-bearing sulfates and carbonates) occur. The supply of sulfate ions from dissolution of sulfate minerals is important in the dedolomitization process. The data plotted in Figure 5.3.4 along with those in Figure 5.3.2 show the association of increased sulfate and magnesium in the slowly circulating fresh-water/saline-water mixing zones.

The sulfate, chloride, and magnesium data shown in Figures 5.3.2–5.3.4 provide evidence for the separation of Edwards Aquifer waters in Kinney and Uvalde counties and evidence for a zone of fresh-water flow north of U.S. Highway 90 and south of Cooks Fault in central Uvalde County. Sulfate concentration data in Figure 5.3.2 reveal that wells in the Edwards Aquifer confined zone near the Kinney County/Uvalde County boundary are higher in sulfate consistent with a zone of slower flow. Fresh-water wells to the east in Uvalde County are lower in sulfate. A connected pathway of fresh water would not likely show this increase in sulfate concentration. In central Uvalde County, fresh-water wells in the confined zone north of U.S. Highway 90 and south of Cooks Fault remain low in sulfate, while fresh-water wells south of U.S. Highway 90 are higher in sulfate, which suggests a slower flow regime to the south. The chloride concentrations shown in Figure 5.3.3 clearly demonstrate the lower chloride concentrations of confined zone fresh- and saline-water Edwards Aquifer wells in Kinney County relative to the higher chloride concentrations in confined zone Edwards Aquifer wells in Uvalde County. The magnesium concentration data shown in Figure 5.3.4 also provide a remarkable demonstration of the difference in Edwards Aquifer waters of Kinney County and the Edwards Aquifer waters of Uvalde County.

Maclay et al. (1980) described a general trend of increasing TDS and an increase in the saturation index of calcite along the groundwater flowpath from west to east in the San Antonio segment of the Edwards Aquifer, but this trend is not apparent from data in this study (Figure 5.3.5). There is no observable tend in the saturation index of calcite along expected flowpaths (Figure 5.3.5), and there does not appear to be any correlation between the two parameters (Figure 5.3.6) for wells with water of TDS<1000 ppm. Although the calcite saturation index data in Figure 5.3.5 appear to show a slightly higher number of saturated wells in Uvalde County relative to Kinney County, the high variability and uncertainties associated with these data make it difficult to draw any inferences regarding groundwater separation or flowpaths. Karst dominated flow systems are likely to have a complex variation in calcite saturation depending on the location of conduits and the scale of conduit flow (Palmer, 2003).

As noted in Section 3, Pearson and Rettman (1976) placed most wells in their sample set from Uvalde County into a cluster they called the varied group, which contained water characteristics of both the main fresh-water and transitional groups. Wells in Uvalde County, identified by Pearson and Rettman (1976) as being in the main fresh-water group, occur in the groundwater fast-flow zone between Cooks Fault and U.S. Highway 90, identified by structural and hydrologic analyses in this study and by hydrochemical

evidence shown in Figure 5.3.2. Strontium and fluoride concentration data shown in Figures 5.3.7 and 5.3.8 also provide evidence of freshwater in a flow channel within the confined zone of the Edwards Aquifer north of U.S. Highway 90 and south of Cooks Fault in central Uvalde County. Concentrations of strontium and fluoride remain low north of U.S. Highway 90 and increase significantly in fresh-water wells to the south. The increased strontium and fluoride concentrations are associated with minerals that are more commonly found in rocks of the saline zone, which is thought to be a zone of slow flow relative to the fresh-water zone of the Edwards Aquifer (Maclay et al., 1980). Increased strontium and fluoride concentrations are also correlated with well depth. Deeper wells tend to have higher strontium concentrations. The strontium and fluoride data also indicate separation of waters between Kinney and Uvalde counties. Higher concentrations of fluoride (Figure 5.3.8) in eastern Kinney County are replaced by lower concentrations in western Uvalde County (although this may also be a feature of dilution due to input of recharge from the Nueces River). Nonetheless, the higher fluoride concentrations in eastern Kinney County suggest slower flow near the Kinney County eastern boundary.

Contour plots of the log activity of sulfate and specific conductivity (Figures 5.3.9 and 5.3.10) highlight the areas within the fresh-water zone of the Edwards Aquifer in Uvalde County interpreted as having slow flow, and accentuate a zone of apparent high flow north of U.S. Highway 90 in central Uvalde County. Sulfate activity contours were determined and plotted for fresh-water wells only to eliminate the effects of probable Trinity Aquifer wells (TD-69-31-801 and YP-69-36-301) and to mitigate the impact of saline-water zone wells. Figure 5.3.9 shows a predicted distribution of sulfate activity (log units) in fresh-water wells with a plot of the sulfate activity (log units) for all Edwards Aquifer wells for comparison. Again, the sulfate activity plot clearly shows the distinction between Edwards Aquifer water in Kinney County and Uvalde County. The sulfate activity plot (Figure 5.3.9) also reveals the flow channel north of U.S. Highway 90 in central Uvalde County and shows the mixing and consolidation of fresh waters near the Uvalde County and Medina County boundary. The plot of the predicted spatial distribution of specific conductivity (Figure 5.3.10) not only illustrates the regions of significant fresh-water input into the Edwards Aquifer, but also delineates the regions of recharge and flow in Kinney, Uvalde and Medina counties. The specific conductivity map suggests water recharge flows from the north-northeast to the south-southwest in Kinney County with lesser flow to the southeast. In Uvalde County, recharge occurs along the Nueces River with significant input at the Frio and Dry Frio rivers. Recharge in northwest Medina County flows southwest and mixes with flow from Uvalde County to combine into a flowpath eastward in central Medina County. The Medina County flow pattern is quite similar to those proposed and outlined by Holt (1965, 1959), Maclay (1995), and Groschen (1996).

Figure 5.3.11 provides a contour plot of the depths of wells completed in the Edwards Aquifer with a plot of strontium concentrations measured in Edwards Aquifer wells (as also shown in Figure 5.3.7). Although not a substitute for the structural maps (because drilling is generally stopped once an adequate water supply is found), the depth contours in Figure 5.3.11 clearly denote the area of the Uvalde Salient (Figure 5.2.7) in central Uvalde County and highlight the embayment trough structure associated with Grass Valley in north-central Kinney County (Figures 5.2.3 and 5.2.4). Because the strontium concentrations are closely related to the depth of the wells, and thus the depth of Edwards Group rocks, it appears likely that the source of the strontium is the Edwards Group rocks and not the numerous igneous intrusions that occur at various depths in the same region. This correlation of strontium with well depth corresponds with limited strontium isotope information in Groschen and Buszka (1997).

A trilinear diagram (Piper plot) of the Edwards Aquifer well chemistries is shown in Figure 5.3.12. As expected, water chemistry in the Edwards Aquifer is dominated by Ca-HCO_3 in the fresh-water zone. Water chemistries trend toward higher concentrations of sulfate and chloride in the saline-water zone. This is the same sequence of fresh-water to saline-water facies transition identified and discussed by Maclay et al. (1980). Similar to the observations of Clement and Sharp (1988), the data in Figure 5.3.12

also show that Kinney County waters remain low in chloride, even in the saline-water zone facies, while those in Uvalde and Medina counties increase in sulfate and chloride.

A principal components analysis was conducted for the representative Edwards Aquifer well samples. Principal components analysis analyses are often helpful in studying the correlations of a large number of factors by grouping variables (in this study, the chemical and other measured groundwater constituents) into principal components that are more highly correlated with variables in that component than with variables in other components. The principal components analysis can be used to summarize many variables with fewer components. These components can be analyzed spatially (or with additional statistical techniques) to explore trends in the data set. Several principal components analysis analyses were conducted using the Edwards Aquifer chemistry data. For the constituents analyzed, results for all wells, fresh-water wells only, and for raw and normalized data were similar in their general meaning and interpretation. Results for the principal components analysis of fresh-water wells are discussed in this report. Results of a principal components analysis using the correlation matrix with varimax (variance maximization along the principal component axes) rotation for Edwards Aquifer well sample constituents (silica, calcium, magnesium, strontium, fluoride, sulfate, sodium, potassium, bicarbonate, nitrate, TDS, and pH) reveal that three principal components can explain 73% of the variance in the data. The loadings plots for the three principal components (factors) are shown in Figure 5.3.13. Based on these loadings, principal component 1 represents the correlation of sodium and chloride. Principal component 2 represents the other set of saline-water constituents: sulfate, magnesium, fluoride, and strontium (note that TDS is split between components 1 and 2, indicating its even influence on both of these saline-water components). Components 1 and 2 identify these correlations even though the analysis was limited to fresh-water samples. Principal component 3 represents the major species in fresh water, calcium and bicarbonate. The spatial distribution of the components is shown in Figure 5.3.14. Figure 5.3.14 reveals similar information about the separation of Edward Aquifer waters in Kinney and Uvalde counties as was shown by individual chemical concentration distributions. In particular, a plot of principal component 1 values shows the isolation of Kinney County water and suggests flow to the southwest in Kinney County. Principal component 1 values also indicate the zone of slow fresh-water flow in southern Uvalde County. The plot of principal component 2 values more clearly shows the zone of high fresh-water flow north of U.S. Highway and indicates zones of recharge influx in Kinney, Uvalde, and Medina counties. The plot of principal component 3 values reveals less information, but suggests the significant influence of recharge from the Frio and Dry Frio rivers in Uvalde County.

In summary, results of the analyses of Edwards Aquifer water chemistry in the study region are consistent with most observations and interpretations of hydrochemical facies found in previous hydrochemical studies of the aquifer (e.g., Maclay et al., 1980; Groschen, 1996). The analyses also provide distinct evidence to indicate the existence of a relatively narrow high-flow zone of fresh water in central Uvalde County and the expansion of the flowpath to the east of the location of recharge from the Frio and Dry Frio rivers. The data also demonstrate that Edwards Aquifer groundwater in Kinney County is chemically distinct (both in the fresh-water and saline-water zones) from Edwards Aquifer groundwater in Uvalde County. The chemistry data are inadequate to confirm proposed flowpaths in Kinney County, but they are consistent with the interpretation of flow to the south and southwest from recharge areas in the northeast of Kinney County.

5.4 Hydrogeology

Investigation of the water resources of Uvalde County entailed evaluation of several water-bearing formations and the interactions among these formations. The Edwards Aquifer is the principal water-bearing formation in Uvalde County. Secondary, but important, water-bearing formations in the study area include the Edwards-Trinity Aquifer, Trinity Aquifer, Buda Limestone, Austin Chalk, and the Leona Formation. Local igneous intrusions and the Anacacho Formation provide occasional, but limited,

groundwater resources in Kinney and Uvalde counties. The Edwards-Trinity Aquifer is defined to include the Edwards Aquifer rocks that are west of the groundwater divide near the City of Brackettville identified by Maclay and Land (1988).

Review of past studies, field investigations, and related analyses highlight the fact that these water-bearing units do not exhibit uniform properties within the limits of the study area. Of particular interest is the identification of specific areas where aquifers have particularly high or low capacity to transmit groundwater. One approach to identifying zones of an aquifer that have high capacity to transmit water is to identify high-capacity wells (e.g., irrigation). An obvious limitation in this technique is the possibility that an area with a high-capacity aquifer is not identified because there is either no well in that area or there is a well that pumps less than the full capacity of the aquifer. However, in practice, irrigation wells are typically developed to pump near the full capacity of an aquifer. Discussions with an experienced (i.e., ~2,500 wells drilled) local driller (Cary Spurgeon, personal communication) indicated that test holes and wells have been drilled over most of the study area in pursuit of water resources. The demand for irrigation wells in the region, and desires of water users to establish a demonstrated use history to retain future water rights, has led to virtually all high-capacity locations having irrigation wells installed. This line of evidence was used to corroborate hypotheses and conceptual models developed during this study.

The Edwards Aquifer exhibits variable hydraulic properties within the study area. This variability is attributed to regional and local factors (Hovorka et al., 1993, 1996) including lithofacies, faulting, and dissolution features (conduits). Other factors that potentially can affect the hydraulic properties of the Edwards Aquifer include igneous intrusions (Rose, 1972; Ewing, 2004) and karst development (Halihan et al., 2000; Hovorka et al., 2004; Worthington, 1999, 2004). One hypothesis proposed prior to this study was that the relatively high density of igneous intrusions in the study area affects the groundwater flow regime. After analysis of the USGS aeromagnetic survey map of most of Uvalde County (Smith et al., 2002), inspection of well logs, and evaluation of the synoptic water-elevation survey for Kinney and Uvalde counties, however, there is no indication that igneous intrusions affect the regional flow of groundwater in the study area. It is probable, however, that local flowpaths are influenced by individual intrusive bodies either from the direct effect of the intrusion on groundwater flow or by the indirect effect of contact metamorphism on aquifer properties. Another factor affecting local flow regimes is the formation of preferential flowpaths associated with karst development. Areas of the aquifer that convey large volumes of groundwater (i.e., north of Uvalde to north of Knippa in Uvalde County and Pinto Valley in Kinney County) are indicative of preferential flow pathways commonly associated with karst development (Halihan et al., 2000; Hovorka et al., 2004; Worthington, 1999, 2004). Also, as will be discussed in Section 6, there may be preferential groundwater flow pathways associated with floodplains.

A principal finding of this investigation is that the hydraulic properties of the Edwards Aquifer in a 20-25 mi wide area that roughly includes the boundary between Kinney and Uvalde counties are significantly different from areas in the Edwards Aquifer to the east and west. This area is referred to as a transition zone between the Uvalde pool of the Edwards Aquifer (to the east) and a segment of the Edwards Aquifer to the west that is identified here as the Kinney County pool. The stratigraphy and sedimentary facies of the Edwards Group may be important factors in the hydrogeologic characteristics of the transition zone.

Kinney and Uvalde counties are located within either the Maverick Basin or the Devils River Trend of the Albian (Lower Cretaceous) Edwards Group (Rose, 1972; Hovorka et al., 1993, 1996). The transition zone is situated in the eastern portion of the Maverick Basin and roughly spans the area from approximately 10–15 miles west to approximately 10 miles east of the Kinney County/Uvalde County line. Comprehensive studies of the rocks of the Edwards Group by Hovorka et al. (1993, 1996) provide the basis for an evaluation of the depositional facies of the Edwards Group in the transition zone. However,

as will be noted, the Hovorka et al. (1993, 1996) studies had few data from the transition zone from which to make an interpretation. A possible extension of their interpretation is provided in this report.

Hovorka et al. (1993, 1996) described the depositional facies of the Edwards Group based on core and thin-section investigation. Core samples were from wells and boreholes that spanned an area from Kinney County in the west to Hays County in the east. There is a gap in available data between approximately Grass Valley in Kinney County to the west and the City of Uvalde to the east. No wells or boreholes in the transition zone were sampled as part of the Hovorka et al. (1993, 1996) studies. This absence of data is understandable because there are relatively few wells in the transitional zone. Water wells in this area are of low capacity [e.g., a few 10's gallons per minute (gpm) at a maximum] and deep (i.e., with groundwater elevations as deep as 500 ft below ground level), with the exception of shallow wells that capture the baseflow in river and stream floodplains. Consequently, previous interpretations of the carbonate facies in the transition zone (Hovorka et al. 1993, 1996) were predicated on an interpolation of data across the transition zone. Compounding the problem is that Kinney County wells in the Hovorka et al. (1993, 1996) studies that are closest to this transitional zone have incomplete records, with core from only selected intervals and horizons. The sampled well from the Hovorka et al. (1993, 1996) studies that is closest to the transition zone (i.e., near Grass Valley; Figure 5.1.1) is characterized as having relatively low porosity.

The transition zone is located in the eastern end of the Maverick Basin. The Devils River Trend is north and east of the Maverick Basin (Figure 5.2.2). Hovorka et al. (1993, 1996) described the Salmon Peak Formation and the Devils River Formation as platform facies and the West Nueces and McKnight formations as basinal facies. The Devils River Formation consists of high-frequency cycles described as low- and high-energy, subtidal and supratidal facies. The Salmon Peak Formation consists of poorly cyclic, light-colored, homogeneous wackestone, packstone, and grainstone. The McKnight Formation is a cyclic dark, fine-grained, laminated, and argillaceous carbonate with massive anhydrite beds. The West Nueces Formation resembles subtidal wackestones, packstones, and grainstones. The West Nueces Formation was abundantly burrowed with the burrows filled with a dark, relatively insoluble material.

Discussions with Cary Spurgeon (personal communication) indicated that the Edwards Group rocks from the transitional zone, as exhibited in well cuttings, are dark. Well cuttings of the Edwards Aquifer from wells and boreholes to the west and east of the transition zone have light colors. This observation suggests that wells in the transition zone were drilled in the McKnight and West Nueces Formations and/or that rocks in the Edwards Group in the transition zone are different (i.e., darker and less soluble) when compared with rocks from the same horizon in Edwards Group to the east and west of the transition zone. Mr. Spurgeon concurred with the hypothesis that rocks from the transition zone are darker than comparable rocks from the same horizon in Edwards Group east and west of the transition zone. Regardless, the water table is deep in the transition zone (i.e., 200-500 ft below ground level), which suggests that the water-bearing horizon is also located within the lower part of the Edwards Group (i.e., McKnight and West Nueces Formations). Additional discussions with Mike Harris (a local ranch owner, personal communication), Vic Hildebran (the Uvalde County Underground Water Conservation District General Manager, personal communication), and Mr. Spurgeon noted that no zones of moderate hydraulic capacity (as indicated by wells with capacity of over 20 gpm, with the exception of floodplain wells), bit drops encountered during drilling, or major springs have been detected in the transition zone. The absence of any of these indicators suggests that layers or zones of high permeability or karst development are nonexistent in the transition zone. The fact that many wells have been drilled in the transition zone without detecting significant water bearing zones supports this interpretation.

There also appears to be a zone of reduced permeability due east of the City of Uvalde, although this so-called dead zone may instead be attributed to a topographic high in the base of the Edwards Aquifer associated with the Uvalde Salient. Discussions with Mr. Spurgeon (personal communication) indicate

that Edwards Aquifer wells in this zone have significantly smaller capacity than nearby wells in the Edwards Aquifer, particularly wells to the north. There is also a zone to the east of Knippa where Edwards Aquifer wells have limited capacity and poorer quality. These Edwards Aquifer wells are in the same area as high-capacity (e.g., irrigation) Austin Chalk wells.

There are areas in Kinney and Uvalde counties where the Austin Chalk is a productive aquifer. The most prominent area in Uvalde County is a structural block located at Knippa and to the east of Knippa. Irrigation wells in this area are set in the Austin Chalk, not the Edwards Aquifer. Water levels measured in wells in the Austin Chalk and the Edwards Aquifer indicate that the western end of the Austin Chalk structural block could be in hydraulic communication with the Edwards Aquifer, where water elevations are within 20 ft, but that the eastern end of the structural block is not in hydraulic communication with the Edwards Aquifer, where water levels are in Edwards Aquifer are significantly lower (i.e., as much as 80 ft) compared with the Austin Chalk. A second area with Austin Chalk wells is to the southwest of the City of Uvalde, near the U.S. Fish and Wildlife Fish Hatchery. Measured water levels measured in these wells suggest that the Austin Chalk is in hydraulic communication with Edwards Aquifer in this area. The third area with Austin Chalk wells is in Kinney County south and east of Brackettville and south of Highway 90. These Austin Chalk wells are not in close proximity to Edwards Aquifer wells.

There are few wells in the Buda Formation with significant hydraulic capacity in the study area. One Buda Formation well with reasonable hydraulic capacity is located southwest of the City of Uvalde, near the U.S. Fish and Wildlife Fish Hatchery. The measured water level in this well suggests that the Buda Formation is in hydraulic communication with both the Edwards Aquifer and the Austin Chalk. There are few wells set in igneous intrusions in the study area with significant hydraulic capacity.

The Leona Formation is a relatively significant aquifer in selected areas in the Leona River floodplain. With the exception of a short reach of gravels along the Sabinal River near the City of Sabinal, the Leona River floodplain, and possibly in Cooks Slough, the sand and gravel deposits of the Leona Formation are insufficiently deep, thick, permeable, or of sufficiently replenished to serve as a viable groundwater resource. The Leona Formation in the Leona River floodplain is replenished with groundwater that originates in the Edwards Aquifer, however, the flowpath from the Edwards Aquifer to the Leona River floodplain appears to include other units such as the Buda Formation and Leona Formation gravels in Cooks Slough. The complexity of the geologic structure at the headwaters of the Leona River near highway 90 makes this interpretation difficult.

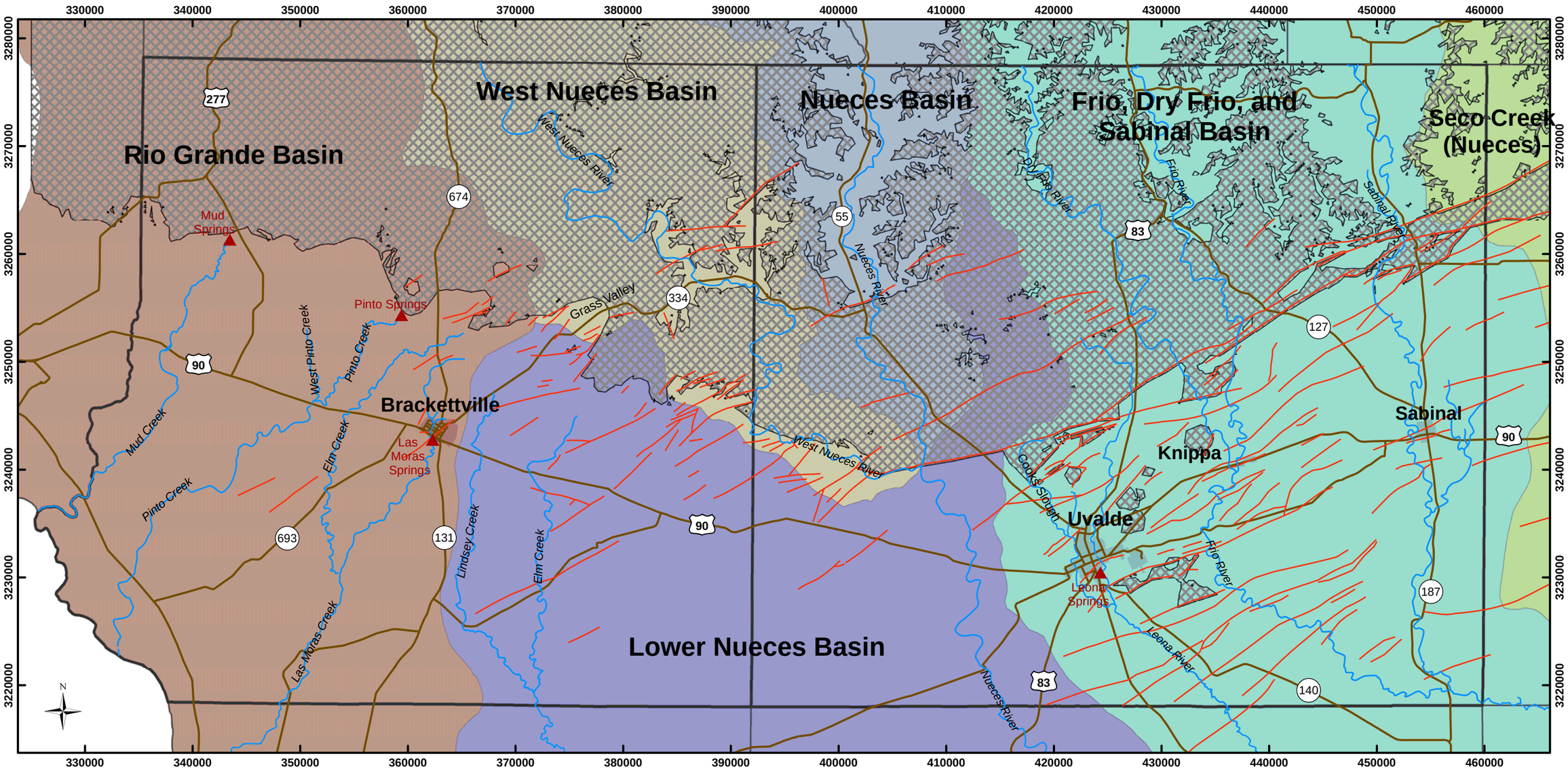


Figure 5.1.1: River drainage basins in the study area.

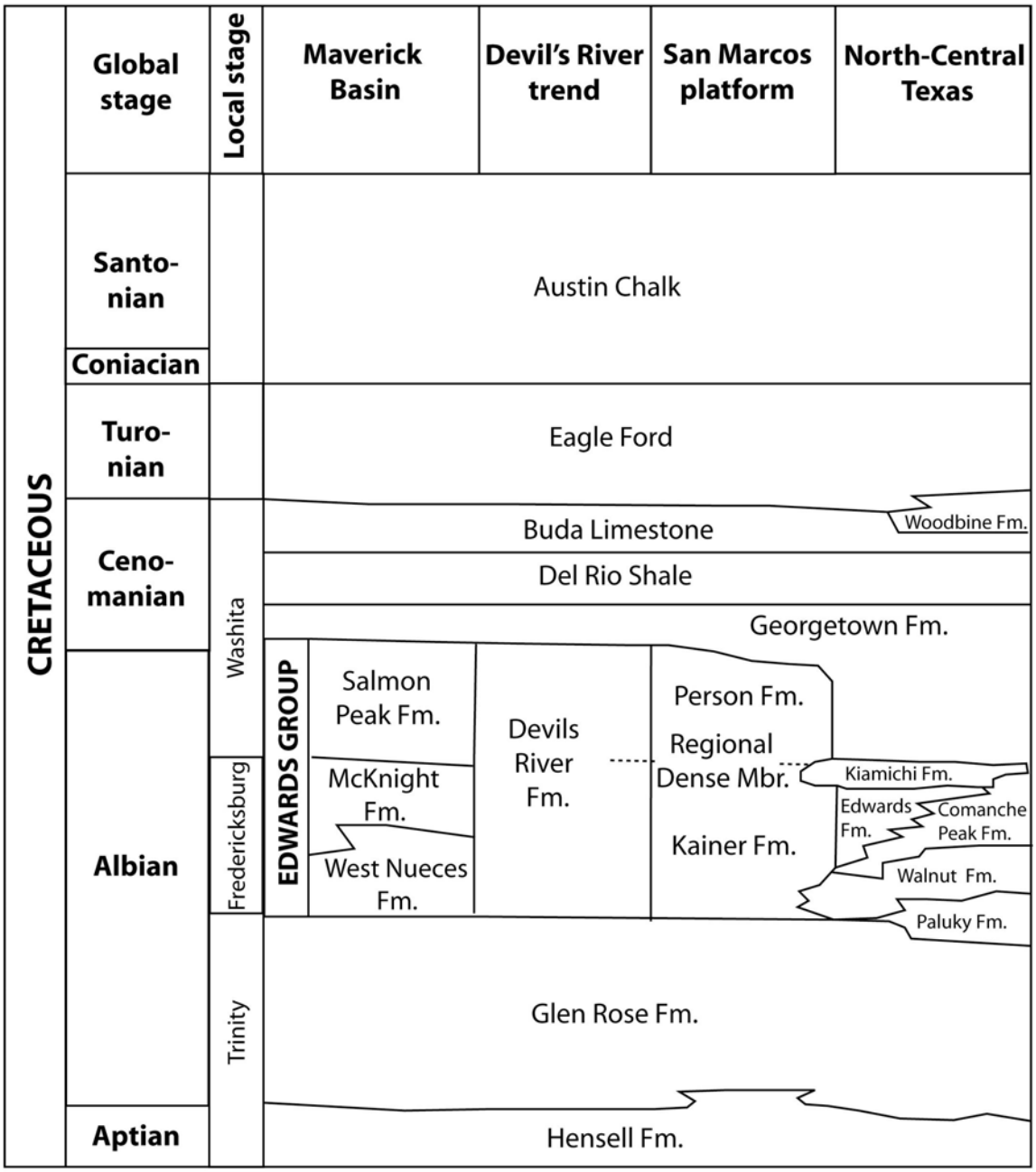


Figure 5.2.1: Cretaceous stratigraphy of south central Texas, from Hovorka et al., 1996.

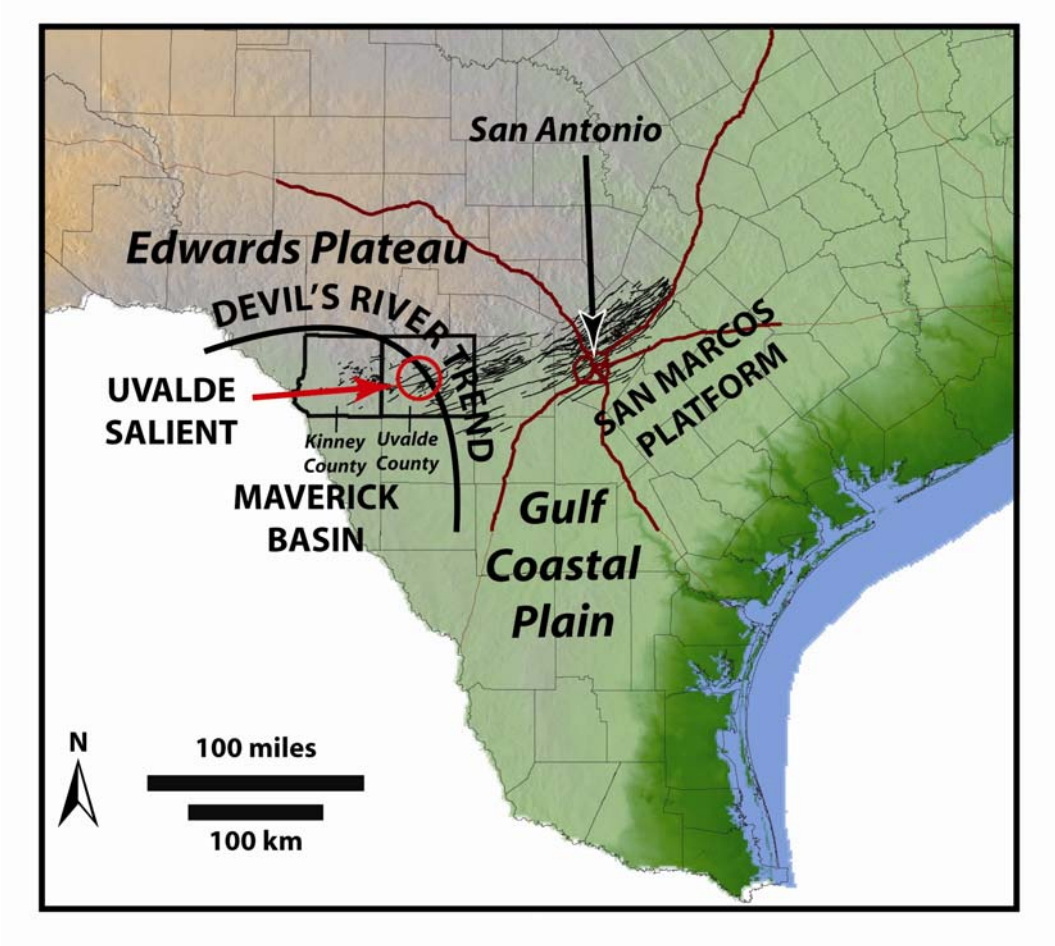


Figure 5.2.2: Map showing outline of Balcones Fault Zone, Maverick Basin, Devil's River Trend, Gulf Coastal Plain, Uvalde and Kinney Counties, and the Edwards Plateau.

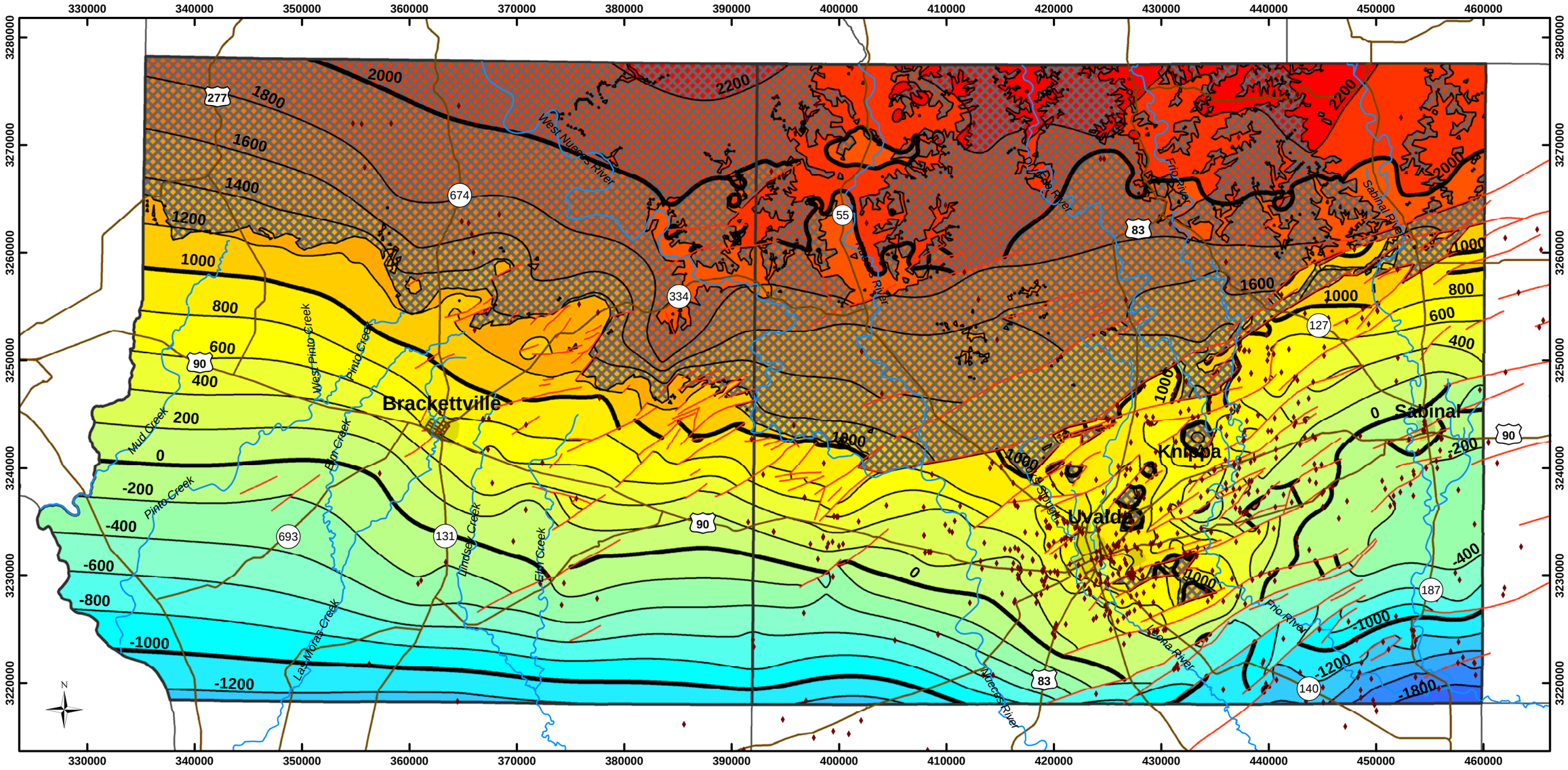


Figure 5.2.3: Geologic structure map of the study area illustrating the elevation of the top of the Edwards Aquifer and the recharge zone of the Edwards Aquifer.

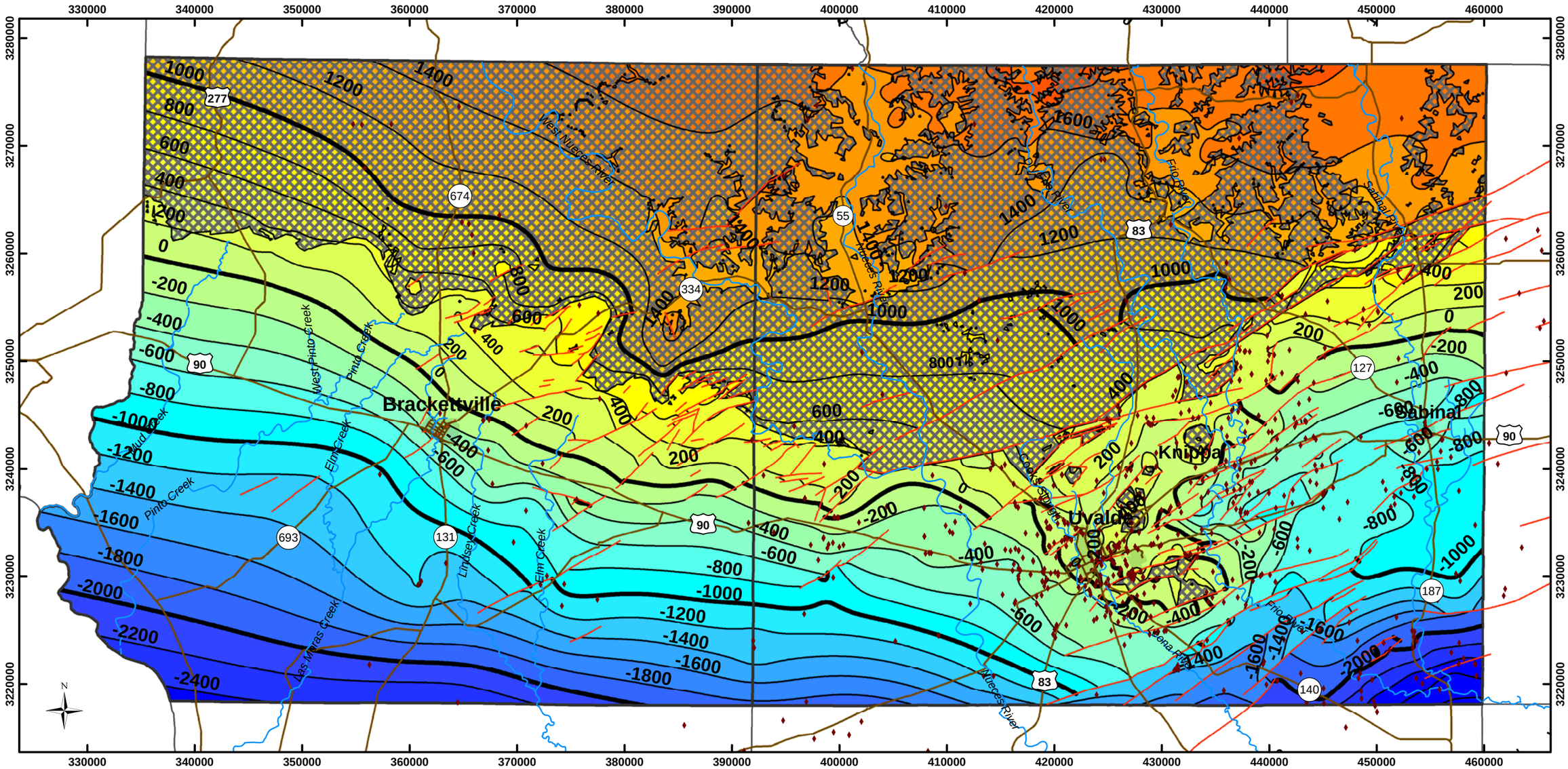


Figure 5.2.4: Geologic structure map of the study area illustrating the elevation of the bottom of the Edwards Aquifer and the recharge zone of the Edwards Aquifer.

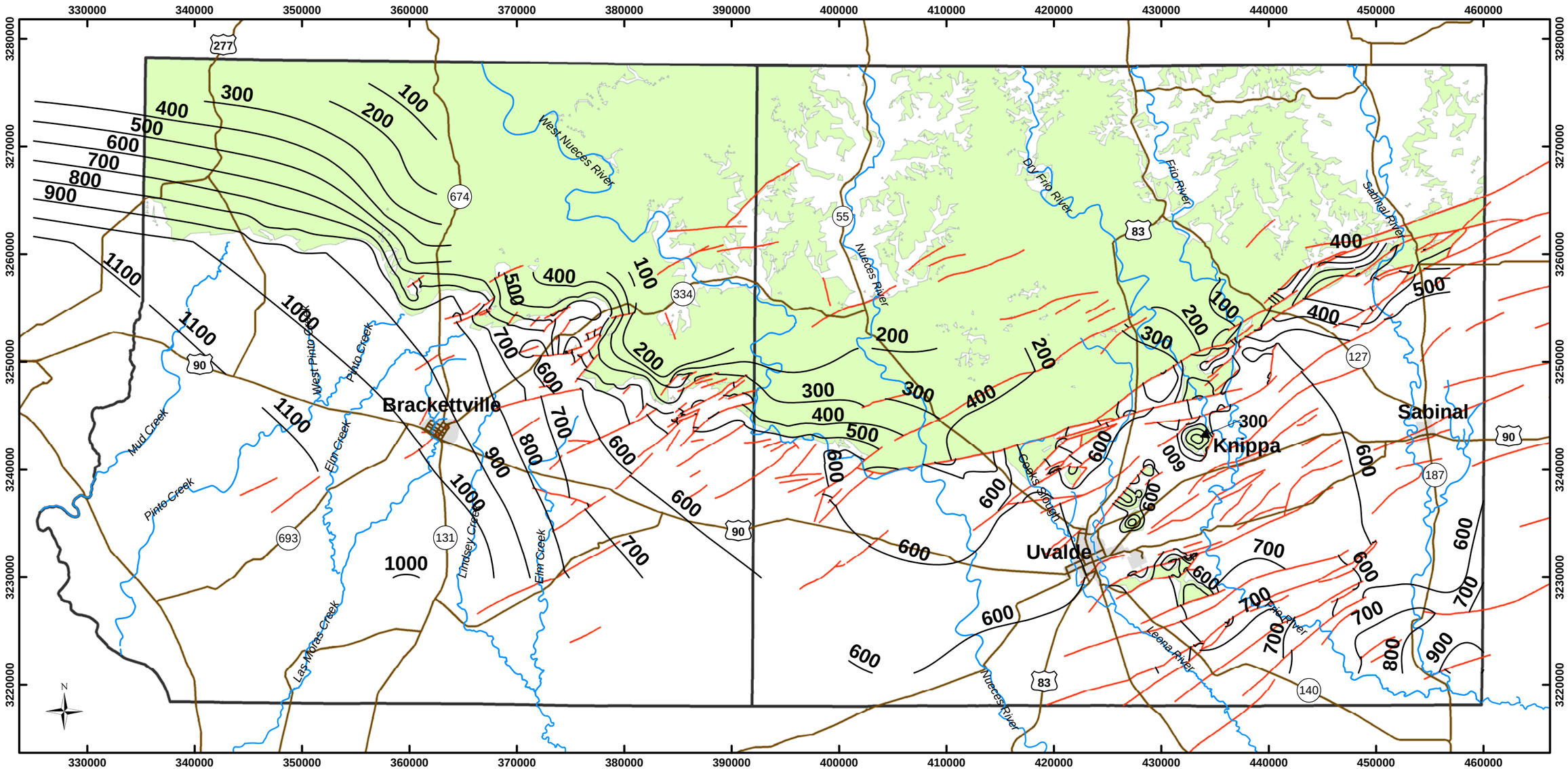


Figure 5.2.5: Geologic structure map of the study area illustrating the saturated thickness of the Edwards Aquifer and the recharge zone of the Edwards Aquifer.

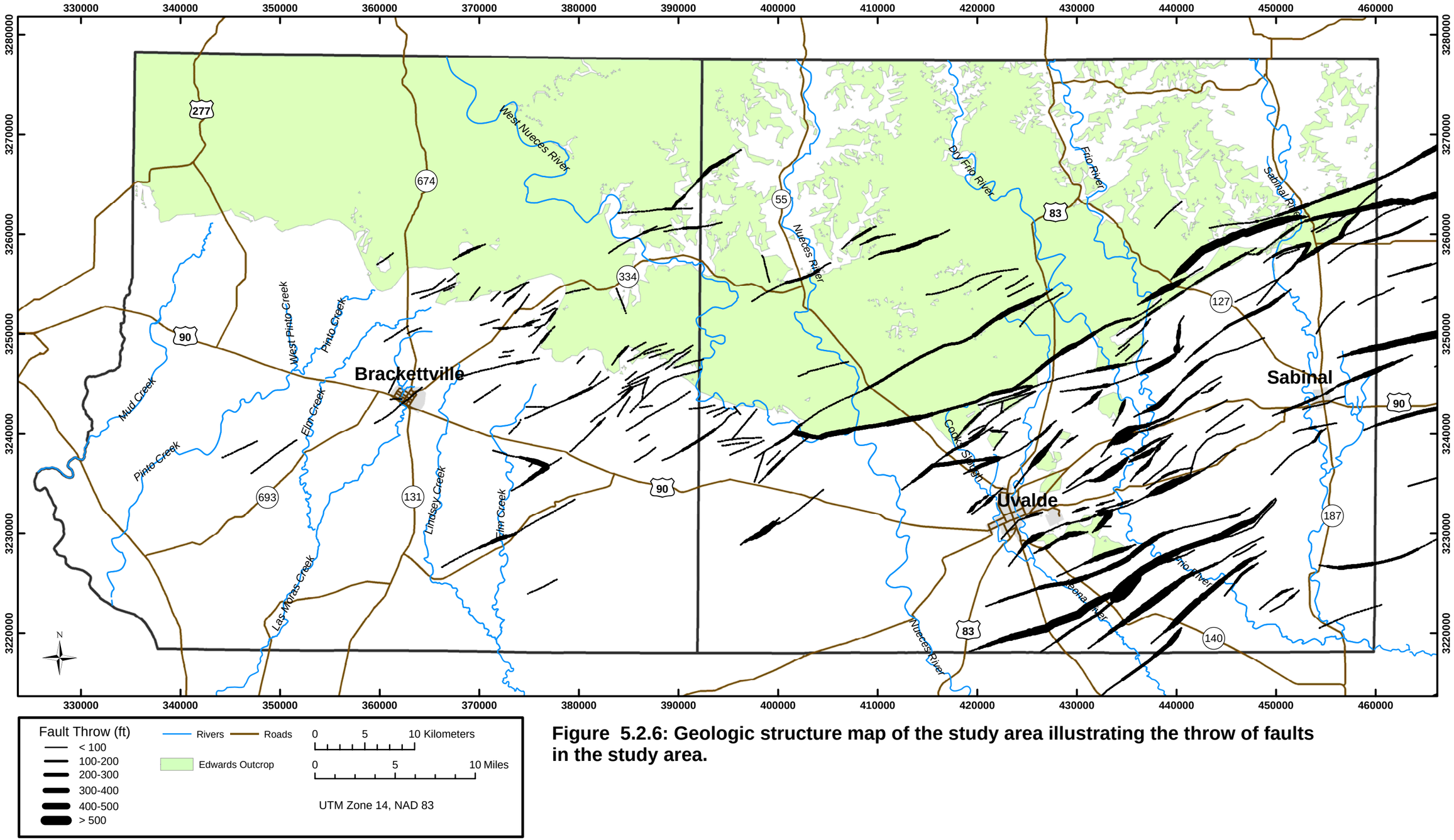
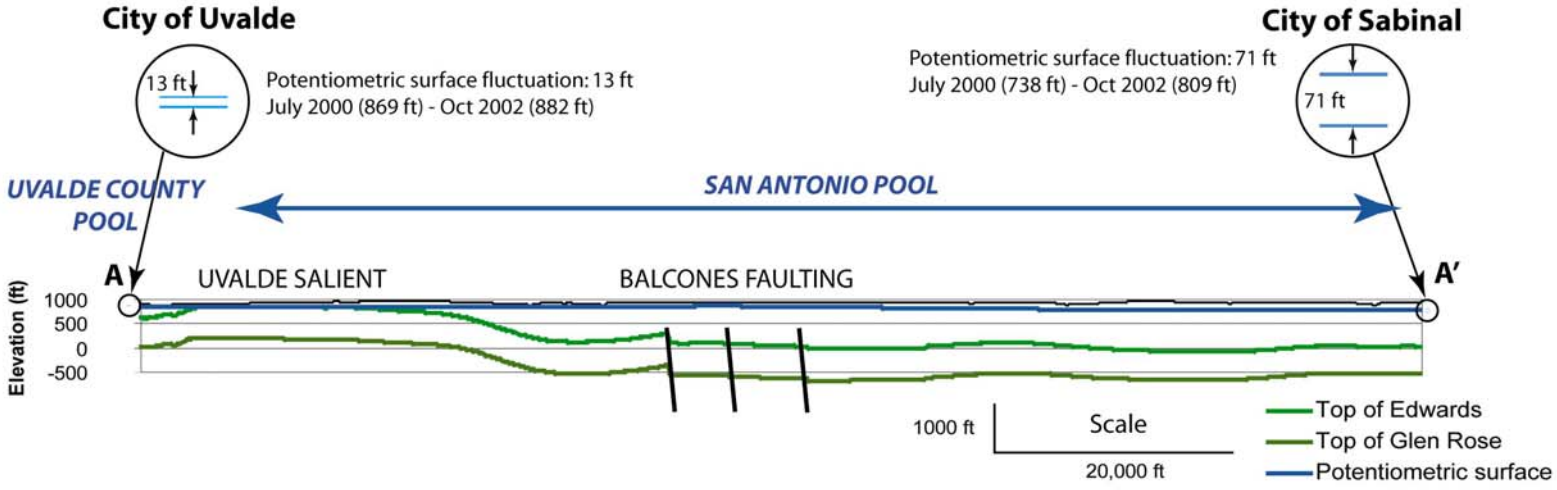


Figure 5.2.6: Geologic structure map of the study area illustrating the throw of faults in the study area.



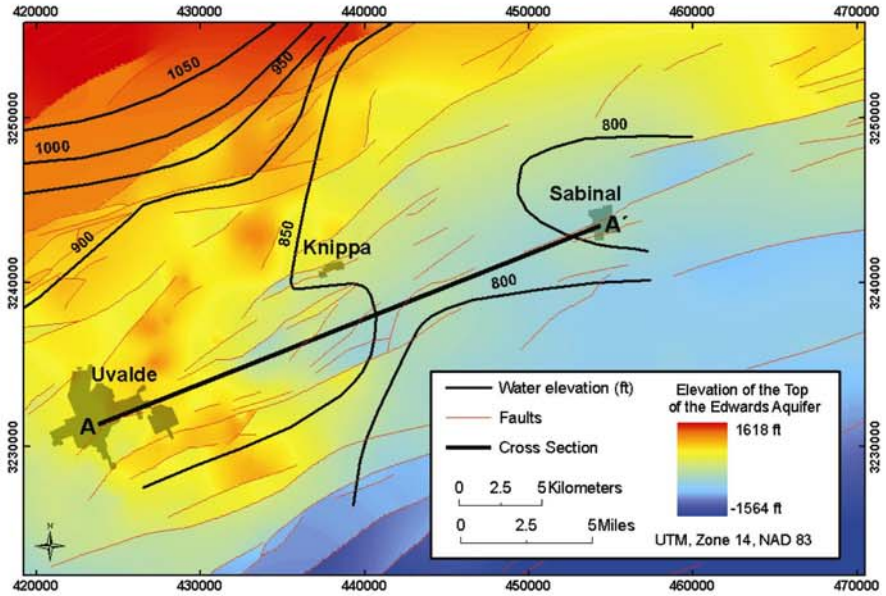


Figure 5.2.7 Vertical cross section illustrating the topographic relief and change in groundwater elevation relative to the Uvalde Salient. Map (left) illustrates location of cross section AA'.

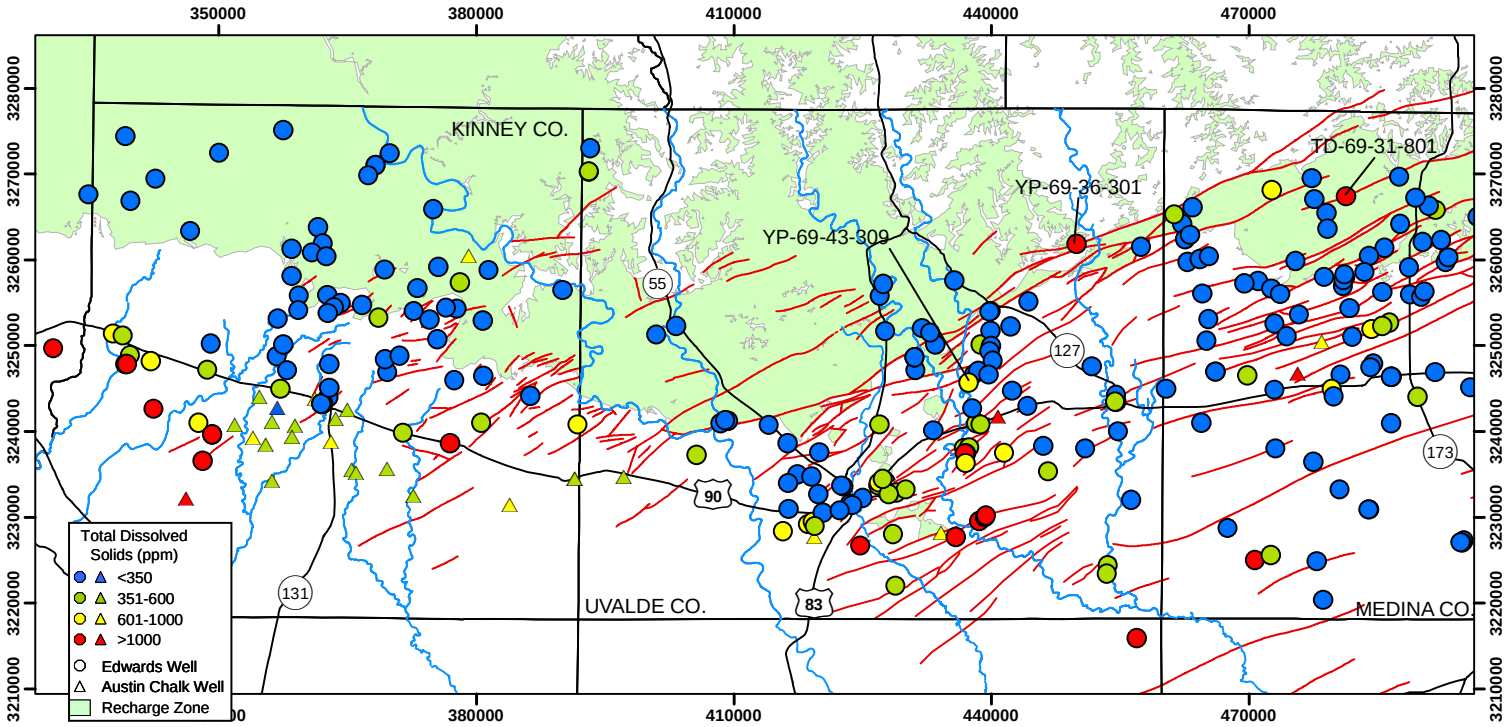


Figure 5.3.1: Map of the concentration of Total Dissolved Solids (TDS) in Edwards Aquifer (circles) and Austin Chalk (triangles) in the Kinney and Uvalde County region. For Edwards Aquifer wells, water quality decreases toward the south and southwest in Kinney County and toward south-central Uvalde County. Wells YP-69-36-301 and TD-69-31-801 are high in calcium and sulfate and likely draw water from the Upper Glen Rose. Well YP-69-43-309 is located near the Frio River and is anomalously high in chloride and nitrate, suggesting possible contamination from surface water. Austin Chalk wells have a higher average TDS content. Map projection is UTM Zone 14, NAD83.

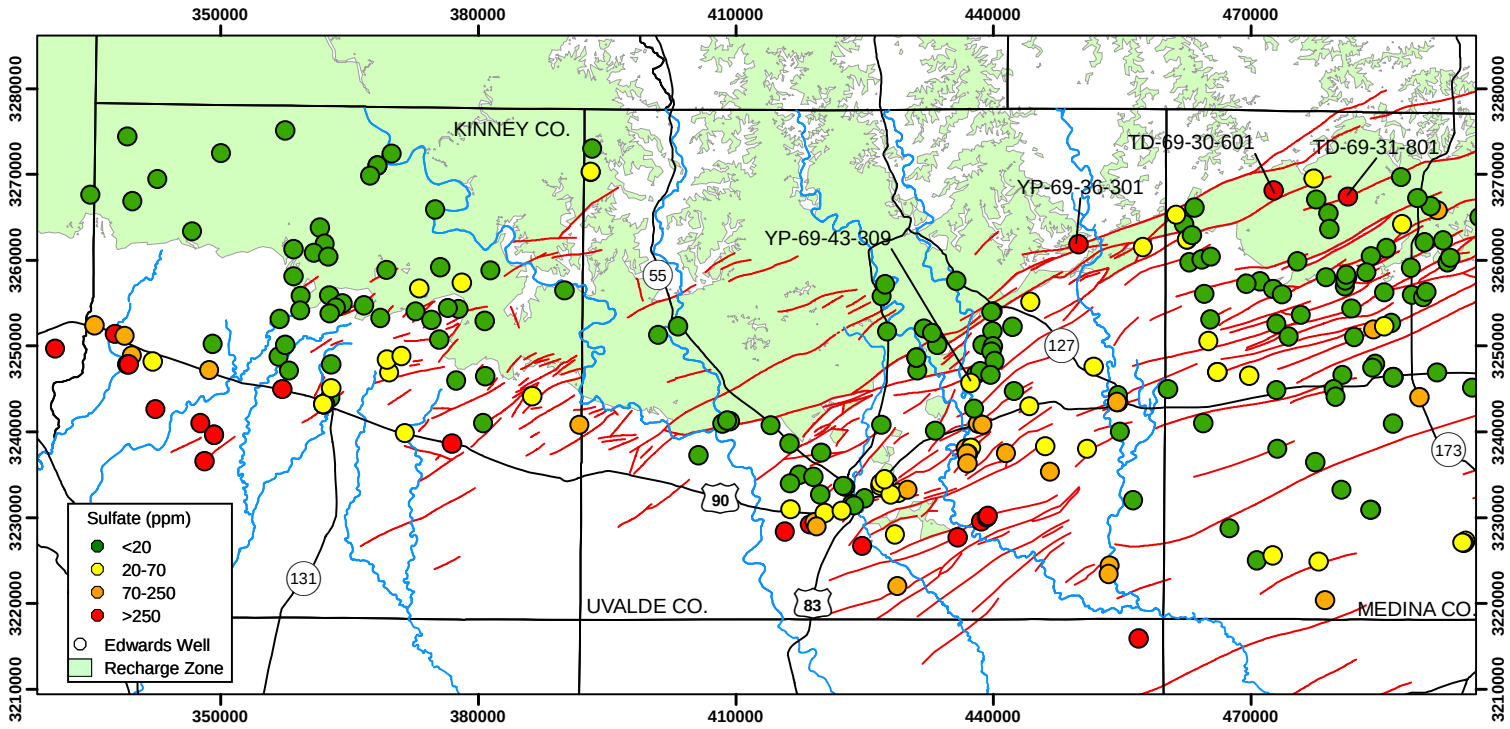


Figure 5.3.2: Map of the concentration of sulfate in Edwards Aquifer wells in the Kinney and Uvalde County region. The concentration of sulfate increases toward the bad water zones in south and southwest in Kinney County and south-central Uvalde County. Zones of slower water circulation tend to have elevated sulfate concentrations (Maclay et al., 1980). Wells YP-69-36-301, TD-69-31-801, and TD-69-30-601 are high sulfate and likely draw water from the Upper Glen Rose. Well YP-69-43-309 is located near the Frio River and, based on other chemical constituents. may have possible contamination from surface water. Map projection is UTM Zone 14, NAD83.

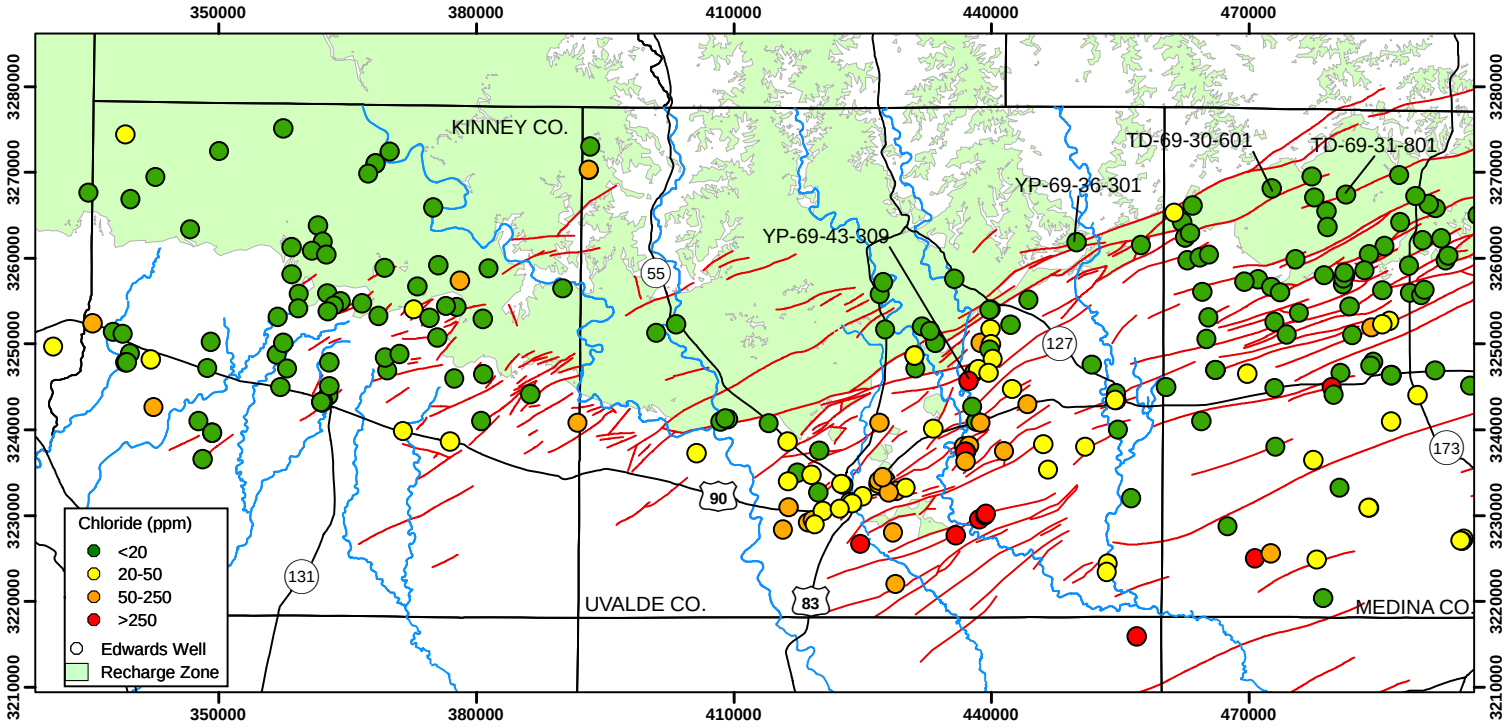


Figure 5.3.3: Map of the concentration of chloride in Edwards Aquifer wells in the Kinney and Uvalde County region. The concentration of chloride increases toward the bad water zone in south-central Uvalde County. Chloride concentrations for both fresh and saline waters in Kinney County are lower than those in Uvalde County. Based on their measured sulfate concentrations, wells YP-69-36-301, TD-69-31-801, and TD-69-30-601 appear to draw water from the Upper Glen Rose. Well YP-69-43-309 is located near the Frio River and has anomalously high chloride and nitrate, indicating possible contamination from surface water. Map projection is UTM Zone 14, NAD83.

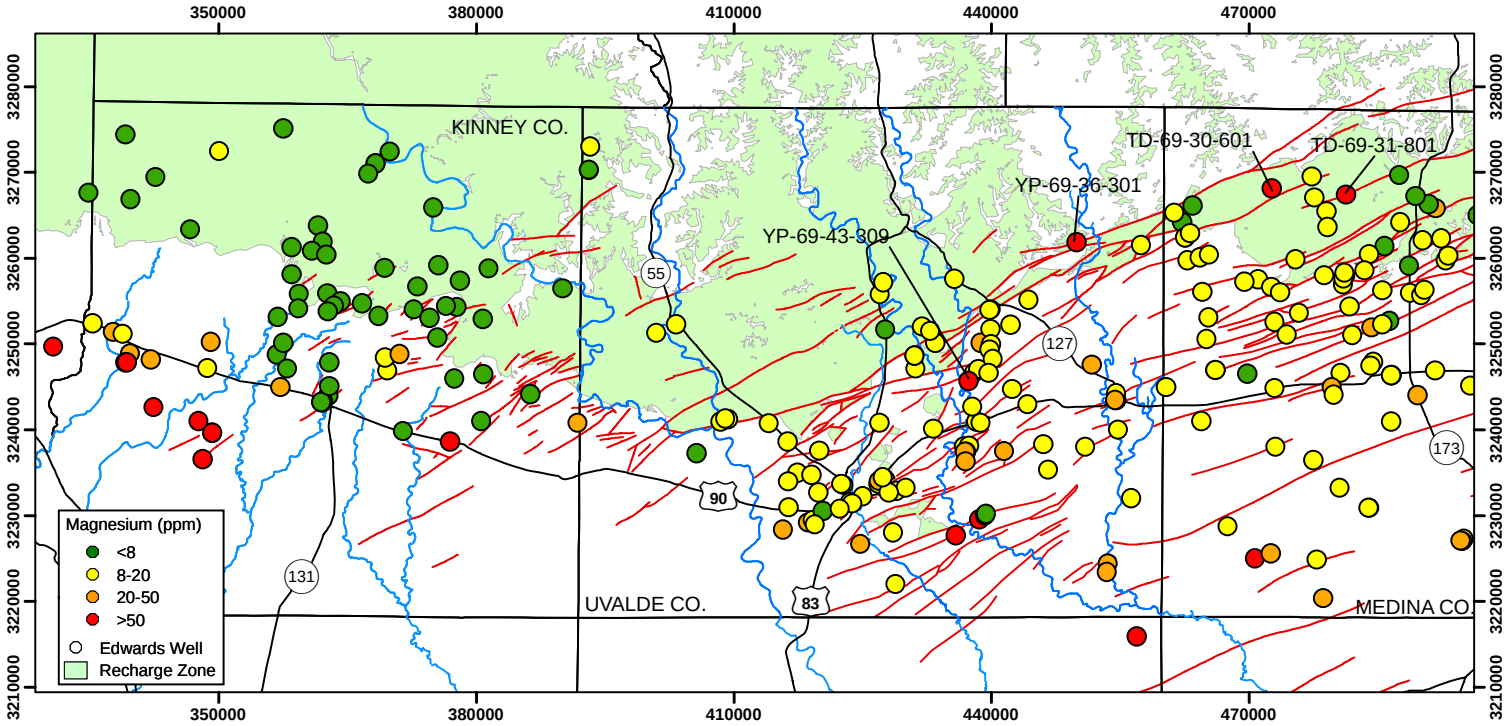


Figure 5.3.4: Map of the concentration of magnesium in Edwards Aquifer wells in the Kinney and Uvalde County region. The concentration of magnesium increases toward the bad water zone in south-southwest Kinney County and toward the bad water zone in southern Uvalde County. Magnesium concentrations in fresh water zones in Uvalde County and to the east are generally greater than those observed for Kinney County. These data highlight the potential separation of water between Kinney and Uvalde counties. Based on their measured sulfate concentrations, wells YP-69-36-301, TD-69-31-801, and TD-69-30-601 appear to draw water from the Upper Glen Rose. Well YP-69-43-309 is located near the Frio River and has anomalously high chloride and nitrate, indicating possible contamination from surface water. Map projection is UTM Zone 14, NAD83.

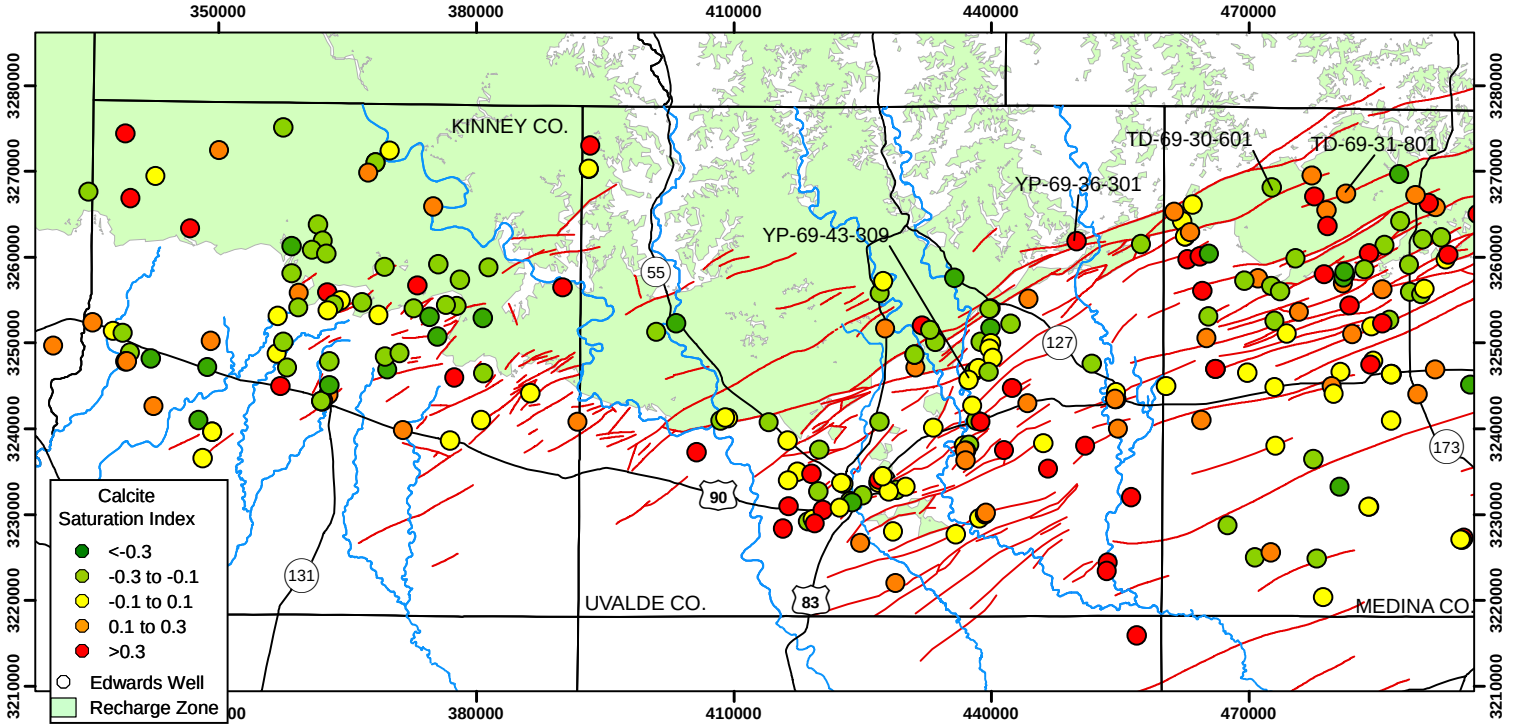


Figure 5.3.5: Map of the calculated saturation index of calcite in Edwards Aquifer wells in the Kinney and Uvalde County region. Waters range from undersaturated (<-0.3), slightly undersaturated (-0.3 to -0.1), saturated (-0.1 to 0.1), slightly oversaturated (0.1 to 0.3), to oversaturated (>0.3) with respect to calcite. Although there is some indication of an increase in the calcite saturation of waters in the bad water zones of south-southwest Kinney County southern Uvalde County, and there appears to be a slightly greater number of calcite saturated waters in the eastern portion of the study area, there is no clear trend from these data. Wells YP-69-36-301, TD-69-31-801, and TD-69-30-601 which appear to draw water from the Upper Glen Rose, and well YP-69-43-309 which may be contaminated with surface water are listed for comparison to other figures. The importance of pH to the calculation of the calcite saturation index and the temporal spacing over which wells were sampled in this region likely increase the uncertainty in these data. Map projection is UTM Zone 14, NAD83.

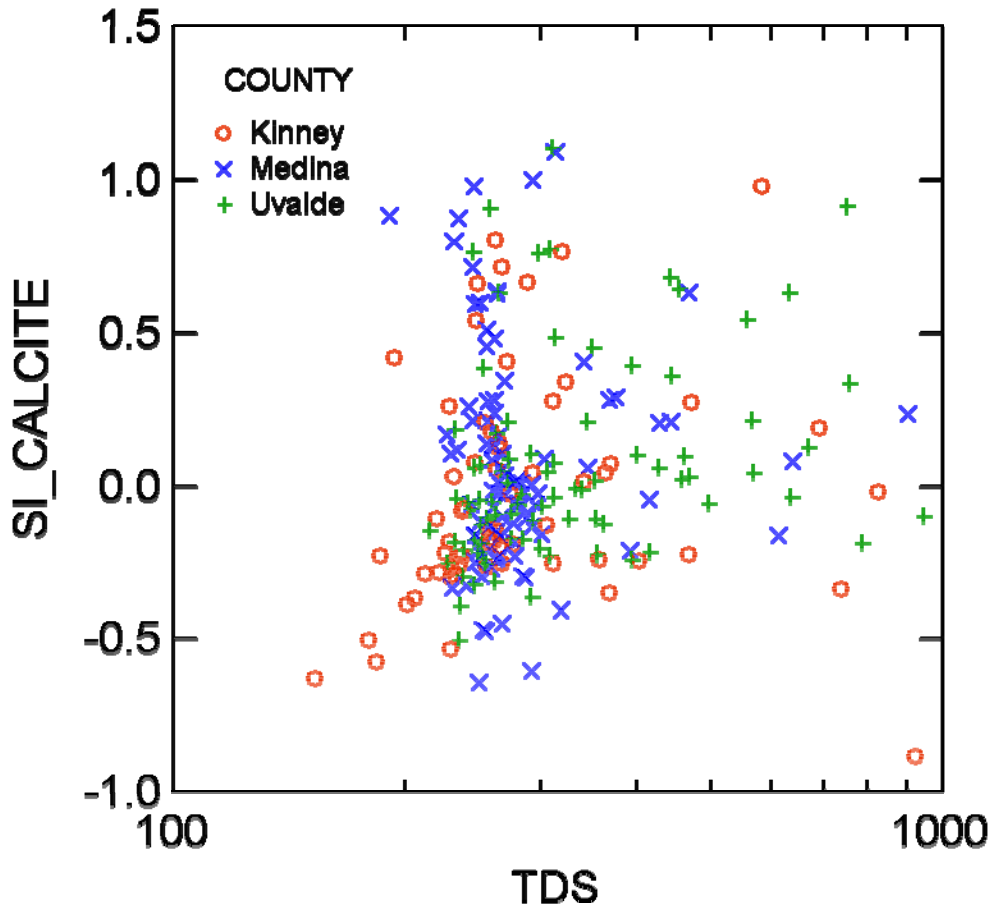


Figure 5.3.6: Plot of the relationship between Total Dissolved Solids (TDS) in parts per million (ppm) and the calculated saturation index of calcite in fresh water wells (TDS < 1000 ppm) of the Edwards Aquifer in the Kinney and Uvalde County region. There appears to be no clear correlation between increased TDS and an increase in the saturation index of calcite for waters in this region.

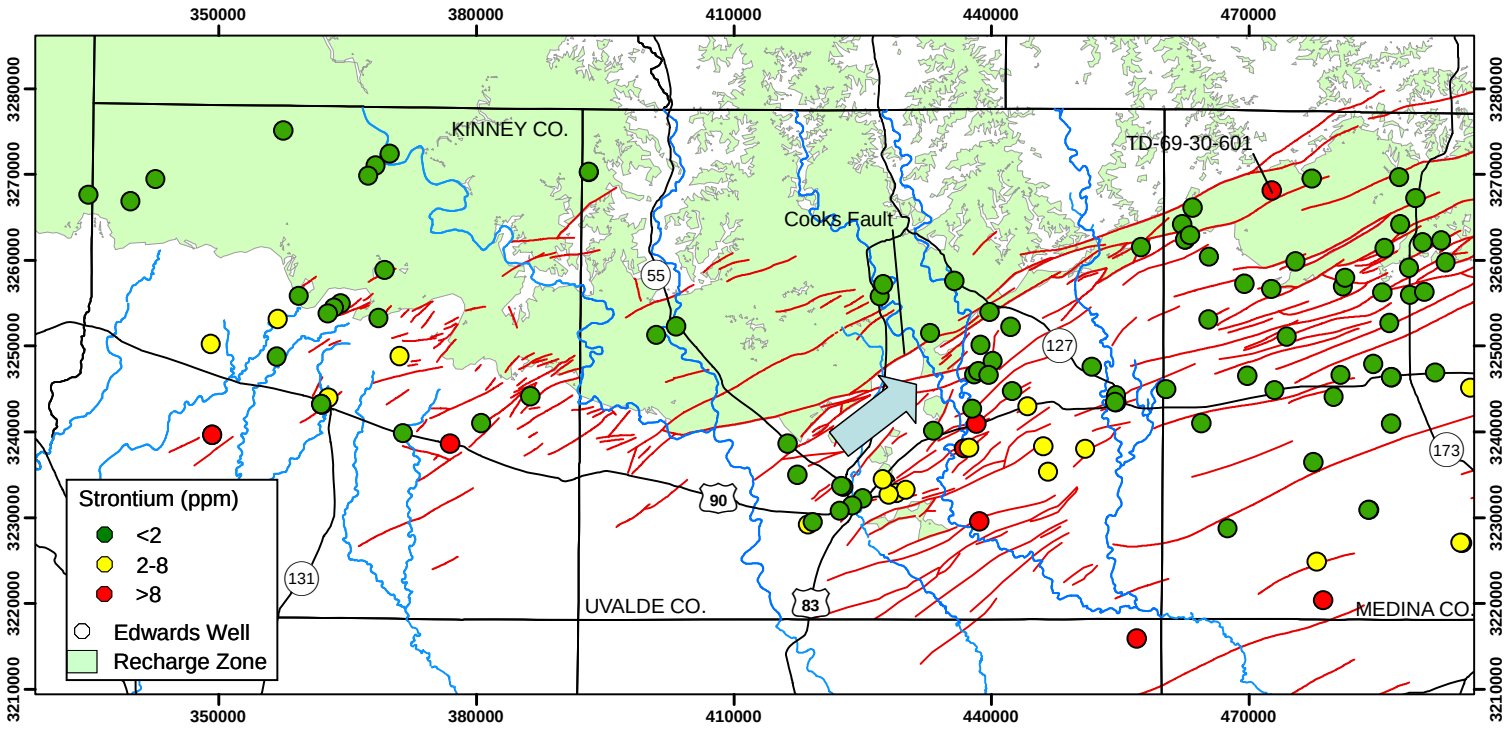


Figure 5.3.7: Map of the concentration of strontium in Edwards Aquifer wells in the Kinney and Uvalde County region. Fewer wells in the Texas Water Development Board groundwater database have been sampled for strontium than for other major chemical constituents. Strontium concentrations increase in areas of slower flow (Maclay et al., 1980). The location (shown by the block arrow) of the proposed high-capacity flow channel north of U.S. Highway 90 and south of Cooks Fault in central Uvalde County is highlighted by these data. Strontium isotope data suggest the source of strontium in Edwards waters is the Edwards Group Limestone and not the igneous intrusions present in eastern Kinney County and southern Uvalde County (Groschen, 1996). Well TD-69-31-801 likely draws water from the Upper Glen Rose. Map projection is UTM Zone 14, NAD83.

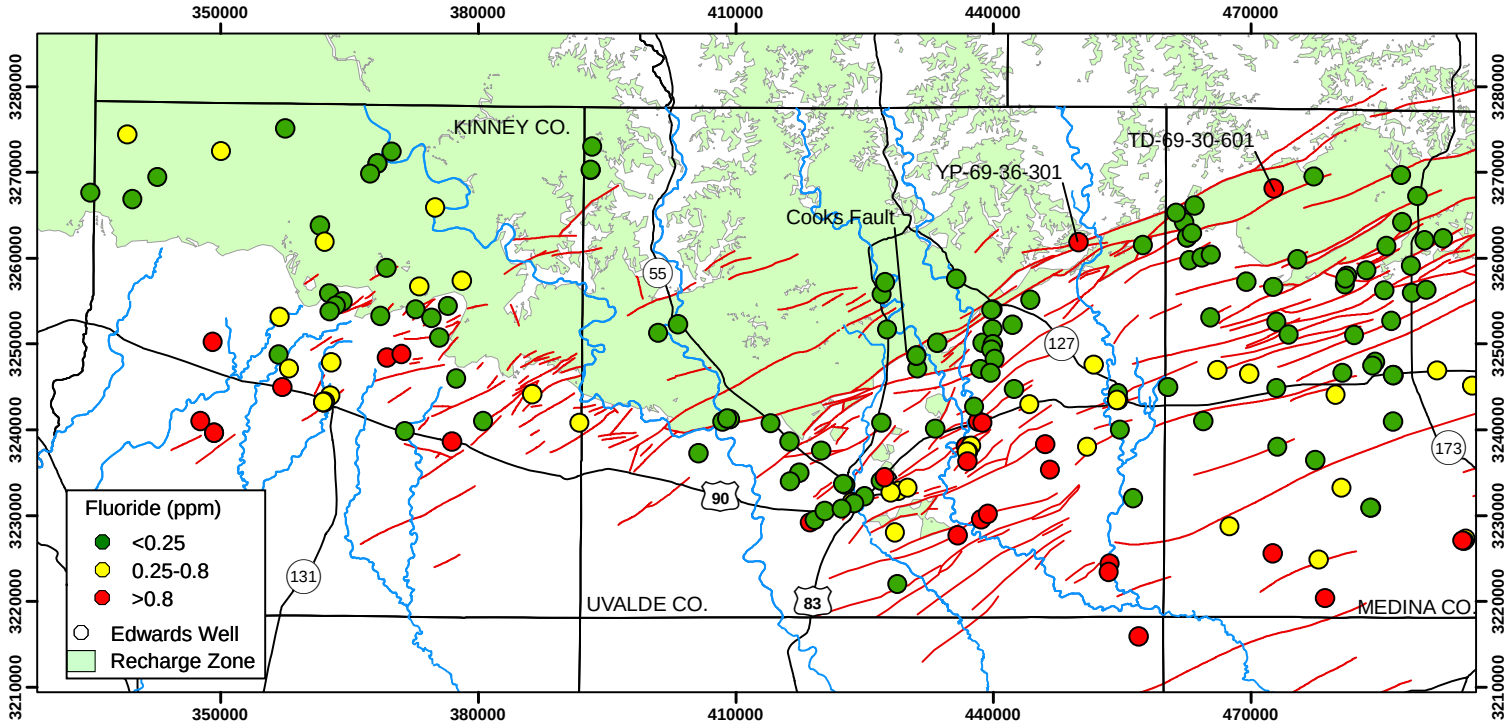


Figure 5.3.8: Map of the concentration of fluoride in Edwards Aquifer wells in the Kinney and Uvalde County region. Fluoride concentrations increase in areas of slower flow (Maclay et al., 1980) and in the bad water zones in southern Kinney and Uvalde counties. The boundary between an area of slower flow south of U.S. Highway 90 and the high-capacity flow channel north of U.S. Highway 90 and south of Cooks Fault in central Uvalde County is highlighted by these data. The fresh water zone in Kinney County appears to be generally higher in fluoride than fresh waters to the east. Wells TD-69-31-801 and YP-69-36-301 likely draw water from the Upper Glen Rose. Map projection is UTM Zone 14, NAD83.

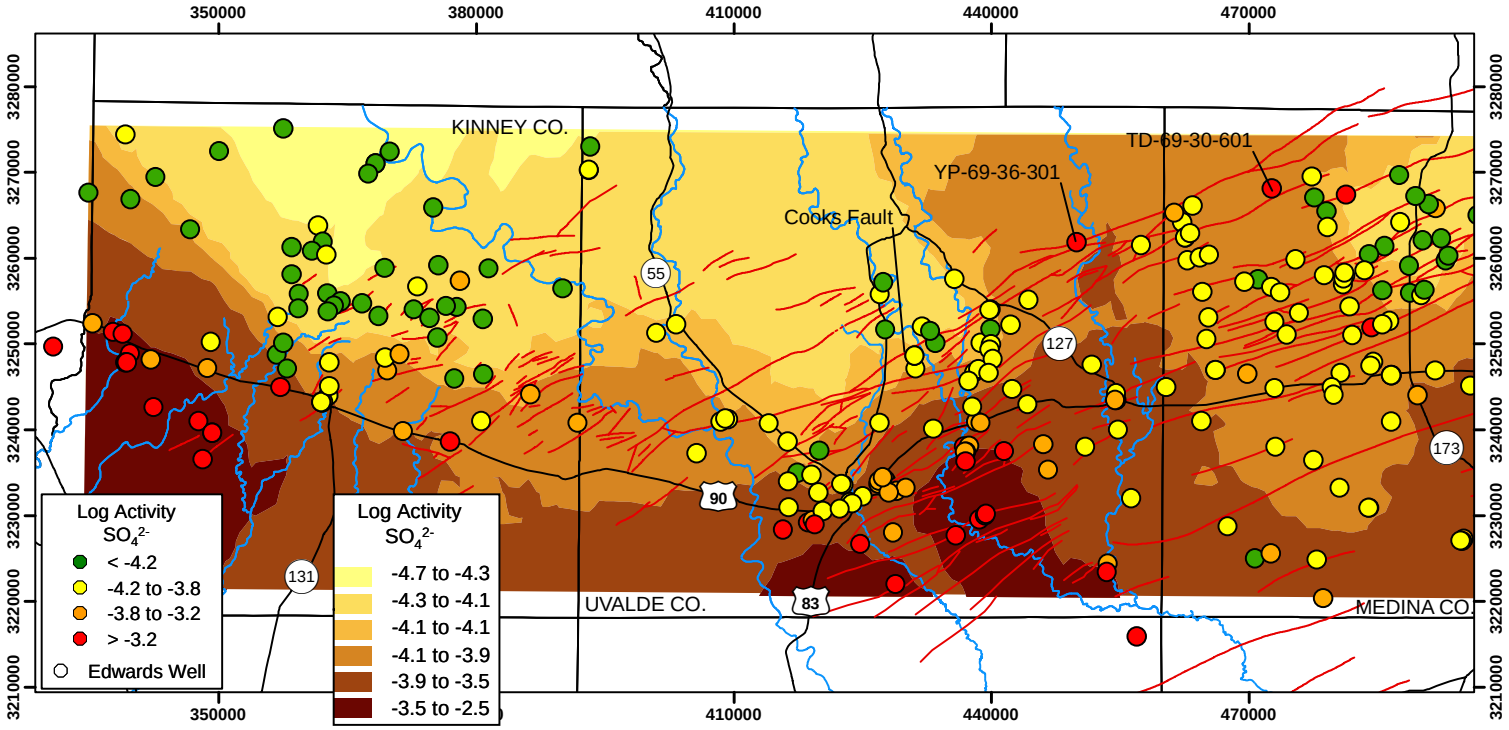


Figure 5.3.9: Contour map of the log activity of SO_4^{2-} in fresh water Edwards Aquifer wells in the Kinney and Uvalde County region. Also shown are values for the log activity of SO_4^{2-} in all Edwards Aquifer wells in the study area (circles). The activity of sulfate in solution is a more realistic measure of the species' ability to participate in chemical reactions. The predicted map was calculated using ordinary kriging of the fresh water sulfate activity values determined by the PHREEQCi version 2.8 code. These data highlight the proposed high-capacity flow channel north of U.S. Highway 90 and south of Cooks Fault in central Uvalde County. The data also illustrate the water chemistry differences between the Uvalde County pool and the proposed Kinney County pool (see discussion in Section 9) and reveal the mixing zone of fresh water recharged from Uvalde and Medina counties. Wells TD-69-31-801 and YP-69-36-301 appear to draw water from the Upper Glen Rose. Map projection is UTM Zone 14, NAD83.

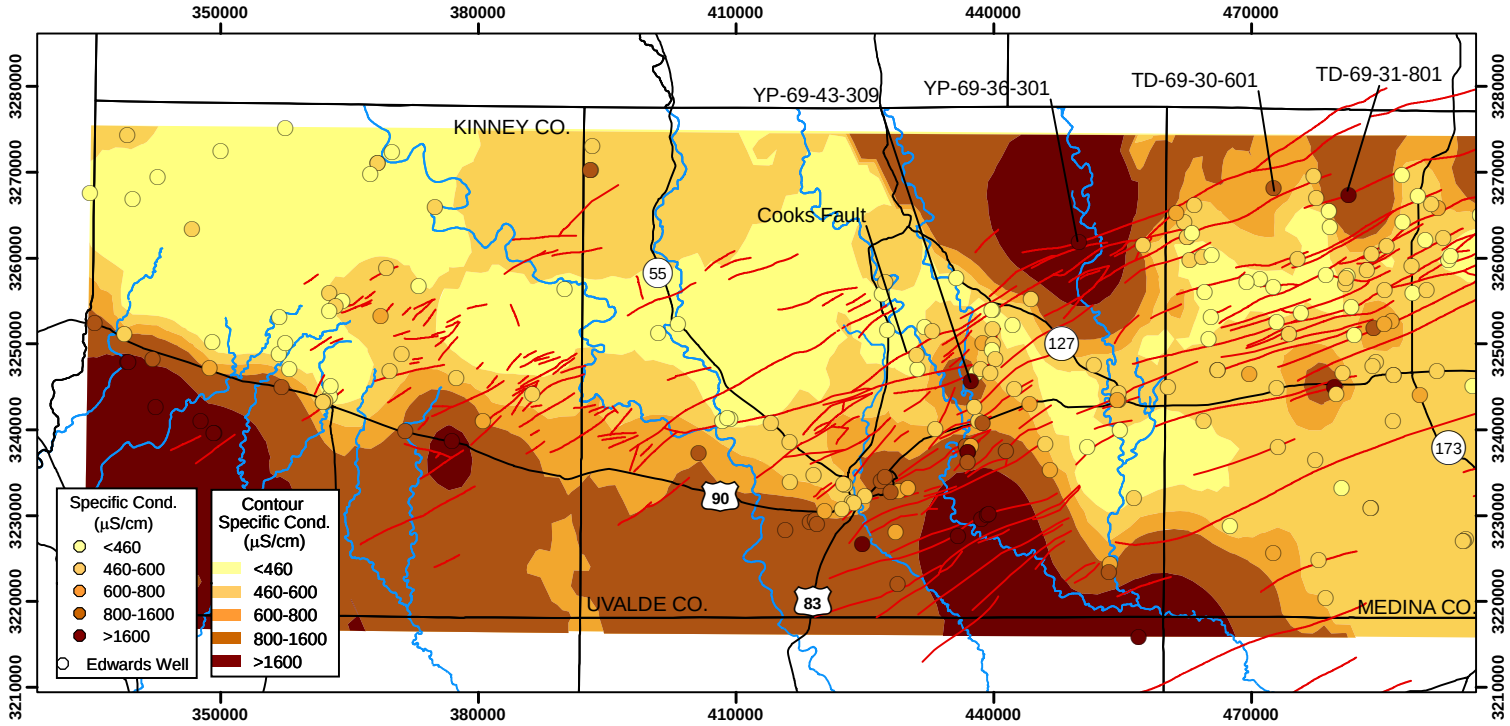


Figure 5.3.10: Contour map of the specific conductivity distribution of Edwards Aquifer wells in the Kinney and Uvalde County region. Also shown are values for the specific conductivity for Edwards Aquifer wells in the study area (circles). The specific conductivity data highlight the zones recharge into the Edwards Aquifer from the West Nueces in Kinney County, the Nueces and Frio/Dry Frio in Uvalde County, and from the Seco Creek area in Medina County. The low conductivity mixing zone from the combination of recharge from northwest Median County and north-central Uvalde County is apparent. Because of limited data near well YP-69-36-301, the high specific conductivity value for this well has significant impact on the contour map, but the recharge dilution zone is apparent nonetheless. Wells TD-69-31-801, YP-69-36-301, and TD-69-30-601 appear to draw water from the Upper Glen Rose, while well YP-69-43-309 has anomalously high chloride content, which may indicate surface water contamination in the well. Map projection is UTM Zone 14, NAD83.

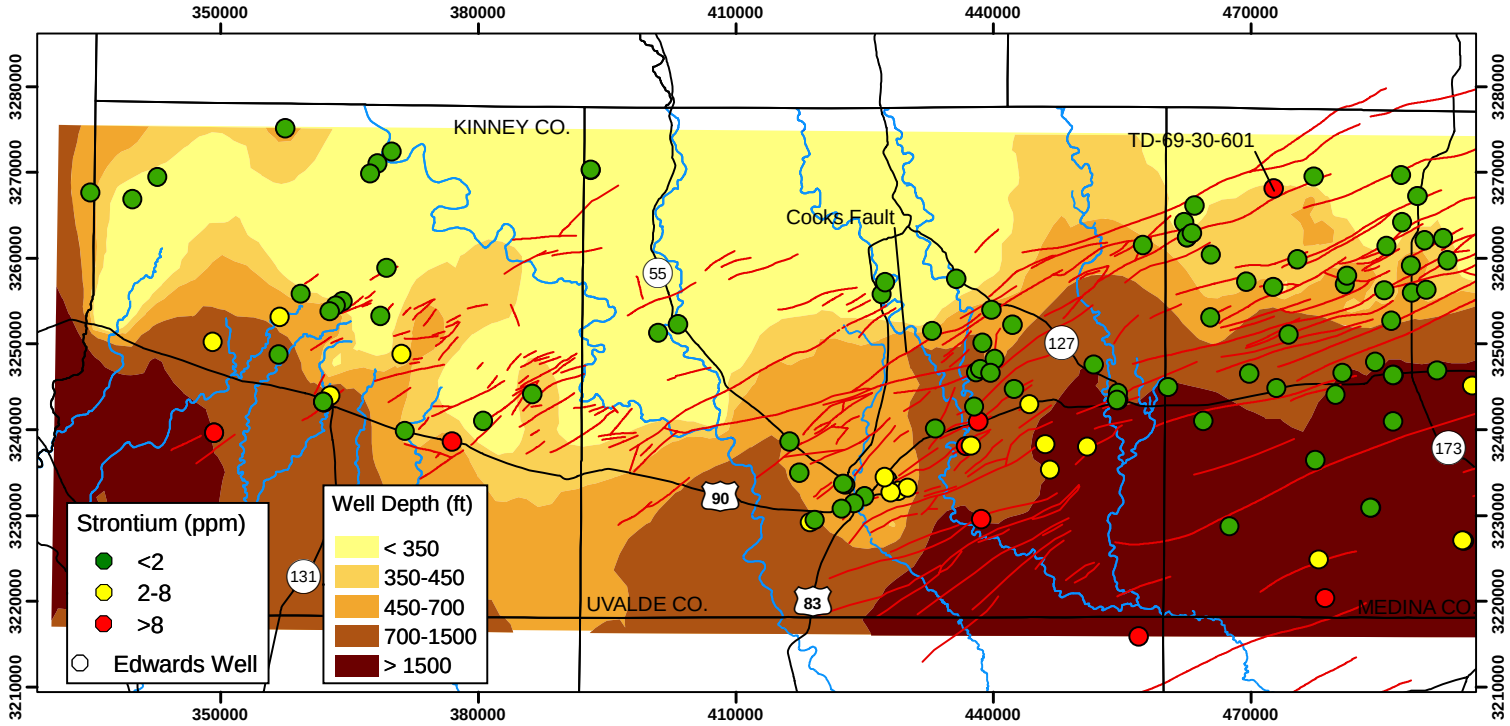


Figure 5.3.11: Contour map of the depth of Edwards Aquifer wells in the Kinney and Uvalde County region. Also shown are strontium concentration values for Edwards Aquifer wells in the study area (circles). Strontium concentrations are correlated with well depth. Although well depth is only an approximate measure of structural topography in the subsurface, the depth contour map clearly delineates the Uvalde Salient (see Figure 5.2.7) in central Uvalde County and reveals the structural embayment (Figure 5.2.6) in Kinney County that may contribute to the southwest flow direction in that area. Well TD-69-30-601 likely draws water from the Upper Glen Rose. Map projection is UTM Zone 14, NAD83.

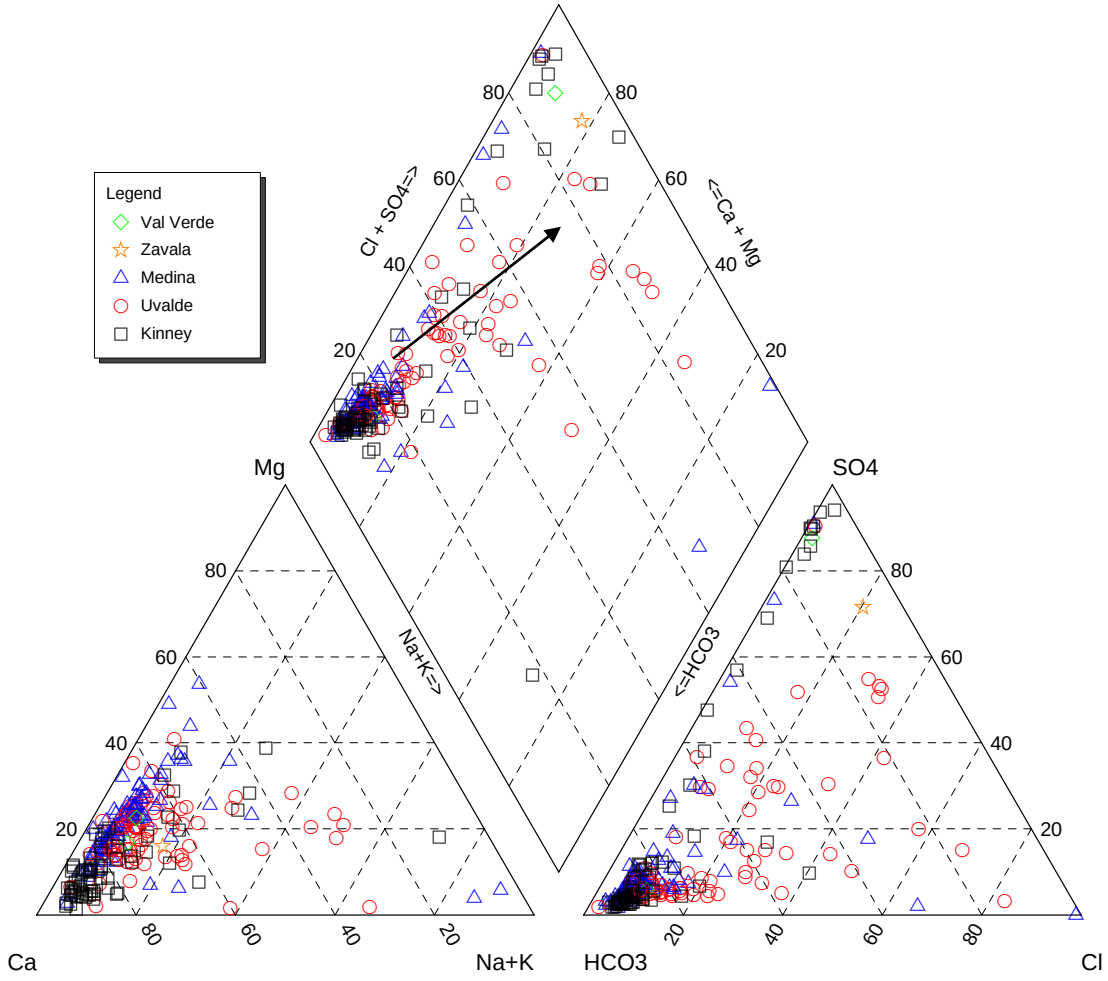


Figure 5.3.12: Trilinear diagram (Piper plot) of major chemical constituents in Edwards Aquifer wells in the Kinney and Uvalde County region. The data are consistent with the sequence of facies changes from fresh to saline water observed by Maclay et al. (1980). Fresh waters are dominated by calcium bicarbonate waters, while saline waters are more concentrated in magnesium, sulfate, and chloride. Also apparent from the data shown is the low concentration of chloride in Kinney County saline waters. Arrow shows general change in composition from fresh water to saline-water facies.

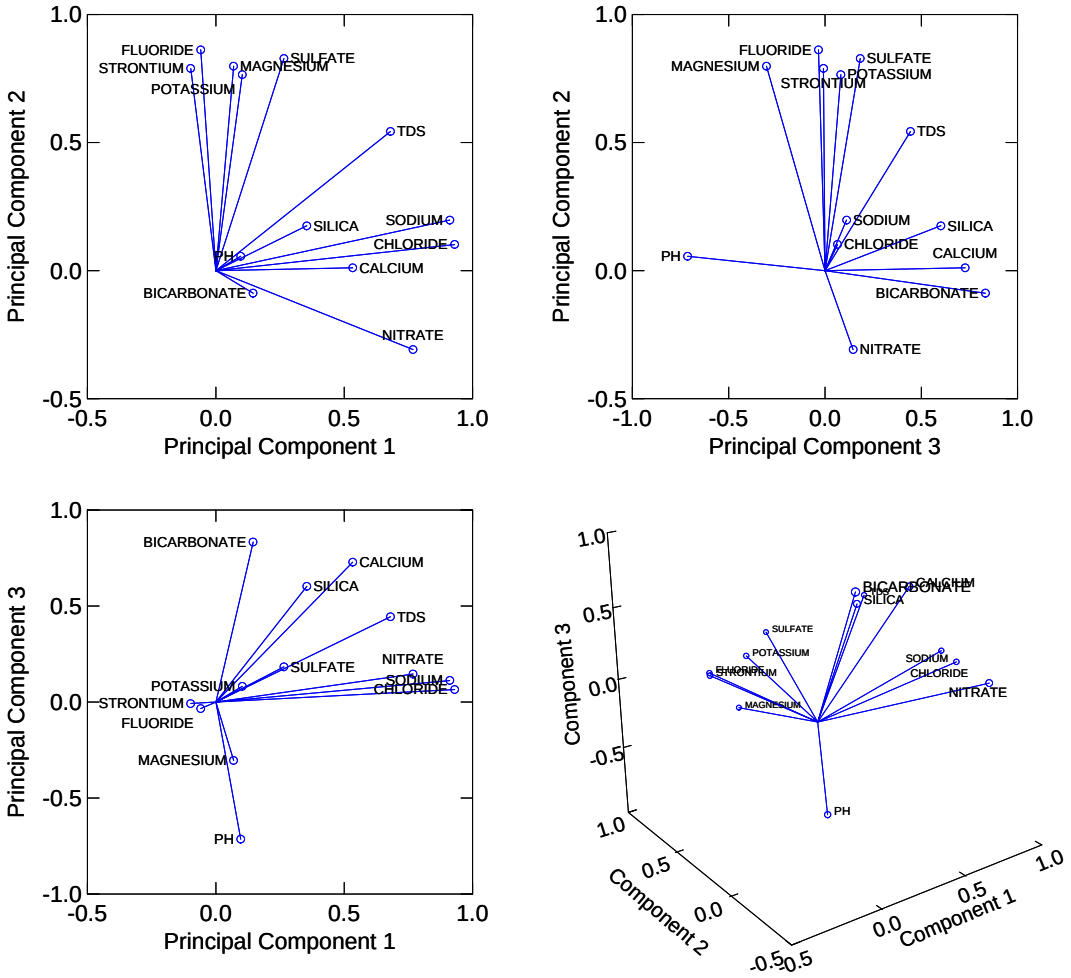


Figure 5.3.13: Summary of component loadings for principal component analysis (PCA) of chemical constituents in wells from the Edwards Aquifer in Kinney and Uvalde counties. Principal Component 1 is representative of sodium-nitrate-chloride waters, Principal Component 2 is representative of magnesium-sulfate-strontium-fluoride waters, and Principal Component 3 is representative of calcium-bicarbonate waters. These component loadings were derived from a PCA using the correlation matrix for these variables and varimax rotation (which attempts to maximize variance of factors on the orthogonal axes). The results shown here do not differ significantly from analyses conducted using normalized data or a subset of variables to maximize number of samples scored. Analysis of fresh water samples only gives similar results. Note the nearly equal distribution of TDS between Components 1 and 2.

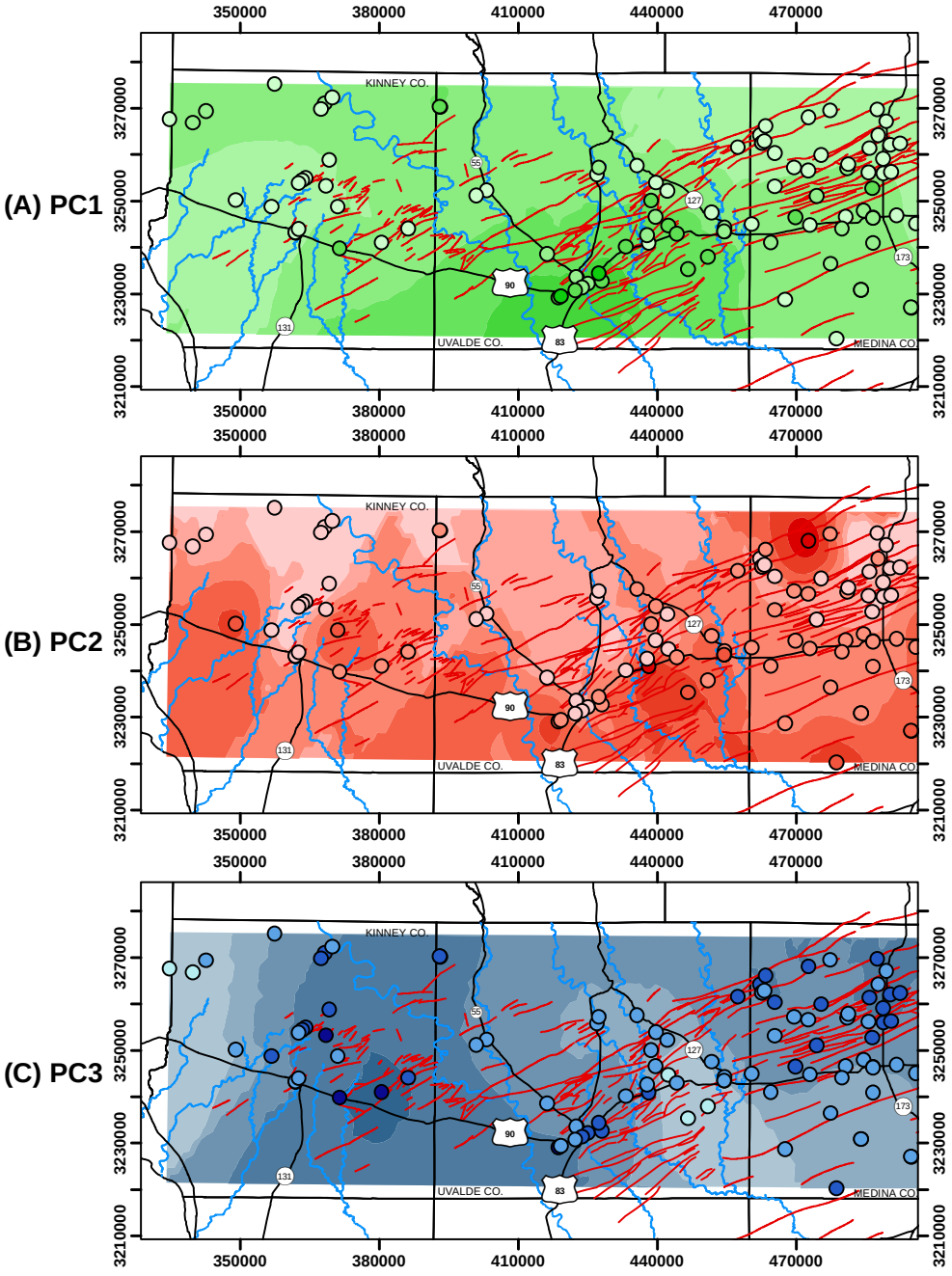


Figure 5.3.14: Contour plots of Principal Components distributions for the Edwards Aquifer well chemical constituent data. Contours are darker where the particular component is positive and lighter where the component is negative. Component 1 [(A) PC1] is more positive (darker) in the region of sodium-chloride dominated bad water in southern Uvalde County. Component 2 [(B) PC2] is positive (darker) in the regions of magnesium-sulfate-strontium waters. Component 3 [(C) PC3] is positive (darker) in regions with greater calcium-bicarbonate concentrations. Together, the plots help to highlight the different chemical regimes of Uvalde and Kinney County and emphasize the areas of fresh water input. Maps projections are UTM Zone 14, NAD83.

6 FLOODPLAIN FLOW

River and stream floodplains provide a complex system of surface water and groundwater conveyance in the study area. For the purposes of this interpretation, floodplains are defined to include not only floodplain sediments, but also nearby hydrostratigraphic units including bedrock. The floodplains convey surface water in the river channel, groundwater through riverbed sediments, and groundwater through the underlying bedrock. Inspection of drilling logs for wells located in floodplains indicates that preferential flowpaths may be present in bedrock in the near-subsurface of floodplains. It is hypothesized that the relatively high volume of groundwater that flows through bedrock in a floodplain has the potential to have developed preferential flow pathways. A self-developing feedback system promotes greater development of preferential flow pathways in the floodplain bedrock by an increase in flow. At some distance from the floodplain, bedrock ceases to actively participate in the transport of groundwater as part of the floodplain conveyance system.

Similar to rivers and streams, floodplains can either gain or lose water. In the case of floodplains, however, water transfer can be more complicated. Water can be transferred both (i) between surface water and groundwater flowpaths, and (ii) between the floodplain and the adjoining subsurface formation. In general, floodplains gain water in the contributing zone, lose water in the recharge zone, and neither gain nor lose water when transiting through zones of low permeability. The transition from gaining to losing, or vice versa, may not be distinct in the complicated hydraulic setting of Kinney and Uvalde counties, oftentimes changing along different reaches of the same river floodplain. A floodplain could also change from gaining to losing water through time as the underlying aquifer level drops or from losing to gaining as the underlying aquifer level rises. This complex behavior is apparent throughout the study area, but is most clearly exhibited along the West Nueces River.

Characterizing the capacity of floodplains to convey water is difficult. Wells provide a data source to qualitatively evaluate the capacity of groundwater flow in floodplains relative to the capacity of groundwater flow outside of the floodplains. Floodplain wells are set in a variety or combination of media, including both sediments (typically gravels) and bedrock. Wells located in floodplains commonly have capacities in excess of nearby wells located outside of the floodplains. Increased well capacity is clearly exhibited in wells drilled in river floodplains located in the contributing and recharge zones of the Nueces, Dry Frio, and Frio rivers and Indian Creek, which are located in the inter-river area between the Nueces and Dry Frio rivers. For example, only low capacity (i.e., less that 10–12 gpm) windmill wells are found elsewhere in the area between the Nueces and Dry Frio rivers whereas the wells in the Indian Creek floodplain (UV021, UV022) have capacities of approximately 20 gpm. Another example area is well UV108, with a capacity of 30–40 gpm, set in the West Nueces River floodplain, approximately three miles east of the Kinney County line and well KY001, located about one mile south of the West Nueces River floodplain and within three miles of UV108, which has a capacity of only 10 gpm. An exception to this generalization would be floodplains that cross high transmissive zones of the Edwards Aquifer recharge zone, in which case, all wells have high capacity. As an example, high capacity wells both in and nearby the floodplain of the Frio River-Dry Frio River are located in an area where the Edwards Aquifer is highly transmissive both in and adjacent to the floodplain.

Floodplains of paleo-stream beds can also convey significant volumes of water. A paleo-stream channel in central Uvalde County that connects the Nueces and Leona river valleys potentially conveys a large volume of water. The channel is comprised of Leona Gravel sediments. The downgradient segment of the channel is referred to as Cooks Slough. The base of the gravels in the channel is at least 30 ft higher at the Nueces River than at the Leona River (Welder and Reeves, 1962). The quantity of water conveyed through the channel has not been measured and is not known, but is thought to provide at least some of the water discharged at the Leona Springs (Welder and Reeves, 1962).

River and stream floodplains south of the recharge zone also have the capacity to convey significant volumes of water. As will be discussed in Sections 9 and 10, the capacity of these southern floodplains to convey water has not been taken into account when making water balance assessments of the water resources of Kinney and Uvalde counties. Recent studies by Green (2003) and Green et al. (2004) highlighted the potential importance of floodplain conveyance off the Edwards Aquifer recharge zone. In their analysis, results from an electrical resistivity survey coupled with a five-day aquifer test provided site-specific information that allowed for more representative calculation of water flow through the Leona River floodplain. They calculated that the Leona River floodplain conveys as much as 100,000 acre-ft/yr south of the recharge zone across the confined zone of the Edwards Aquifer (Green, 2003; Green et al., 2004).

The 100,000 acre-ft/yr calculation provided by Green (2003) and Green et al. (2004) has been modified using additional geophysical field data collected during this investigation. The studies by Green (2003) and Green et al. (2004) were predicated on the interpretation that all zones of high electrical resistivity detected in the Leona River floodplain are associated with sand and gravel paleo-stream channels. A magnetic survey was performed along electrical resistivity transect UVAL7 to test this assumption. An unambiguously large magnetic signature associated with the distinct zone of high electrical resistivity located at the mid-point of UVAL7 strongly suggests that the high electrical resistivity zone is an igneous intrusion and not a sand and gravel paleo-stream channel (Figure 6.1). Wells located in high electrical resistivity zones in the other transects verified that sand and gravel deposits, and not igneous intrusions, were correlated with those high electrical resistivity zones. Removal of the high-resistivity cross-sectional area associated with the igneous intrusion at the mid-point of transect UVAL7 reduces the estimate of the cumulative cross-sectional area of the paleo-stream channels by approximately 15%. The revised estimate of groundwater flow in the Leona River floodplain is 74,000 acre-ft/yr, which, when added to channel flow, indicates that 87,000 acre-ft/yr is discharged from the Edwards Aquifer via the surface flow in Leona River and subsurface flow (underflow) through floodplain sand and gravel deposits.

The contribution of floodplain flow to discharge from the Edwards Aquifer has not been fully recognized in recent water resource evaluations. A volume of 11,220 acre-ft/yr was used by Lindgren et al. (2004) for the calibration target for annual discharge from Leona Springs in their numerical model of groundwater flow in the San Antonio segment of the Edwards Aquifer. No Leona River underflow was included in their model. Starting in the mid-1990's, the USGS measurements of discharge at Leona Springs included subsurface flow in the floodplain (referred to as underflow by the USGS and Edwards Aquifer Authority; Edwards Aquifer Authority, 2005). The 1998–2004 average discharge for Leona Springs, including underflow, was 27,000 acre-ft/yr (as reported in the 1998-2004 Edwards Aquifer Authority annual hydrogeological data reports). Calculations and measurements by Lindgren et al. (2004) and the Edwards Aquifer Authority (Edwards Aquifer Authority, 2005) may, therefore, underestimate the total volume of discharge from Leona Springs as surface flow and underflow. The contribution of floodplain flow needs to be quantified in the Nueces and Frio rivers, and the Las Moras and Pinto creeks to allow for meaningful water balance evaluations of Kinney and Uvalde counties.

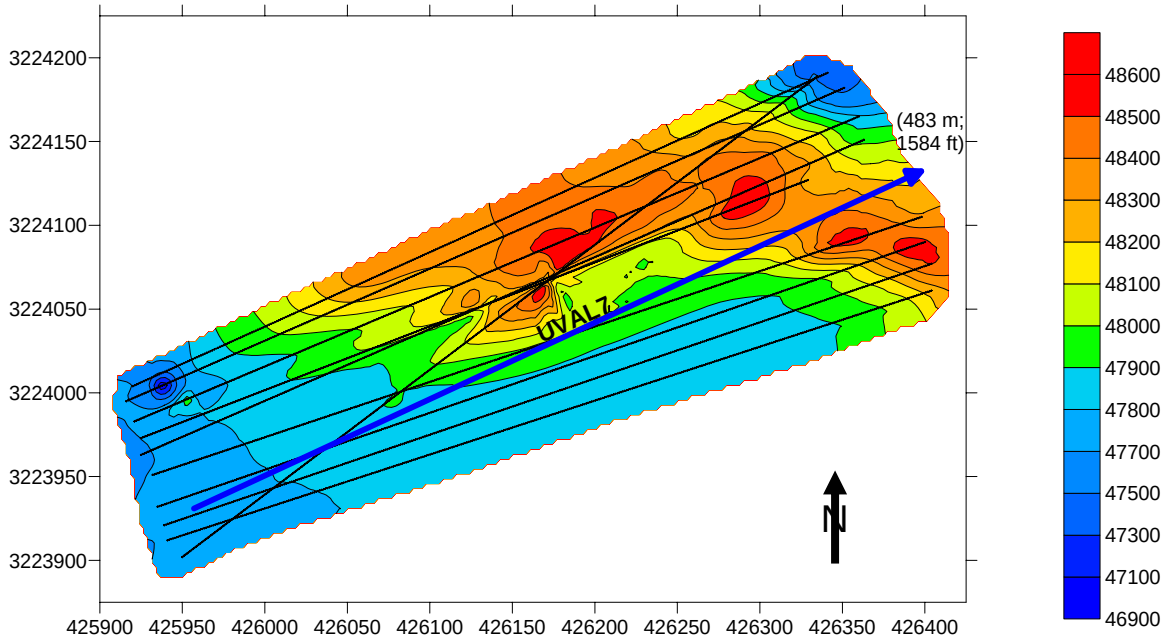


Figure 6.1: Magnetic survey results of the Leona River floodplain at transect UVAL7. The area with a large magnetic signature (indicated by orange and red colors) is interpreted to indicate a buried igneous intrusion. UVAL7 is indicated by a blue line. Values are in gammas. Coordinates are in Universal Transverse Mercator (meters) Zone 14, World Geodetic System Datum 1984.

7 RECHARGE TO THE EDWARDS AQUIFER

Comprehensive assessment of the water systems in Uvalde County cannot be undertaken without evaluating recharge. The fundamental basis for recharge assessment in the study area is the structural geology conceptual model of the Balcones Fault Zone and its influence on the Edwards Aquifer. The transition from the Edwards Plateau in the north to the confined area of the Edwards Aquifer in the south is represented by a system of normal faults such that the Edwards Aquifer is at increasingly greater depths toward the Gulf Coast. The contributing zone consists of the Glen Rose Formation either exposed at the surface of capped with mostly Edwards Group rocks above the water table. Drainages systems incised into the Glen Rose Formation near the southern margins of the Edwards Plateau provide the potential for surface water runoff to the south. The southern limit of the contributing zone terminates at the recharge zone of the Edwards Aquifer where the Edwards Group is exposed at the surface. Continuing south, the recharge zone is terminated as additional faulting positions the Edwards Group limestones beneath the surface at greater depths, and the aquifer eventually transitions to a confined system.

Potential sources of recharge to the Edwards Aquifer are: (i) subsurface recharge as groundwater underflow from hydrostratigraphic units such as the Trinity Aquifer, Buda Limestone, Austin Chalk, and the Leona Gravel, where some of these units are in stratigraphic contact or fault-juxtaposed with the Edwards Aquifer; (ii) surface recharge focused in stream beds; and (iii) distributed recharge (also referred to as diffuse recharge) from precipitation in inter-stream areas. Both subsurface and distributed recharge are difficult to quantify. Typically, the only meaningful way to estimate this quantity is to determine all other sources, perform a water-balance analysis, measure the total discharge, and back calculate the amount of recharge in the subsurface to balance flow.

The common approach to calculate focused recharge is to measure surface flow at the point where the stream or river crosses into and out of the recharge zone, and assume that the quantity of recharge is equal to the decrease in flow between the two points (Land et al., 1983). Less frequently directly measured is the distributed recharge as precipitation in inter-stream areas. Measurement of precipitation and evapotranspiration is required to directly measure distributed recharge. Evapotranspiration has not been measured in the study area. In the absence of evapotranspiration measurements, a host of methods to calculate the combined recharge from focused recharge and distributed recharge have evolved over the past 50 years.

Early estimates of focused and distributed recharge to the Edwards Aquifer employed an empirical approach originally developed by Lowry (1955), advanced by Petitt and George (1956), and refined by Garza (1962, 1966). The method was further refined by Puente (1975, 1976, 1978). The Puente method was used for the next 25 years to estimate recharge to the Edwards Aquifer. In the Puente method, the contribution of distributed recharge is calculated as a percentage of focused recharge using an empirically determined, quasi-linear relationship between the base flow discharge of a river and the groundwater in storage contributing to base flow. This relationship is approximately linear for average- and high-flow rates. Estimated distributed recharge decreases when the base flow of the rivers is low. Under linear conditions, distributed recharge contributes the following percentages to total surface recharge for each river basin: Nueces – 20%; Dry Frio – 72%; Frio – 72%; and Sabinal – 8% (Puente, 1978).

Recently, the recharge approach was again modified in Edwards Aquifer recharge studies by HDR Engineering (2002) and LBG-Guyton (2005). Analyses by LBG-Guyton (2005) provide the most current estimates for surface recharge on individual watershed basins of the San Antonio segment of the Edwards Aquifer; however, their work was completed in the absence of direct evapotranspiration measurements and the associated calculations for distributed recharge. Of particular interest in the LBG-Guyton (2005) analyses are those basins that include the recharge zones for the Trinity, Edwards, Austin Chalk, and Buda Aquifers in the study area. The study area (i.e., Kinney and Uvalde counties) comprises parts of

several watershed basins: Rio Grande, Nueces River-West Nueces River, Frio River-Dry Frio River, Sabinal River, and a small segment of the un-named basin between the Sabinal River and Medina River basins. The LBG-Guyton (2005) analyses did not include the Rio Grande River basin.

As previously discussed, methods to quantify recharge are based on stream and river flow measurements located a short distance up-gradient of the northern edge and down-gradient of the southern edge of the recharge zone (Land et al., 1983). The calculated quantity of recharge is the stream-volume loss that occurs between the two gages. Quantifying recharge with this method assumes that all flow in the floodplain is surface water and that subsurface flow in the floodplain is insignificant at the measurement locations. As demonstrated by a study of the Leona River channel and floodplain (Green, 2003; Green et al., 2004) and hypothesized by the floodplain conveyance system conceptual model (Section 6), this assumption may not be valid. To date, subsurface flows in the Mud Creek, Pinto Creek, Elm Creek (W), Las Moras Creek, Lindsey Creek, and Elm Creek (E) floodplains in Kinney County and Turkey Creek, West Nueces River, Nueces River, Dry Frio River, Frio River, and Sabinal River floodplains in Uvalde County have not been measured or estimated. This lack of information is a significant data gap that needs to be resolved in water-balance calculations for both Kinney and Uvalde counties.

7.1 Recharge in Uvalde County

Previous calculations of recharge in Uvalde County assume that the two major sources of recharge to the Edwards Aquifer are from the Nueces River-West Nueces River basin and from the Frio River-Dry Frio River basin (Edwards Aquifer Authority, 2005). The average and median annual recharge predicted for the Nueces River-West Nueces River basin are 119,594 and 106,000 acre-ft/yr, respectively (LBG-Guyton, 2004). These predicted values are based on the assumption that all recharge from the West Nueces River recharges the Uvalde pool of the Edwards Aquifer. As will be discussed in Section 9, most of the recharge from the West Nueces River basin recharges the Kinney County pool of the Edwards Aquifer and not the Uvalde pool. Recharge from the Nueces River and the Frio River-Dry Frio River basins does recharge the Uvalde pool of the Edwards Aquifer. Although the Sabinal River basin recharges the Edwards Aquifer in Uvalde County, all of it is believed to recharge the Edwards Aquifer to the east of the Knippa Gap and into the San Antonio pool of the Edwards Aquifer.

As illustrated in Figure 5.2.3, a longer reach of the Dry Frio River occurs over the recharge zone, compared with the Frio River. This fact may, in part, explain why the Dry Frio River is “drier” than the Frio River. Simulations of streamflow for the Frio River by LBG-Guyton (2005) were more successful than simulations of streamflow for the Nueces River and West Nueces River basin at matching actual streamflow rates. The LBG-Guyton (2005) model provided particularly good agreement in simulating flow from the contributing zone into the recharge zone of the Frio River, but overestimated flow in the Frio River downstream from the recharge zone. The LBG-Guyton (2005) study estimated that 65% of recharge in the Frio River-Dry Frio River basin is from stream loss, varying from 5,070 to 188,000 acre-ft with an average of 87,133 acre-ft, and 35% is distributed recharge, varying from 3,653 to 150,100 acre-ft with an average of 48,913 acre-ft. For comparison, Puente (1978) calculated distributed recharge to be 72% in the Frio River-Dry Frio River basin.

For the 50-yr period through 2000, the average and median total annual recharge in the Frio River-Dry Frio basin were estimated by LBG-Guyton (2005) to be 136,047 and 123,700 acre-ft, respectively. Comparatively, HDR Engineering (2002) and USGS average annual recharge estimates for the Frio River-Dry Frio basin were 119,933 and 148,887 acre-ft, respectively. These predicted quantities could also vary if distributed recharge estimates were modified. Nonetheless, recharge from the Nueces River and the Frio River-Dry River basins is believed to be the greatest source of recharge to the Edwards Aquifer in Uvalde County.

7.2 Recharge in Kinney County

Documentation describing the Hydrologic Simulation Program-Fortran (HSPF) recharge model notes that the geology and hydrogeology of the Nueces River-West Nueces River basin are relatively complex and not entirely understood (LBG-Guyton, 2005). LBG-Guyton (2005) cites several factors that contribute to this variability: (i) the floodplain of the Nueces River is wider than the West Nueces River, (ii) there is a larger volume of alluvium upgradient of the recharge zone in the river channel of the Nueces River than the West Nueces River, and (iii) alluvium in the Nueces River channel is underlain by the relatively impermeable lower Glen Rose Formation, thereby contributing to higher baseflow. Detailed assessment of the geological structure of the Edwards Aquifer, performed as part of this study, illustrates the complex relationship between the Nueces River basin, including the West Nueces River, and the recharge zone of the Edwards Aquifer (Figure 5.2.3). As illustrated in this map, the West Nueces River has alternating reaches where the river bed overlies the Trinity Aquifer (where recharge is limited and subsurface flow is enhanced) and where the river bed overlies the Edwards Aquifer (where recharge is enhanced). USGS generally attempts to locate gaging stations on impermeable material to prevent underflow from bypassing the measuring stations (Land et al., 1983). Field inspections conducted as part of this investigation and related studies (Green, 2003; Green et al., 2004), however, indicate that many rivers and streams in the study area have conditions favorable for subsurface flow, even at the locations of the gaging stations. This potential for subsurface flow in floodplains complicates the method of streambed recharge measurement using two river gages located at the upstream and downstream boundaries of the recharge zone.

Rivers and some of the larger streams on the Edwards Plateau in eastern Kinney County and Uvalde County have cut through the Edwards Group rocks and flow on the Glen Rose Formation. Because of the low permeability of the Glen Rose Formation relative to the Edwards Group rocks, water is frequently found to issue from the base of the Edwards Aquifer into the river and stream beds overlying the Glen Rose Formation. Accordingly, much of the water that recharges into the Edwards Aquifer, particularly in the contributing zone, reappears as discharge in the river and stream beds (Bennett and Sayre, 1962). This water forms much of the baseflow that sustains flow in larger rivers and streams.

No streams to the west of the West Nueces River in Kinney County have eroded to the Glen Rose Formation. The West Nueces River has only cut through the Edwards Aquifer (Figure 5.2.3) along selected stretches (Bennett and Sayre, 1962; Barnes, 1977). At locations along the West Nueces River where the Edwards Group strata are exposed at the incised channel floor, water enters the Edwards Aquifer rather than discharging into the river. For those reaches of the West Nueces River that have the Glen Rose Formation in the river channel base, spring discharge into the river bed and surface water flow in the river bed is observed. Geologic structural maps developed as part of this project support this conceptualization (Figure 5.2.3). Examples are two perennial surface water bodies in the West Nueces River floodplain, Silver Lake and an un-named water body located one mile north of where Highway 334 crosses the West Nueces River. These small lakes are at locations where the Glen Rose Formation is exposed in the West Nueces River bed. The Edwards Aquifer is found in the river bed downstream from both localities where perennial surface water is absent.

Brune (1981) documented these characteristics in the West Nueces River channel. Silver Springs and Schwandner Springs discharge into the West Nueces River near Silver Lake. Schwandner Springs are located 1.2 miles east, and downstream, from Silver Springs, which issue into Silver Lake. Brune (1981) noted that West Nueces River flow disappeared into the cobble and gravel in the base of the river 3.1 miles downstream from Schwandner Springs and reappeared as surface flow two kilometers farther downstream. Brune's (1981) observations support the interpretation that the stream bed transitioned from Glen Rose Formation to the Edwards Aquifer at the point the water disappeared into the subsurface.

LBG-Guyton (2005) noted that their HSPF model of the West Nueces River basin produced large differences between simulated and observed annual runoff. Although trends are similar, simulated flow of the West Nueces River was consistently higher than observed flow for the period 1997 to 2001. Conversely, the simulated flow of the Nueces River was consistently lower than the observed flow for the same period. The simulation of flow in the contributing zone of this combined basin was recognized as poor (LBG-Guyton, 2005), which supports the premise that the focused and distributed recharge of this region are not well understood.

The LBG-Guyton (2005) HSPF model estimated that stream recharge accounts for 38% of the Nueces River basin compared with 62% attributed to distributed recharge in the inter-stream area. Annual focused recharge for the Nueces River-West Nueces River basin simulated for the period 1950 to 2000 varied from 18,100 to 65,900 acre-ft with an average of 44,751 acre-ft. Simulated annual distributed recharge varied greatly, from 5,550 to 231,000 acre-ft with an average of 74,863 acre-ft. Although the total average recharge estimated in the pilot study of the Nueces River basin by HDR Engineering (2002) (i.e., 117,280 acre-ft) was similar to the estimate by LBG-Guyton (2005) (i.e., average of 119,594 and median of 106,000 acre-ft), the pilot study estimated that only 52% of recharge derived from distributed infiltration in the inter-stream area, compared with the refined LBG-Guyton (2005) study estimate of 62%. Both estimates exceeded the previous total average recharge estimate of 88,608 by the USGS (LBG-Guyton, 2005), which was determined using the original Nueces River-West Nueces River basin inter-stream recharge estimate of 20% by Puente (1976). The important point in this assessment is that distributed recharge in the Nueces River-West Nueces River basin is currently assumed to be significantly greater than earlier estimates. Further refinement of estimates for distributed recharge may require better data, such as field measurement of evapotranspiration (Brad Wilcox, personal communication).

There have been several assessments of total recharge to the Edwards Aquifer in Kinney County. The first evaluation was performed by Bennett and Sayre (1962) based on data from 1939-1950 and did not include the period of the drought of record during the 1950's. Key assumptions in the Bennett and Sayre (1962) analysis were that: (i) the portion of the West Nueces River basin in Kinney County is about half the total area of the basin, and (ii) the recharge area of the rest of the county is about equal to the portion of the West Nueces River basin in Kinney County. Subsequent analyses of total recharge to the Edwards Aquifer in Kinney County by Muller and Price (1979), Kier (1998), and Khorzad (2002, 2003) appear to have been based on the approach of Bennett and Sayre (1962).

Muller and Price (1979) estimated recharge to the Edwards Plateau in the Nueces River-West Nueces River basin at 107,500 acre-ft/yr, although not all of this recharge is expected to flow into Kinney County. A consultant report by Kier (1998) estimated Kinney County recharge at 70,000 acre-ft/yr, factoring in contributions from Real and Edwards counties and assuming an annual average recharge rate of 1.4 in/yr. Kier (1998) increased the estimate to 90,000 to 95,000 acre-ft/yr for an assumed annual average distributed recharge rate of 2.0 in/yr. Although Kier (1998) did not explicitly mention an underflow contribution from the Trinity Aquifer, a later report by Mace and Anaya (2004) asserted that the Kier (1998) estimate included an underflow contribution from the Trinity Aquifer to the Edwards Aquifer.

Khorzad (2002, 2003) asserted that recharge calculations of the Nueces River-West Nueces River basin that are based on the USGS stream gaging stations at Laguna, Brackettville Station, and Uvalde underestimate actual recharge because streamflow losses along ungaged tributaries within the drainage basin, such as Live Oak Creek and Sycamore Creek, are not included in the recharge estimates. Khorzad (2002, 2003) modified the basin size calculated by Bennett and Sayre (1962) and included an additional period of time in the recharge data base (increased to 1934 to 1998) to arrive at 71,382 acre-ft/yr. An assumption of 5% underflow recharge from the Trinity Aquifer was included in the estimate by Khorzad (2002, 2003).

A recent analysis by Mace and Anaya (2004) provides the most comprehensive estimate of total recharge to the Edwards Aquifer in Kinney County. The Mace and Anaya (2004) assessment evaluated the analyses by Bennett and Sayre (1962), Muller and Price (1979), and Khorzad (2002, 2003). The analysis of Mace and Anaya (2004) used the same general approach as Bennett and Sayre (1962). They detected errors in two assumptions in the original Bennett and Sayre (1962) analysis. First, that the portion of the West Nueces River basin in Kinney County is only 30% of the total area of the basin, not the 50% as reported by Bennett and Sayre (1962). Second, Bennett and Sayre (1962) used the wrong streamflow value for the Nueces River for one year of the analysis. Mace and Anaya (2004) noted that analyses by Muller and Price (1979), Kier (1998), and Khorzad (2002, 2003) are in error because they relied on the inaccurate data in the Bennett and Sayre (1962) analysis. The Mace and Anaya (2004) analysis corrected the estimates of area and streamflow in the Bennett and Sayre (1962) analysis and included a longer period data base (1939 to 1950 and 1956 to 2001). They calculated that annual average recharge of the Edwards Aquifer in Kinney County was 69,800 acre-ft for the period of analysis (1939 to 1950 and 1956 to 2001).

7.3 Recharge from the Trinity Aquifer

Groundwater from the Trinity Aquifer can recharge the Edwards Aquifer in two ways: (i) as subsurface cross-formational inflow across the updip margin of the Balcones Fault zone where the Trinity Aquifer is juxtaposed with the downfaulted Edwards Aquifer, and (ii) as upward flow from the Trinity Aquifer into the Edwards Aquifer along faults, fractures, and dissolution enhanced conduits. The volume of inflow is difficult to determine and is typically estimated or constrained using numerical groundwater flow models and water-balance calculations. Models by Maclay and Land (1988), Kuniansky and Holligan (1994), and Lindgren et al. (2004) included inflow from the Trinity Aquifer as a source of groundwater. These models are regional in scope and provide limited insight on these inflow relationships in Kinney and Uvalde counties. Maclay (1995) identified two areas of groundwater inflow along the updip limit of the San Antonio segment of the unconfined Edwards Aquifer, one area is northeastern Medina County and the other is in Comal County (Maclay and Land, 1988). The Maclay and Land (1988) model did not indicate inflow from the Trinity Aquifer to the Edwards Aquifer in either Kinney or Uvalde counties.

Kuniansky and Holligan (1994) estimated that 53% of average annual recharge to the entire Edwards Aquifer is from the Upper Glen Rose Formation of the Trinity Aquifer. Mace et al. (2000) contended that the Kuniansky and Holligan (1994) estimate of contributions to the Edwards Aquifer from the Trinity Aquifer is excessive. The recent groundwater flow model of the San Antonio segment of the Edwards Aquifer by Lindgren et al. (2004) attributed 6.5% of the flow to the segment to inflow from the northern and northwestern boundaries of the model with most of the inflow from the Trinity Formation coming from the northern boundary. Khorzad (2002, 2003) estimated inflow of groundwater from the underlying rocks of the Trinity Aquifer into the Edwards Aquifer to be 5% of the total water recharged, similar to the estimate of Lowry (1955). Mace and Anaya (2004) contended there is negligible recharge of the Edwards Aquifer from the Trinity Aquifer in Kinney County because the Trinity Aquifer is not exposed at the surface in the Edwards Plateau and, therefore, is not easily recharged. The consensus of these analyses is that inflow from the Trinity Aquifer to the Edwards Aquifer is not large and probably does not exceed 5% of the total water that recharges the Edwards Aquifer in Kinney and Uvalde counties. Additional analysis, however, is required to substantiate this hypothesis.

8 DISCHARGE FROM THE EDWARDS AQUIFER

Discharge from the Edwards Aquifer in Kinney and Uvalde counties can occur through a variety of mechanisms and at different locations. Groundwater flow can be discharged at springs, as subsurface flow into other hydrostratigraphic units that function as aquifers, continue as flow through the Edwards Aquifer to adjoining counties, and as surface and subsurface flow through floodplain flow systems to the south.

There are numerous springs within the study area. These springs are classified into two categories for the purposes of this assessment: artesian springs and river basin discharge springs. Discharge from artesian springs is believed to originate at depth and flow along faults associated with the Balcones Fault Zone. River basin discharge springs are those that issue at the contact between the permeable Edwards Group and the underlying, less impermeable Glen Rose Formation. The Edwards Aquifer is interpreted to be the primary source for most springs in the study area, although the actual point of spring discharge may be another formation. It is possible that other aquifers, such as the Buda Limestone, Austin Chalk, or Leona Gravel contribute to spring discharge. Detailed water chemical analyses and/or tracer tests would help resolve the source(s) of spring discharge if concurrent water sampling of potential source areas, flowpaths, and spring discharge was conducted. Artesian springs discharge from the Edwards Aquifer where the Edwards Aquifer is under confined conditions. The Edwards Aquifer is under phreatic conditions at river basin springs. Consequently, springs in the Edwards Aquifer contributing and recharge zones are typically river basin discharge springs and springs in the Edwards Aquifer confined zone are typically artesian springs.

Springs identified by Brune (1981) as fault related are considered to be artesian springs. Brune (1981) identified Las Moras, Mud, Government Water Hole, and Elm springs in Kinney County as fault related. The largest capacity spring in Kinney County, Las Moras Springs, discharges at a point where the top of the Edwards Aquifer is at a depth greater than 400 ft below ground level (Welder and Reeves, 1962). Although there is faulting at Las Moras Springs, there is no indication that there is sufficient vertical structural offset to juxtapose the Edwards Aquifer with the Austin Chalk or any other permeable unit located closer to the surface. Bennett and Sayre (1962) described Las Moras Springs as an artesian spring that discharges after passing through the Grayson Shale (local equivalent of the Del Rio Clay), Buda Limestone, Eagle Ford Shale, and Austin Chalk. It is possible that the Austin Chalk contributes to discharge at Las Moras Springs. Again, detailed water chemistry analyses of discharge from Las Moras Springs may help to resolve the sources of water for the springs.

Discharge at Las Moras Springs is variable, with measured flow rates that have ranged from a maximum of 60 cubic feet per second (cfs) recorded on June 30, 1988 to a minimum of 2.54 cfs recorded on July 17, 1953 (Bennett and Sayre, 1962). The average of 155 recorded measurements for Las Moras Springs provided in Bennett and Sayre (1962) during the period of 1895 to 1965 was 23.1 cfs, which equates to an annual average discharge of 16,724 acre-ft. Using measurements from September 1939 to October 1940, Bennett and Sayre (1962) calculated the cumulative discharge from Las Moras, Pinto, and Mud springs to be 23,000 acre-ft/yr of which discharge from Las Moras Springs accounted for 73% of the total. This suggests that the total discharge from Las Moras, Pinto, and Mud springs would have been 22,900 acre-ft/yr during the period of 1895 to 1965. Bennett and Sayre (1962) estimated that discharge by pumping and flowing wells was 4,000 acre-ft/yr for this period. Thus, total discharge from the Edwards Aquifer in Kinney County during the period 1895 to 1965 was estimated to by 26,900 acre-ft/yr by Bennett and Sayre (1962).

The average of discharge measurements from January 1955 to September 1956 was 15.3 cfs, which equates to 11,000 acre-ft/yr (Bennett and Sayre, 1962). If the 73% contribution was valid during the January 1955 to September 1956 time period, then the cumulative discharge from all three springs would

have been 15,000 acre-ft/yr for this period. Thus, total pumping and spring discharge from the Edwards and related limestones in Kinney County would have been at a rate of 19,000 acre-ft/yr during 1955–1956.

Las Moras Springs annual discharge during the past two years (2004 to 2006), when calculated using point measurements, varied from a low of about 15,000 acre-ft/yr (April 2006) to as high as 37,000 acre-ft/yr (January 2005). These annual rates were calculated from gage height measured in ft (by the USGS), converted to discharge in cfs (by the USGS), and converted to annual rates in acre-ft/yr (by Southwest Research Institute). If the contribution of Las Moras Springs to the total spring discharge in Kinney County is 73%, as asserted by Bennett and Sayre (1962), then the total annual spring discharge by Las Moras, Pinto, and Mud springs would have varied from approximately 20,500 acre-ft/yr in April 2006 to 50,700 acre-ft/yr in January 2005. This analysis does not imply that spring discharge was 50,700 acre-ft-yr in 2005 because the actual rate of spring discharge declined during most of the year. Groundwater pumping in Kinney County is currently estimated to be relatively constant at 6,000 acre-ft/yr (Mace and Anaya, 2005).

Other springs in Kinney County, such as Dutch Water Hole, Lost, Silver, Schwandner, and Moran springs on the West Nueces River, are considered river basin discharge springs. Pinto Springs at the headwaters of Pinto Creek, are considered river basin discharge springs; however, downstream springs in Pinto Creek, such as Stricklin and Pecan springs, are believed to be fault related. An ongoing hydrochemical study of spring discharge into Pinto Creek by Uliana et al. (2006) will help identify sources of recharge into Pinto Creek. All springs in Live Oak Creek (which is located in the Edwards Aquifer contributing and recharge zones) such as Elm and Garden springs, are considered river basin springs. Brune (1981) provides detailed descriptions on spring characteristics and locations.

Springs in Uvalde County that are classified by Brune (1981) as artesian include Leona Springs on the Leona River, Soldiers Camp Spring on the Nueces River, Turkey Springs on Turkey Creek, and Sabinal Springs on the Sabinal River. Leona Springs are significantly larger than the other Uvalde County artesian springs. Leona Springs issue at four main locations along a 6–7-mile reach of the Leona River, starting at the center of the City of Uvalde, and going south (Livingston, 1947; Welder and Reeves, 1962; Brune, 1981). Brune (1981) associated each spring location with a fault of the Balcones Fault Zone. As illustrated in the geologic structural maps in Figures 5.2.3 and 5.2.6, there are sufficient faults southeast of the City of Uvalde to support this interpretation. Leona Springs discharge through the faults into the Leona Gravel and then into the Leona River; however, the primary source of spring water is considered to be the Edwards Aquifer.

There are numerous river-basin discharge springs in northern Uvalde County that discharge into tributaries of the Nueces, Dry Frio, Frio, and Sabinal rivers (Brune, 1981). These springs may flow intermittently and typically do not have significant flow rates as individual springs, with the possible exception of periods of intense rainfall when individual spring discharge levels may be elevated. Even though these springs may not individually have significant flow rates, their aggregate discharges may be substantial.

9 GROUNDWATER FLOW IN KINNEY COUNTY

Current conceptual models of the hydraulic relationship of the Edwards Aquifer between Kinney and Uvalde counties are based on early USGS studies (Sayre, 1936; Sayre and Bennett, 1942; Bennett and Sayre, 1962; Welder and Reeves, 1962). The first comprehensive description of the Kinney County hydrogeological regime was given by Sayre and Bennett (1942) and refined by Bennett and Sayre (1962). Bennett and Sayre (1962) published the first detailed piezometric surface contour maps of Kinney County. In these maps, groundwater elevations are greatest in northern Kinney County at over 1250–1300 ft asl. The highest groundwater gradient is to the south with smaller gradients to the east and west. These USGS reports identified a north-trending groundwater ridge, defined by the smaller east and west groundwater gradients. The groundwater ridge was placed in the general vicinity of the City of Brackettville. This groundwater ridge was identified as a groundwater divide and designated as the western limit of the San Antonio segment of the Edwards Aquifer. Maclay (1995) provides a comprehensive discussion of principal features of groundwater flow in the San Antonio segment, including the groundwater divide at the western boundary.

Subsequent focused studies of the hydrogeology of Kinney and Uvalde counties embraced this original conceptual model, including the designation of a groundwater divide in Kinney County as the western extent of the San Antonio segment of the Edwards Aquifer. The only differences in these subsequent studies are where they locate the groundwater divide and the amount of recharge in Kinney County. Otherwise, the main tenets of the Sayre and Bennett (1942) conceptualization have been consistently adopted by later investigators. The following sections present assessments of the hydrogeology of Kinney and Uvalde counties, including a modified conceptual model for the hydraulic relationship between the two counties.

The Sayre and Bennett (1942) and Bennett and Sayre (1962) conceptual model of groundwater flow assumes that most recharge to the Edwards Aquifer in Kinney County originates in the Nueces River-West Nueces River basin. Additional recharge that originates on the Edwards Plateau to the west of the Nueces River-West Nueces River basin contributes to the Edwards Aquifer in western Kinney County. Contours of the piezometric surface of the Edwards Aquifer in maps by Bennett and Sayre (1962) are parallel to the strike of the limestone (i.e., Balcones Fault Zone), suggesting that groundwater flow is downdip to the south in Kinney County. Their only recognized points of discharge of groundwater were through artesian springs and wells. Sayre and Bennett (1942) noted there is no visible natural discharge south of a line of springs (i.e., Pinto, Mud, and Las Moras) in Kinney County. Sayre and Bennett (1942) noted that water in the Edwards Aquifer to the south of the springs contains hydrogen sulfide and farther to the south is highly mineralized, suggesting that groundwater movement southward beyond the line of springs into the zone of highly mineralized water is negligible, owing to the low permeability of the limestone. Sayre and Bennett (1942) further concluded that considerable quantities of water must flow parallel to the strike of the formation (i.e., east or west) and issue at springs far from the recharge area. Over 70% of water recharged to the Edwards Aquifer in Kinney County was thought by Sayre and Bennett (1942) and Bennett and Sayre (1962) to eventually discharge outside of Kinney County as underflow.

Bennett and Sayre (1962) provided contour maps of the piezometric surface of the Edwards Aquifer for the period 1937 to 1940, January 1952, and August 1956. The general features of the piezometric surface did not change during the drought of the 1950's, as indicated by the August 1956 map. The contour map of the piezometric surface by Bush et al. (1993) exhibited the same general trend. All these maps are consistent with the piezometric surface 1,100 ft asl contour line near Brackettville, a north-south gradient of about 100 ft/mile, and general concave shape to the piezometric surface, with an eastward component in the hydraulic gradient near Uvalde County, and a westward component to the hydraulic gradient near Val Verde County. This general concave shape and a subtle north-trending groundwater ridge based on

the relative elevations of groundwater (i.e., approximately 1,100 ft asl at Las Moras Springs, 950 ft asl to the west at San Felipe Springs, and 860 ft asl to the east at Leona Springs), were interpreted by Sayre and Bennett (1942) and Bennett and Sayre (1962) to indicate that there is a groundwater divide somewhere in the vicinity of Brackettville. Subsequent studies supported the existence of the groundwater divide near Brackettville (Bush et al., 1992; Hovorka et al. 1993; LBG-Guyton, 1995; Maclay, 1995; Groschen, 1996; Khorzad, 2002, 2003; and Snyder, 2004), although the inferred location of the groundwater divide varied in the different studies.

Bennett and Sayre (1962) made an important observation that some groundwater in central Kinney County is not moving at right angles to groundwater elevation contours, a feature indicative of karst development and karst flow or fault/fracture anisotropy. Bennett and Sayre (1962) inferred from prompt increases in discharge of Las Moras Springs in response to rainfall in the Edwards Aquifer recharge zone that well-developed solution channels extend from the spring northward to the outcrop area. They suggested a similar solution channel between Pinto and Mud springs. Bennett and Sayre (1962) identified synclinal structures in the geologic structure along Road 334 between Brackettville and Laguna and the Brackett Anticline along Silver Lake Road. The folds seem to be plunging toward the southwest (S50°W). They noted that these structures could compliment the effects of solution channels to funnel water toward Las Moras Springs.

Bennett and Sayre (1962) further surmised that eastward-trending solution channels along faults of the Balcones fault system are probably better developed than north-south trending solution channels. They noted that it is probable that a large volume of water is moving eastward through these east-west oriented solution channels, nearly parallel to the trend of the regional, generalized groundwater contours. This interpretation was developed to support their conceptual model that a large volume of underflow goes east and west from Kinney County.

LBG-Guyton (1994) refined the Bennett and Sayre (1962) groundwater contour map by correcting land-surface elevations and concurred with the Bennett and Sayre (1962) conceptual model that groundwater is generally moving south-southwest toward Las Moras Springs, and then eastward once groundwater passes the springs. LBG-Guyton (1995) also noted there were no observed rises in water levels east of Val Verde County in association with the filling of Lake Amistad in 1968. This observation helps constrain interpretations of the hydraulic relationship of the Edwards Aquifer in Kinney County with aquifers in Val Verde County.

Kier (1998) placed the groundwater divide to the east of the City of Brackettville. East of the divide, groundwater is interpreted to flow toward the San Antonio segment of the Edwards Aquifer. On the western side of the groundwater divide, groundwater flow was interpreted to be south toward major discharge points such as Las Moras Springs and San Felipe Springs (in Del Rio). Kier (1998) believed flow on the western side of the divide to be controlled mainly by the topography.

Khorzad (2002, 2003) also used the Bennett and Sayre (1962) data set with corrected land-surface elevations to infer a groundwater divide near the City of Brackettville. Khorzad (2002, 2003) interpreted the Brackettville groundwater divide to be east of all major springs in Kinney County. From this interpretation, he inferred that the source of water to Las Moras Springs most likely originates on the western side of the divide (i.e., the Edwards-Trinity Aquifer).

Snyder (2004) suggested the Kinney County groundwater divide is associated with a north-trending fault, referred to as the Spofford Fault, aligned with Pinto and Las Moras springs. In support of this interpretation, Synder asserted that parallel and conjugate surface faults in the Edwards-Trinity Group strata overlying the deeply wrenched Paleozoic and Precambrian substrate function to canalize and direct groundwater flow. Snyder claimed this to be corroborative evidence that this resulting flow system

establishes a groundwater divide in the vicinity of the Spofford Fault. Snyder also cited a low correlation in spring discharge among Mud, Pinto, and Las Moras springs as support of their location relative to the groundwater divide.

The response of groundwater elevation and spring discharge to rainfall offers evidence of hydraulic connectivity within the Edwards Aquifer and with the recharge zone of the Edwards Aquifer. Bennett and Sayre (1962) noted that, although the Las Moras Springs response is sensitive to stage, the spring discharge is, in general, less responsive to rainfall in the north-central and northwest parts of Kinney County than to the northeast. Bennett and Sayre (1962) noted that Las Moras Springs is fed for the most part by water that enters the aquifer in areas on the Edwards Plateau northeast of the springs. They also noted that fluctuations in discharge at Las Moras Springs were more correlated with rainfall at Montell and Camp Wood, located 30 miles and 45 miles, respectively, to the northeast, than with rainfall at either Brackettville or Del Rio. Kier (1998) noted a similar correlation in his observation that Las Moras Springs responded within a day after recharge events near Rock Springs (located 55 miles northeast of Las Moras Springs) and Camp Wood. These observation highlights two important points. The first is that groundwater from northeast Kinney County flows toward Las Moras Springs. Secondly, the rapid hydraulic response illustrates the high transmissivity of the Edwards Aquifer in this area and supports the characterization that this portion of the Edwards Aquifer is karstic.

It is important to note that Montell and Camp Wood are located in the Nueces River basin, not the West Nueces River basin, which raises a question on the hydraulic relationship between the Nueces River basin and the Edwards Aquifer in Kinney County. Although Montell and Camp Wood are within the Nueces River basin, they are only located about 5–6 miles from the West Nueces River basin. Additionally, Rock Springs is located near the surface water divide separating the West Nueces River basin from the Nueces River basin. Rainfall at these locations has been cited in past and present hydrology analyses as representing an area that includes the West Nueces River basin because there are no locations in the West Nueces River basin with recorded rainfall. Therefore, rainfall amounts recorded at Rock Springs, Montell, and Camp Wood are interpreted to also represent the West Nueces River basin and are not interpreted to indicate a significant hydraulic relationship between the Edwards Aquifer in Kinney County and the Nueces River basin.

9.1 Modified Conceptual Model of Groundwater Flow in Kinney County

A modified conceptual model of the groundwater flow regime in Kinney County is proposed. It is hypothesized that there is a separate groundwater pool in the Edwards Aquifer that extends from eastern Kinney County to a groundwater divide located between Pinto Creek and Mud Creek (Figure 9.1.1). This separate pool is referred to as the Kinney County pool. Although there is no groundwater divide separating the proposed Kinney County pool from the Uvalde pool, evidence supports the premise that minimal groundwater flows through the Edwards Aquifer from Kinney County to Uvalde County. The principal evidence is a low permeability transition zone in the Edwards Aquifer located near the Kinney County/Uvalde County line that is interpreted based on a region where drilling and well testing have revealed no high, or even moderate, capacity wells (i.e., wells with capacity >10-15 gpm) (Figure 9.1.1). The hypothesis offered in this study is that the permeability of Edwards Group rocks is lower in the transition zone than in Edwards Group rocks located west and east. According to this hypothesis, the transition zone impedes the flow of significant volumes of water from the Kinney County pool to the Uvalde pool. It is important to note that it is not suggested that there is no groundwater flow from Kinney County to Uvalde County, only that there is minimal groundwater flow. Groundwater tracer and aquifer tests are required to test the validity of this hypothesis and substantiate this conceptual model.

The transition zone that separates the Kinney County pool from the Uvalde pool of the Edwards Aquifer is responsible for limiting the hydraulic connectivity of the two Edwards Aquifer pools. The transition

zone is distinguished by several remarkable features and the absence of several others. Features of interest are: (i) the Edwards Aquifer groundwater elevation decreases from approximately 1,100 ft asl near Brackettville in Kinney County to approximately 900 ft asl near the Nueces River; and (ii) the capacity of water wells decreases from wells with capacities in excess of 1,000 gpm near Brackettville to wells with capacities of less than 10–15 gpm near the Kinney County/Uvalde County line. The large hydraulic gradient to the east is the single compelling observation that indicates groundwater flow is from the Kinney County pool to the Uvalde pool. However, as discussed, a different conclusion is drawn when all evidence is examined and interpreted.

No evidence of significant groundwater flow from the Kinney County pool to the Uvalde pool was found during the investigation. As discussed in Section 5.4, no indication of karst development or conduit groundwater flow was found in the transition zone, even though there is ample evidence of karst development and conduit flow to the west (i.e., Grass Valley and Pinto Valley) and east (north of Knippa) of the transition zone. Evidence of karst is interpreted here to include bit drops during drilling of wells and boreholes, groundwater troughs, surface karst features such as sinkholes and solution cavities, and springs (Worthington, 1999), with the exception of springs located in the bed of the West Nueces River, Nueces River and their major contributing tributaries. There is an important caveat to this hypothesis. This hypothesis assumes there is no karst (i.e., conduit) flow from the Kinney County pool to the Uvalde pool, particularly along the southern extent of the Edwards Aquifer in the vicinity of the saline-water line. Should evidence of significant conduit flow be found in this area, then the hypothesis proposed here would need to be substantially modified.

Structural geological analyses performed as part of this assessment support the hypothesis of a separate Kinney County pool. An embayment in the base of the Edwards Aquifer at Grass Valley is identified as the depression in the base of the Edwards Aquifer in Figures 5.2.3, 5.2.4, and 5.2.6. The greater depth in the base of the Edwards Aquifer in this locality would explain, in part, the presence of high capacity wells in Grass Valley (Khorzad, 2002, 2003). The presence of the synclinal structural feature in Grass Valley is consistent with a schematic illustration of the conceptual model of the geologic structure of Kinney County in Bennett and Sayre (1962). The southwest-trending alignment of faulting in Kinney County, illustrated in Figures 5.2.3, 5.2.4, and 5.2.6, supports the conceptual model that groundwater flows along solutionally enlarged faults from Grass Valley to Las Moras Springs. The saturated thickness contour map also supports the interpretation of Grass Valley as an embayment in the Edwards Aquifer (Figure 5.2.5).

Hydrochemical data from Kinney County are not sufficient to independently support the modified conceptual flow model, but are consistent with the proposed hypothsis. There are few wells in the transition zone between the location of the proposed Kinney County pool and the Uvalde pool. Some wells in this region with available hydrochemical data generally have higher specific conductivities and sulfate concentrations consistent with other Edwards Aquifer wells along the trend of U.S. Highway 90. It is interesting to note that the chemistry of water discharging from Las Moras Springs (RP-70-45-501) has low sulfate and strontium concentrations, similar to the chemistry of wells in the Grass Valley area, while wells (RP-70-45-503, 504, and 505) that tap the Edwards Aquifer in the immediate vicinity of Las Moras Springs have significantly higher sulfate and strontium concentrations and originate from a different source than the springs. Chemistry data for TDS, sulfate, chloride, magnesium, and specific conductivity (Figures 5.3.1–5.3.4, 5.3.9, and 5.3.10), as well as spatial distribution of principal component analysis values (Figure 5.3.14) suggest a southwesterly flowpath in Kinney County and strongly suggest separate groundwater pools in Kinney and Uvalde counties.

The contour map of the piezometric surface for January-February 2006 (Figure 4.2) can be interpreted to support the argument that there is a groundwater divide to the west of Brackettville. There are limited groundwater elevation data in the area to the west of Brackettville to define the precise location of the groundwater divide, however the divide appears to be between Mud Creek on the west side and Pinto

Creek on the east side. If this interpretation is valid, then recharge from the Edwards Plateau that is west of the West Nueces River basin that recharges the Edwards (or Edwards-Trinity) Aquifer in western Kinney County either flows to the west and discharges at the San Felipe Springs or flows to the southwest and discharges through floodplains of Mud Creek and other floodplains in southwest Kinney County. The ultimate destination for both of these flowpaths to the west of the groundwater divide is the Rio Grande basin, not the Nueces River basin.

An observation by Bush et al. (1992) that groundwater flow in the West Nueces River basin is to the southwest supports the conceptual model of a separate pool in Kinney County. This is a clear example of subterranean piracy which is defined as surface water flowing in a different direction (which is to the southeast in the West Nueces River) than the direction of groundwater flow (which is to the southwest). Subterranean piracy is not uncommon in karst terrains (Ford and Williams, 1991). Extending the observation by Bush et al. (1992), the conceptual model for a separate Kinney County pool indicates that recharge from the upper reaches of the West Nueces River basin goes to the Kinney County pool and recharge from the lower reaches goes to the Uvalde pool. Of interest is where groundwater flow transitions from going to the Kinney County pool to going to the Uvalde pool. Reliance on the argument formulated to support the separate Kinney County pool conceptual model provides a basis on where this transition is located. The foundation of this argument is that the Edwards Aquifer in the transition zone has sufficiently lower permeability than does the Edwards Aquifer in most other localities. If this premise is valid, then the low permeability limestone of the Edwards Aquifer in the bed of the West Nueces River in the transition zone would limit recharge of the Edwards Aquifer along that reach of the river. Therefore, there is no distinct “divide” between where groundwater goes east to the Uvalde pool and where groundwater goes west to the Kinney County pool. There is simply a transition zone where minimal water is recharged and minimal groundwater flows in the subsurface. Boreholes would need to be drilled in this area and aquifer tests would be required to delineate and verify the limits of the transition zone, the permeability of the limestone, the amount of recharge, and the local direction of groundwater flow.

To support the conceptual model of a separate Kinney County pool proposed by this study, it is necessary to identify the destination of water recharged into the Kinney County pool. It is proposed here that there is sufficient capacity for groundwater discharge through a number of stream floodplains in southern Kinney County to account for the quantity of groundwater flow south from the Edwards Plateau into the Kinney County pool. Potential streams as points of discharge include (from east to west) Elm Creek (E), Lindsey Creek, Las Moras Creek, Elm Creek (W), Pinto Creek, possibly Mud Creek, and other smaller tributaries, although the flow capacity of these smaller tributaries is probably limited. Groundwater can transfer from the Edwards Aquifer to the stream floodplains by way of different flow mechanisms. The transfer could occur under phreatic conditions at locations where the floodplain crosses the Edwards Group. Pinto Creek is a possible example of this mechanism. Flow along faulting, as observed at Las Moras Springs, would be required to allow for groundwater transfer from the Edwards Aquifer to stream floodplains at locations where the Edwards Aquifer is confined and at depth. Groundwater flow transfer could occur as a combination of both mechanisms. The concave shape of contours in the piezometric surface in the Kinney County pool indicates discharge occurs at multiple locations, i.e., Mud, Pinto, Elm (W), Las Moras, Elm (E), and Lindsey creeks.

9.2 Water Budget of the Kinney County Pool

Bennett and Sayre (1962) estimated recharge to the Edwards Aquifer in Kinney County at 70,000 acre-ft/yr. Subsequent analysis by Mace and Anaya (2004) modified and corrected the original Bennett and Sayre (1962) analysis, but came to the same conclusion that annual average recharge of the Edwards Aquifer in Kinney County is approximately 70,000 acre-ft/yr. The average total discharge by springs and pumping was estimated by Bennett and Sayre (1962) at 26,900 acre-ft/yr. Bennett and Sayre (1962)

concluded that the remaining 43,000 acre-ft/yr is discharged from Kinney County as underflow, either to the east to the Uvalde pool of the Edwards Aquifer or to the west toward San Felipe Springs. Discharge by pumping and flowing wells is currently estimated to be 6,000 acre-ft/yr. Therefore, total discharge from the Edwards Aquifer by spring flow and pumping in Kinney County is approximately 29,000 acre-ft/yr. This would suggest an average of 41,000 acre-ft/yr are discharged from the Edwards Aquifer in Kinney County through a combination of subsurface floodplain flow and subsurface outflow through the Edwards Aquifer.

It is reasonable to expect that because precipitation in Kinney County is highly variable, that the annual recharge of the Edwards Aquifer would be highly variable. Historical annual precipitation values for Del Rio (located 30 miles west of Brackettville) have varied from 4.34 inches in 1956 to 37.75 inches in 1914 with a median of 17.94 inches (National Weather Service, 2005). With large variations in precipitation possible, it is conceivable that annual recharge to Kinney County could vary from as low as 35,000 to 40,000 acre-ft/yr during a drought year to as high as 100,000 acre-ft during a wet year. Spring flow could exceed 40,000 acre-ft during a wet year, suggesting that floodplain discharge would be 60,000 acre-ft. Given that discharge through the Leona River floodplain is estimated at 87,000 acre-ft/yr, it is hypothesized that even during wet years floodplains south of the Edwards Aquifer in Kinney County could have sufficient capacity to discharge water from the Edwards Aquifer to balance the water budget of the Kinney County pool. In particular, floodplains associated with Las Moras and Pinto creeks are thought to have the greatest capacity in Kinney County for subsurface flow. The capacity of stream floodplains in Kinney County to convey groundwater needs to be evaluated to know if the cumulative capacity of all stream floodplains could account for sufficient discharge to balance the water budget of the Kinney County pool.

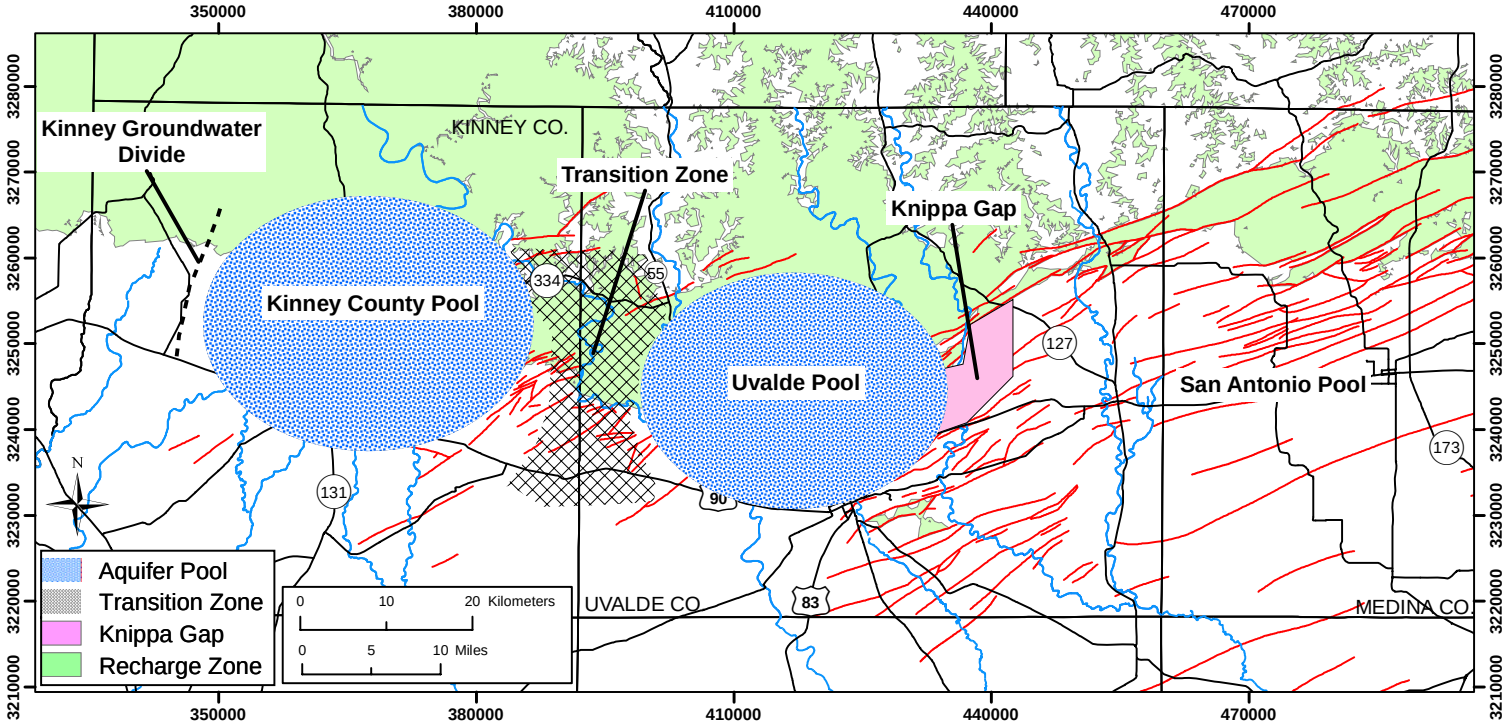


Figure 9.1.1: Map of the Kinney County, Uvalde, and San Antonio pools of the Edwards Aquifer. The Kinney County and Uvalde pools are separated by a transition zone of low permeability. The Uvalde and San Antonio pools are separated by the Knippa Gap, a constriction in the Edwards Aquifer. A groundwater divide defines the western limit of the Kinney County pool. Map projection is UTM Zone 14, NAD83.

10 GROUNDWATER FLOW IN UVALDE COUNTY

An interpretation of the groundwater flow regime in the Uvalde pool of the Edwards Aquifer was formulated using the integrated results of the water chemistry, geologic structure, and hydrogeological investigation. This interpretation is discussed in terms of the Edwards Aquifer, its relationship with adjoining aquifers, sources of recharge, and points of discharge. The Edwards Aquifer in Uvalde County is recognized as an aquifer that can support high-volume irrigation wells. In general, areas with high-volume irrigation wells are interpreted as areas of the Edwards Aquifer that have the capacity to transmit significant volumes of water. Well information was included with water chemistry, structural, and other hydrogeological data to identify a high-volume capacity channel of the Edwards Aquifer in central Uvalde County.

The high-capacity zone of the Edwards Aquifer is restricted to an east-trending narrow (i.e., 4–5-mi wide) band or channel in the middle of Uvalde County. The location of this high-capacity flow channel concurs with the fresh-water channel identified using water chemistry data. The northern and southern limits of the Edwards Aquifer extend over a much broader area than the limited width of the channel. The contributing and recharge zones of the Edwards Aquifer extend north of the channel where the saturated thickness of the Edwards Aquifer is insufficient to transmit significant volumes of groundwater. To the south, the high-capacity flow channel of the Edwards Aquifer is bordered either by the saline-water portion of the Edwards Aquifer, where permeability is reduced by igneous intrusions, geologic structure, localized zones of reduced permeability, or some combination of these factors.

An analysis of geologic structure establishes the foundation for the interpretation of the high-capacity flow channels in Uvalde County. Maclay and Land (1988) identified geologic barriers that restrict groundwater flow, and geologic gaps and channels that convey groundwater flow in Uvalde County. The most notable geologic feature that affects groundwater flow in Uvalde County is the Knippa Gap (Maclay and Land, 1988; Maclay, 1995). Maclay and Land (1988) describe the Knippa Gap as a narrow opening within an extensive, complex barrier system that includes the combination of the Uvalde and Sabinal horsts and the Medina Lake Fault.

Examination of the more detailed geological structure maps developed as part of this project (Figures 5.2.3-5.2.6) provides refinement to the structural geologic interpretation inherent in the Maclay and Land (1988) conceptual model. Geologic structural features that define the Knippa Gap and the associated high-capacity flow channel in Uvalde County are the Uvalde Salient, Cooks Fault, a graben located due east of Knippa, and a deepening of the Edwards Aquifer to the east of Knippa. This list of geologic features differs somewhat from the list by Maclay and Land (1988), but the underlying structural premise to the Knippa Gap is the same. That is, faulting associated with the Balcones Fault Zone and uplift identified as the Uvalde Salient have developed a constriction in flow through the Edwards Aquifer near the City of Knippa. The constriction is bounded to the north by Cooks Fault, north of which is the Edwards Aquifer recharge zone. The ENE-trending Cooks Fault is located about 4 miles north of the City of Uvalde and about 6 miles north of the City of Knippa. Cooks Fault effectively defines the northern limit of high-capacity Edwards Aquifer irrigation wells, which in turn, effectively define the high-capacity flow channel in Uvalde County. A continuation of Cooks Fault to the east where it crosses the Frio River is referred to as the Trio Fault by Blome et al. (2005). The northern boundary of the constriction and the high-capacity flow channel is referred to in this report as Cooks Fault for simplicitiy and because of uncertainty in the precise northern location of these features. Irrigation wells are not prevalent north of Cooks Fault (or Trio Fault), mostly because of the limited saturated thickness of the Edwards Aquifer in the recharge zone (Figure 5.2.5).

The base of the constriction is defined by the Uvalde Salient, a geologic structural high located east of the City of Uvalde, where the base of the Edwards Group is shallower than to the east and west (Welder and

Reeves, 1962; Clark and Small, 1997; Clark, 2003). The structural topography of the Uvalde Salient, as represented by the base of the Edwards Group (Figure 5.2.4), is highly variable. The shape of the Uvalde Salient can be described as a north-trending ridge that is wider to the north and narrows and plunges to the south. The highest points on the Uvalde Salient ridge (i.e., the base of the Edwards Aquifer) are approximately 200 ft asl at several locations and 400 ft asl in the area about 6-8 miles east of Uvalde.

The base of the Edwards Aquifer slopes relatively steeply south at the southern end of the Uvalde Salient ridge, dropping from about 400 ft asl to 1,200 ft below sea level (bsl) within 3 miles where the Uvalde Salient is terminated somewhat abruptly by a series of ENE-trending faults 8–10 miles southeast of the City of Uvalde. This deepening of the base of the Edwards Aquifer is south of the saline-water interface, an area where the Edwards Aquifer has decreased permeability. Consistent with this interpretation, no high-capacity irrigation wells are found in the Edwards Aquifer any farther south than about 9–10 miles to the south of the City of Knippa (i.e., Pat Johnson's Ranch) where the quality of water is poor (i.e., TDS>1,000 ppm) and the capacity of wells is limited.

The contour map of the saturated thickness of the Edwards Aquifer illustrates that its saturated thickness is relatively uniform at 600 ft in central Uvalde County with the exception of the Uvalde Salient (Figure 5.2.5). The localized topographic highs of the base of the Edwards Aquifer are sufficient to expose the Edwards Aquifer at the surface and decrease the resulting saturated thickness by 100–300 ft at each point. These prominent high points in the base of the Edwards Aquifer focus groundwater flow through the three resulting "topographic saddles". Additional focusing of groundwater flow occurs because the southern most saddle does not appear to provide as much flow as do the two northern saddles. A local zone of reduced transmissivity extends from Highway 90 on the north to slightly south of highway FM 1023 to the south, and from the eastern side of the City of Uvalde to about 1 to 2 miles to the east of the Frio River. The cause of this reduced capacity zone is not known, but may be a function of a reduced thickness of the Edwards Aquifer, a higher density of igneous intrusions, or a local change in the permeability of the Edwards Aquifer. Although the source of the reduced hydraulic capacity zone is not known, evidence of it is supported by the limited capacity of all Edwards Aquifer wells in this area. This interpretation is supported by water chemistry trends as wells in this region exhibit significant increases in sulfate, chloride, fluoride, strontium, and TDS.

Relatively intense faulting in central Uvalde County resulted in an E-W-trending graben located at the City of Knippa and continuing to the east. The upper portion of the graben block is composed of the Austin Chalk Formation. Most, if not all, large-capacity irrigation wells within the graben are set in the Austin Chalk Aquifer. Wells within the graben that are set in the underlying Edwards Aquifer tend to have lower capacity and lower quality (i.e., higher TDS). Groundwater elevations in the Austin Chalk Aquifer in the graben are higher than elevations in the Edwards Aquifer (i.e., increasing from a difference of about 20 ft at the western end of the graben to as much as 100 ft higher in the eastern end of the graben), indicating that the Austin Chalk Aquifer is not hydraulically well-connected to the Edwards Aquifer particulary in eastern end of the structural block. This structural block is roughly aligned with Highway 90 and is coincident with the southern boundary of the high-capacity flow channel that transects Uvalde County.

The recharge zone of the Edwards Aquifer extends south to Cooks Fault, located about 6 miles north of the City of Knippa. The Frio and Dry Frio rivers recharge the Edwards Aquifer north of Cooks Fault. To the south of the Edwards Aquifer recharge zone, the Frio and Dry Frio rivers provide recharge to the Austin Chalk graben located to the east of the City of Knippa. Based on the earlier discussed estimates for recharge (LBG-Guyton, 2005), the volume of groundwater flow in the Edwards Aquifer approximately doubles at the Knippa Gap due to recharge from the Frio and Dry Frio rivers.

Based on the relatively high density of groundwater elevation data from the synoptic survey, a groundwater trough is interpreted in the groundwater surface of the high-capacity flow channel immediately to the north of Knippa (Figure 4.2). A groundwater trough is interpreted as an indicator of preferential groundwater flow (Worthington, 1999). This interpretation of a high-capacity flow channel is consistent with Welder and Reeves (1962) who indicated that most groundwater flow is along the west and northern part of the Uvalde Salient. Hovorka et al. (2004) inferred that a somewhat restricted zone of karst conduits is located north of Knippa and south of the recharge zone (i.e., Cooks Fault). Interestingly, Hovorka et al. (2004) placed another conduit roughly collinear with the Frio River, which would support the presence of a preferential pathway associated with a floodplain flow conveyance system. The change in the groundwater flow regime across the Knippa Gap is evidenced by the low hydraulic gradient to the west (<2 ft/mile) and the high hydraulic gradient to the east (>10 ft/mile) of the Knippa Gap (Figures 4.2 and 5.2.7).

Because the Knippa Gap acts as a constriction and because the Frio River-Dry Frio River basin recharges mostly at the Knippa Gap, groundwater elevations to the west of the Knippa Gap tend to be more stable than to the east. This effect is clearly illustrated with the results of water-elevation synoptic surveys conducted by the Edwards Aquifer Authority on July 2000, a period of low groundwater elevation, and October 2002, a period of high groundwater elevation (Edwards Aquifer Authority, 2006). The differences in groundwater elevation between stages are 13 ft at the City of Uvalde well and 67 ft at the City of Sabinal well, to the west and east of Knippa Gap, respectively (Figure 5.2.7). The stabilizing effect of the Knippa Gap is attributed mostly to the damming effect caused by constricted flow through the Knippa Gap, but also to a reduction of recharge from the Frio River-Dry Frio River basin to the San Antonio pool of the Edwards Aquifer during low stage. This effect is accentuated by the dramatically larger offset in Cooks Fault immediately east of the Frio River that results in focusing of recharge from the Frio River-Dry Frio River basin to the Edwards Aquifer (Maclay, 1995) (Figure 5.2.6). Insufficient water elevation data are available in the recharge zone to ascertain whether groundwater from the northeast contributes recharge to the Edwards Aquifer where the Frio River crosses Cooks Fault. It is possible that the large fault offset to the east of the Frio River was instrumental in determining the location where the Frio and Dry Frio rivers formed.

The Knippa Gap constriction opens to the east of Knippa. This increase is supported by several observations: (i) the saline-water interface tends to be farther south at Sabinal than at the Knippa; (ii) the zone of water with reduced mineralization expands to the east of Knippa; (iii) Cooks Fault, which forms the northern boundary of the constriction, continues to the northeast to the east of Knippa; and (iv) the saturated thickness of the Edwards Aquifer, which is reduced by the Uvalde Salient, laterally increases to its full thickness of 600 ft to the east of the Knippa Gap. As a consequence of this large increase in cross-sectional area and the significant decrease in the basal elevation of the Edwards Aquifer, there is a decrease in groundwater elevation from approximately 875-900 ft asl west of the City of Uvalde to approximately 800 ft asl near Sabinal, with most of the decrease occurring immediately east of the Knippa Gap. Based on these observations, the eastern end of the Knippa Gap is interpreted to be the effective transition from the Uvalde pool to the San Antonio pool of the Edwards Aquifer (Figure 9.1.1).

Igneous intrusions are found throughout much of the study area (Rose, 1972, Smith et al., 2002; Ewing, 2004). Evaluation of groundwater flow relative to the locations of the igneous intrusions indicates that the intrusions do not affect the regional flow of groundwater in the Edwards, Austin Chalk, and Leona Gravel aquifers. Their presence in Kinney and Uvalde counties are interpreted to only affect the local flow of groundwater.

10.1 Water Budget of the Uvalde Pool

The primary interest in the calculation of water budget of the Uvalde pool of the Edwards Aquifer is to determine how much water is transferred from the Uvalde pool to the San Antonio pool. Past studies identified the sources of recharge for the Edwards Aquifer in Uvalde County as focused and distributed recharge from the Nueces River-West Nueces River basin and the Frio River- Dry Frio River basin and inflow from the Trinity Aquifer. Findings from this investigation indicate that recharge in the West Nueces River basin is diverted west to the Kinney County pool and that focused and distributed recharge is not well characterized. Previous studies indicated that inflow recharge from the Trinity Aquifer is limited, however, these past assessments were based on limited data and are highly uncertain. Additional uncertainty in the water budget calculation results from poor understanding of discharge from the Edwards Aquifer in Uvalde County. Discharge through the Leona River floodplain exceeds past estimates (Green, 2003; Green et al., 2004). It is probable that additional discharge occurs through both the Nueces River and Frio River floodplains that have not been included in past water budget calculations.

Given these uncertainties, groundwater flow through the constriction at the Knippa Gap has been calculated to determine the hydraulic relationship between the Uvalde pool and the San Antonio pool of the Edwards Aquifer. Darcy's Law for volumetric flow is used to make the calculation for flow across a vertical cross section of the Edwards Aquifer (i.e., about 1–2 miles southeast of UV081) south to the southern boundary of the high-capacity flow channel (i.e., UV077). The northern boundary of the high-capacity flow channel is delineated by the recharge zone. The southern boundary is delineated by a change in water chemistry that is interpreted to indicate a different, slower flow regime to the south. Darcy's Law for volumetric flow through the high-capacity flow channel can be expressed

$$Q = AK\nabla h$$

where Q is volumetric flow, A is the cross-sectional area, K is hydraulic conductivity, and ∇h is the hydraulic gradient. The width and height of the cross section are 4 mi and 600 ft, respectively. The hydraulic gradient is approximately 10 ft/mile. An appropriate hydraulic conductivity for the karst limestone is 1.3×10^3 ft/day (Freeze and Cherry, 1978; Hovorka et al., 1995; Mace and Hovorka, 2000; Painter et al., 2002). Darcy's Law predicts flow of 270,000 acre-ft/yr through the high-capacity flow channel from the Uvalde pool to the San Antonio pool of the Edwards Aquifer for these assigned property values.

It must be recognized that this calculation is not well constrained, nor are the contributions to flow from the Uvalde pool to the San Antonio pool by groundwater north (in the recharge zone) and south (through a zone or reduced flow) of the high-capacity flow channel included in the flow calculation. Confirmation of the total flow estimate would require local aquifer tests to determine the hydraulic conductivity in the high-capacity flow channel and other lesser channels, local measurement of the hydraulic gradient, and refinement of the cross-section of the channels to determine the specific dimensions of flow. The greatest sources of uncertainty are the estimated value for hydraulic conductivity and the channel cross section. It is possible that the actual hydraulic conductivity value could vary by a factor of 2–5 from this estimate. However, hydraulic conductivity values significantly less than 1.3×10^3 ft/day are considered unlikely given the high density of high-volume irrigation wells in the channel and the suspected presence of karst flow through the channel (Hovorka et al., 2004; Worthington, 2004). Additional site-specific detailed assessment of the different flowpaths would reduce uncertainty in the potential for multiple flow channels between the Uvalde pool and the San Antonio pool of the Edwards Aquifer.

The value for flow between the two pools is informative to understanding the hydraulic dynamics of the Edwards Aquifer, even in light of the relatively high level of uncertainty in the calculation. The

calculation of 270,000 acre-ft/yr indicates that the Uvalde pool is, in fact, a source of significant recharge to the San Antonio pool of the Edwards Aquifer. Based on water-budget considerations, the calculation also suggests that the sources of recharge to the Uvalde pool are underestimated. Additional water must be recharging the Uvalde pool to balance the lack of recharge from the West Nueces River basin and the excessive discharge from the Leona River floodplain and possibly the Nueces and Frio river floodplains. Potential additional sources of recharge are distributed recharge in the Nueces River and the Frio River-Dry Frio River basins, previously unrecognized subsurface floodplain flow, and inflow from the Trinity Aquifer.

11 CONCLUSIONS

An integrated investigation of the groundwater systems in Uvalde County has been performed to evaluate the Edwards Aquifer in Uvalde County and provide a clearer understanding of the hydraulic relationship between the Uvalde pool and the San Antonio pool of the Edwards Aquifer. Understanding this relationship is central to the effective management of water resources in the Edwards Aquifer. Of primary concern is the quantity of groundwater flow from the Uvalde pool to the San Antonio pool.

The integrated investigation included assessments of structural geology, water chemistry, and hydrogeology of the study area. The study area was specified to include the natural hydrologic boundaries of groundwater systems that are intrinsically linked with the groundwater systems of Uvalde County. The investigations initially included the eastern half of Kinney County and the western portion of Medina County. Early assessments, however, indicated that groundwater flow in Kinney County may be different from the existing conceptual model that there was a groundwater divide in central Kinney County that causes groundwater in eastern Kinney County to flow to Uvalde County. Early findings from this investigation indicated the existence of a separate pool in the Edwards Aquifer in Kinney County. This hypothesis prompted the expansion of the study area to include all of Kinney County. In addition, early assessment in eastern Uvalde County and western Medina County indicated that there is no groundwater flow in the confined zone of the Edwards Aquifer from Medina County into Uvalde County. Because of this second assessment, western Medina County was not included in the investigation. Therefore, to better meet the objectives of the investigation, the study area was defined to include all of Kinney and Uvalde counties and no part of Medina County.

New or refined conceptual models of the groundwater systems in the study area were developed using the data and information assembled during this investigation. These data included:

- Detailed interpretations of the structural geology of the study area, with primary focus on the structure of the Edwards Aquifer. Of greatest benefit were the preparation of high resolution maps of the: (i) the base of the Edwards Aquifer; (ii) the top of the Edwards Aquifer; (iii) surface exposure of the Edwards Aquifer (i.e., recharge zone); and (iv) saturated thickness of the Edwards aquifer.

- The chemistry of water sampled from wells and springs in the study area. These data provided a means to identify: (i) different source areas for water in groundwater systems; (ii) different flow paths in the subsurface; (iii) the degree of hydraulic communication among different aquifers; (iv) areas of recharge and mixing; and (v) the presence of separate groundwater pools.

- Water well and focused synoptic water-level elevation surveys. Detailed examination of water wells in the study area provided insight into the different groundwater systems and their relationships. Of great benefit was the qualitative assessment of aquifer characteristics based on well capacity. Zones where groundwater systems have high and low capacity for flow were identified using assessment of well capacity. This evaluation technique allowed for the identification of a low permeability zone separating the Edwards Aquifer in Uvalde and Kinney counties and a high-capacity flow channel in the Edwards Aquifer in Uvalde County. Results from the synoptic surveys provided the opportunity to generate a detailed groundwater piezomentric contour map and to assess the hydraulic relationship between the Edwards Aquifer and the other aquifers in the study area.

Refined, or new, conceptual models of the groundwater systems were developed for Kinney and Uvalde counties. Assessment of the stratigraphic and facies geology, structural geology, water chemistry, and hydrogeology provided the basis to the designation of a separate pool in the Edwards Aquifer in Kinney

County (Figure 9.1.1). This pool, referred to as the Kinney County pool, extends from a groundwater divide between Mud and Pinto creeks on the west to a zone of low permeability near the Kinney County/Uvalde County line on the east. Although the elevations of groundwater are higher in eastern and central Kinney County than in Uvalde County, this low permeability zone impedes the eastward flow of groundwater in the Edwards Aquifer from Kinney to Uvalde counties. The permeability of the Edwards Aquifer in the Kinney County pool is significantly higher than in the low permeability zone, thereby allowing for an avenue for flow for the large volume of water recharged into the Edwards Aquifer in Kinney County. Most of the West Nueces River basin is west of this low permeability zone. All evidence suggests that most of the recharge from the West Nueces River basin recharges the Kinney County pool, not the Uvalde pool. This new conceptual model does not assert that there is no groundwater flow from the Kinney County pool to the Uvalde pool, only that there is limited or minimal flow.

Evaluations indicate that an average of 70,000 acre-ft annually recharges the Kinney County pool. Of this, approximately 23,000 acre-ft and 6,000 acre-ft are annually discharged from Las Moras, Pinto, and Mud springs and pumping, respectively. This conceptual model for the Kinney County pool contends that there is sufficient opportunity for discharge of the remaining 41,000 acre-ft primarily through the floodplains of Pinto and Las Moras creeks and secondarily through the floodplains of Mud, Elm (W), Elm (E), Lindsey, and possibly Turkey creeks.

An embayment in the base of the Edwards Aquifer is identified in the Grass Valley region using structural geologic analysis results. The SSW-trending faults and water chemistry in Kinney County support the hypothesis that groundwater in the Kinney County pool, including the Grass Valley area, flows toward Las Moras Springs. No evidence was found during the investigation to support the conventional conceptual model that groundwater flow is from the Las Moras Springs area to either the west toward San Felipe Springs near Del Rio or to the east toward the San Antonio pool of the Edwards Aquifer.

Interpretations formed as part of this investigation helped refine the conceptual model of the Uvalde pool of the Edwards Aquifer. Estimates of recharge and discharge of the Edwards Aquifer have been modified from values that were part of the pre-existing conceptual model of groundwater systems in Uvalde County. As mentioned, essentially all recharge from the West Nueces River basin is believed to recharge the Kinney County pool, not the Uvalde pool. Previous investigations indicated a large volume of water is discharged from the Edwards Aquifer into the Leona River floodplain. Recognition of floodplain flow through the subsurface supports the potential for additional discharge from the Edwards Aquifer through the Nueces River and Frio River floodplains. These refinements in the conceptual model for the groundwater systems in Uvalde County indicate that sources of recharge and volumes of discharge assumed in previous water-budget calculations require adjustment.

The structure of the Knippa Gap was evaluated to help understand groundwater flow in Uvalde County. Geologic structural maps of the Edwards Aquifer provided an improved understanding of the principal components to groundwater flow through the Knippa Gap. Of greatest interest in this interpretation is the structure of the base of the Edwards Aquifer to the east of the City of Uvalde. There is a prominent ridge in the base called the Uvalde Salient that reduces the saturated thickness of the Edwards Aquifer to as little as 400 ft compared with 600 ft to the east and west of the Uvalde Salient. The resulting topography of the base of the Edwards Aquifer is a series of prominent high points in the ridge that constrict groundwater flow through topographic saddles between the high points. This constriction results in a 4-mile wide channel of high-capacity flow through central Uvalde County. The channel is located immediately north of the City of Knippa. Cooks Fault forms its northern boundary and the structure of the Knippa Gap effectively forms its southern boundary. The chemistry of water in the channel is different from water south of the channel. Groundwater elevations suggest a groundwater trough coincident with the channel, which is an often indication of high-capacity flow.

The quantity of groundwater flow in the channel is essentially doubled by the addition of recharge from the Frio River-Dry Frio River basin at the Knippa Gap. A dramatic increase in the offset of Cooks Fault to the east of the Frio River effectively limits the area over which the Edwards Aquifer is recharged by the Frio River-Dry Frio River basin. The combined effect of the structural constriction and focused recharge at the Knippa Gap causes a damming of groundwater upgradient and to the west of the Knippa Gap. This explains why groundwater elevations to the west of Knippa Gap only change by 10–15 ft compared with changes in groundwater elevations of 65–80 ft to the east of the Knippa Gap during different stages in the Edwards Aquifer.

Recharge and discharge volumes of the Edwards Aquifer in Uvalde County are highly uncertain, although progress has been made to limit this uncertainty. As noted in this investigation, recharge from the West Nueces River is believed to recharge the Kinney County pool, not the Uvalde pool. Discharge from the Edwards Aquifer through the Nueces, Leona, and Frio river floodplains significantly exceeds previously estimated discharge rates. These changes cast doubt on the existing water budget calculation for Uvalde County which is based on the long-term average of 226,300 acre-ft/yr of recharge from the Nueces River-West Nueces River and the Frio River-Dry Frio River basins.

Given this uncertainty, it is not feasible to calculate the water budget of the Edwards Aquifer in Uvalde County using previously estimated recharge and discharge volumes. It is possible, however, to directly calculate the quantity of water flowing from the Uvalde pool through the high-capacity flow channel to the San Antonio pool. Using reasonable assumptions and characterizations, it is calculated that 270,000 acre-ft/yr flows through the high-capacity flow channel located in central Uvalde County. Although the assumptions inherent in this calculation make this calculation uncertain, it appears likely that total recharge in Uvalde County at least meets, if not exceeds, previous estimates of recharge in Uvalde County. If the hypotheses provided in this report are valid, then recharge from the Nueces River and the Frio River-Dry Frio River basins must exceed previous estimates. In addition, the prospect for additional sources of recharge in Uvalde County, such as increased distributed recharge and inflow from the Trinity and Austin Chalk aquifers, needs to be evaluated.

12 RECOMMENDATIONS FOR FUTURE WORK

Conceptual models for groundwater flow in Uvalde and Kinney counties have been refined using conclusions drawn from this investigation. Additional information and data needs have been identified that would support or refute the proposed conceptual models. These needs are presented separately for Uvalde and Kinney counties.

Uvalde County:

- Flow in the Nueces River and Frio River floodplains should be measured at locations where the rivers leave the Edwards Aquifer recharge zone. In the case of the Frio River, it is important that floodplain recharge of the Austin Chalk Aquifer be taken into consideration when measuring floodplain flow down gradient from the Edwards Aquifer recharge zone. Of greatest importance is to measure or estimate the quantity of subsurface flow through the floodplains. This may require a combination of subsurface geophysical characterization and aquifer testing.

- A focused evaluation of the recharge zone at the points where the Dry Frio and Frio rivers leave the Edwards Aquifer would help resolve what portions of recharge from the Dry Frio river and Frio River basin contribute to the Uvalde pool and the San Antonio pool of the Edwards Aquifer. This evaluation would help resolve whether there is a southwest component to groundwater flow in the recharge zone east of the Frio River.

- It would also be advisable to measure or estimate floodplain flow in the Nueces River upstream from the recharge zone or possibly at discrete locations along the river.

- Measurement or estimation of the contribution of distributed recharge to total recharge should be refined. This may require local measurement of evapotranspiration and other site specific measurement and characterization.

- Measurement or estimation of the quantity of water flowing through the Edwards Aquifer immediately down gradient from the Knippa Gap should be refined. This will require a focused structural geological analysis, water chemistry assessment, and synoptic water-level survey.

Kinney County:

- The hypothesis of a low permeability zone between the Kinney County pool and the Uvalde pool should be substantiated. This would require aquifer testing in the low permeability zone.

- Additional groundwater elevation data should be collected in western Kinney County to resolve the location of the groundwater divide at the western boundary of the Kinney County pool.

- The hypothesis that groundwater flow from Grass Valley to Las Moras Springs should be substantiated with a tracer test.

- Measurement of the contribution of distributed recharge to total recharge should be refined. This may require local measurement of evapotranspiration and other site specific measurement and characterization.

- Flow in the major creek floodplains should be measured at locations where the creeks leave the Edwards Aquifer recharge zone. Las Moras and Pinto creeks are the most prominent creeks that

should be measured. Additional creeks that warrant consideration include Lindsey, Elm (E), Elm (W), Mud, and possibly Turkey creeks. Of greatest importance is to measure the quantity of subsurface flow through the floodplains. This will require a combination of structural geological analysis, subsurface geophysical characterization, and aquifer testing. Having this information will provide the basis for a more complete water-budget assessment of the Kinney County pool.

Throughout the Kinney and Uvalde counties, field checking of the revised structural interpretation and outcrop pattern of the Edwards Aquifer and confining units should be performed. This is necessary to confirm newly interpreted and reinterpreted faults, and to evaluate the mapped outcrop pattern of the Edwards Aquifer strata.. Field checking is particularly important because this outcrop pattern is directly relevant to any definition or potential modification to the interpreted distribution of the Edwards Aquifer recharge zone.

Results of these investigations will provide the basis for: (i) more complete water-budget assessments of the Kinney County and Uvalde pools; (ii) evaluation of the hypothesis that the Kinney County pool flow is generally to the SSW toward Las Moras Springs; and (iii) determine whether floodplain flow conveys significant quantities of water south from the study area and out of the Edwards Aquifer. Results from these recommended investigations will increase confidence in the conceptual models for the water systems of Kinney and Uvalde counties, which, in turn, will allow for a better understanding of the hydraulic relationship and the quantity of groundwater flow between the Uvalde pool and the San Antonio pool of the Edwards Aquifer.

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Appendix A – Part 1

Well ID	Northing	Easting	Well Elevation	Northing	Easting	Formation	Owner
	meters	meters	ft MSL	(Deg, min, sec)	(Deg, min, sec)		
KY001	3242646.0	391913.8	1181.3	29 18 29.513428 N	100 6 46.785301 W	Edwards	Mike Harris
KY002	3254410.3	363407.0	1236.7	29 24 41.671365 N	100 24 28.560674 W	Edwards	Shahan Ranch
KY004	3255907.5	362548.5	1255.9	29 25 29.965308 N	100 25 1.081247 W	Edwards	Shahan Ranch
KY006	3275095.9	357499.7	1633.9	29 35 51.179832 N	100 28 17.412044 W	Edwards	Texas Parks & Wildlife
KY007	3243914.4	362657.4	1113.1	29 19 0.449865 N	100 24 51.652877 W	Edwards	City of Bracketville
KY008	3240072.3	368878.4	1130.8	29 16 58.036712 N	100 20 59.437720 W	Edwards	Don Hood
KY010	3247116.2	361722.1	1171.0	29 20 44.081235 N	100 25 27.763365 W	Edwards	John Boerschig
KY011	3247083.4	361688.8	1170.1	29 20 43.004530 N	100 25 28.984163 W	Edwards	John Boerschig
KY012	3248779.1	369177.6	1278.6	29 21 40.970426 N	100 20 52.069698 W	Edwards	John Boerschig
KY013	3244518.5	367420.1	1170.7	29 19 21.910584 N	100 21 55.391287 W	Edwards	Randall Halbert
KY014	3242937.2	369160.0	1230.5	29 18 31.201621 N	100 20 50.224601 W	Edwards	Randall Halbert
KY015	3238506.4	376831.4	1119.4	29 16 10.056401 N	100 16 4.126488 W	Edwards	John Locke
KY017	3269292.5	342625.9	1295.4	29 32 36.251572 N	100 37 27.148093 W	Edwards	Bob Price
KY018	3270288.8	332295.1	1319.6	29 33 3.760552 N	100 43 51.393982 W	Edwards	John Boerschig
KY019	3272664.1	335072.8	1399.9	29 34 22.235708 N	100 42 9.511809 W	Edwards	John Boerschig
KY020	3266857.4	339732.3	1282.8	29 31 15.838294 N	100 39 13.333924 W	Edwards	Billey C. Lewis
KY021	3244498.1	366888.6	1167.2	29 19 21.047918 N	100 22 15.084657 W	Edwards	Bob Halbert
KY022	3243936.6	370829.9	1170.6	29 19 4.286610 N	100 19 48.755539 W	Edwards	Bob Halbert
KY023	3255742.6	377665.6	1356.9	29 25 30.248315 N	100 15 40.110690 W	Edwards	Grass Valley
KY024	3254646.5	375438.7	1368.8	29 24 53.852082 N	100 17 2.291836 W	Edwards	Grass Valley
KY025	3254284.8	382247.4	1310.8	29 24 44.471622 N	100 12 49.541059 W	Edwards	unk windmill
KY026	3253594.2	360821.8	1224.8	29 24 14.139557 N	100 26 4.092097 W	Edwards	Shahan Ranch
KY027	3255789.2	359284.8	1260.6	29 25 24.818872 N	100 27 2.118565 W	Edwards	Shahan Ranch
KY028	3241032.6	380821.1	1154.3	29 17 33.499793 N	100 13 37.296193 W	Edwards	RC Fuller
KY029	3241753.0	388971.3	1119.5	29 17 59.579464 N	100 8 35.525108 W	Edwards	George Rose

Well ID	Northing	Easting	Well Elevation	Northing	Easting	Formation	Owner
	meters	meters	ft MSL	(Deg, min, sec)	(Deg, min, sec)		
KY030	3252865.0	366110.7	1271.2	29 23 52.527682 N	100 22 47.578601 W	Edwards	HFF Ranch
KY031	3253768.1	362673.6	1231.7	29 24 20.522249 N	100 24 55.479530 W	Edwards	Shahan Ranch
KY032	3260191.7	347153.8	1246.6	29 27 42.693900 N	100 34 34.386895 W	Edwards	Clyde Earwood
KY036	3240421.8	382850.2	1253.6	29 17 14.340795 N	100 12 21.870248 W	Edwards	DeSpahn
KY037	3254389.1	376504.0	1381.8	29 24 45.872644 N	100 16 22.666630 W	Edwards	Grass Valley
KY038	3271937.6	355598.2	1534.2	29 34 7.809493 N	100 29 26.570662 W	Edwards	Mann
KY039	3242777.3	366226.3	1146.1	29 18 24.899766 N	100 22 38.881308 W	Edwards	Petit
KY040	3247699.2	387186.2	1217.4	29 21 12.171814 N	100 9 43.872467 W	Edwards	Dunbar
KY041	3247883.8	348860.7	1127.8	29 21 3.686198 N	100 33 24.943872 W	Edwards	Baker
KY042	3251426.4	357773.1	1187.5	29 23 2.498573 N	100 27 56.172488 W	Edwards	Dooley Estates
UV014	3234337.1	440460.1	900.6	29 14 11.184395 N	99 36 45.670111 W	Austin?	V. Niemeyer
UV015	3240851.0	444364.6	950.4	29 17 43.465100 N	99 34 22.212903 W	Austin	Tom Olithant
UV016	3237571.5	442822.1	937.3	29 15 56.664881 N	99 35 18.774836 W	Edwards	J.E. Miles
UV017	3239438.9	444349.1	946.7	29 16 57.584687 N	99 34 22.531713 W	Edwards	4 M Ranches
UV019	3237798.8	438979.0	949.9	29 16 3.403152 N	99 37 41.222006 W	Edwards	Rickey Gimbler
UV020	3240535.5	433015.9	987.4	29 17 31.228637 N	99 41 22.778664 W	Edwards	Bruce Gilleland
UV021	3250082.0	416365.0	1210.3	29 22 37.793412 N	99 51 42.504740 W	Edwards	Jack Stone
UV022	3245970.3	416570.9	1138.6	29 20 24.261690 N	99 51 33.743361 W	Edwards	Jack Stone
UV023	3247103.4	431118.4	1098.1	29 21 4.246577 N	99 42 34.582182 W	Edwards	Dolph Briscoe
UV024	3247643.8	431854.9	1082.1	29 21 21.946399 N	99 42 7.389711 W	Edwards	Bruce Gilleland
UV025	3247954.1	432531.5	1050.9	29 21 32.160901 N	99 41 42.364938 W	Edwards	EAA Recharge Well
UV026	3244637.8	430677.9	1073.1	29 19 44.052101 N	99 42 50.359429 W	Edwards	Box K Ranches
UV027	3247054.5	427976.0	1080.6	29 21 2.024262 N	99 44 31.104473 W	Edwards	T.R. Hutcherson
UV028	3250168.8	398343.0	1187.5	29 22 35.827383 N	100 2 50.985928 W	Edwards	E.J. Chivey
UV029	3249497.3	458222.0	1001.7	29 22 26.318978 N	99 25 49.761300 W	Edwards	Dan Saunders
UV030	3242636.7	437717.7	1005.9	29 18 40.362715 N	99 38 28.940829 W	Edwards	Town of Knippa

Well ID	Northing	Easting	Well Elevation	Northing	Easting	Formation	Owner
	meters	meters	ft MSL	(Deg, min, sec)	(Deg, min, sec)		
UV031	3249248.4	454255.9	1011.1	29 22 17.736708 N	99 28 16.842789 W	Edwards	Edgar Kinraid
UV032	3249915.1	454080.8	1009.9	29 22 39.373098 N	99 28 23.437763 W	Edwards	E. B. Kinraid
UV036	3241828.5	455795.7	930.4	29 18 16.855373 N	99 27 18.654409 W	Edwards	
UV039	3260406.5	453882.0	1202.1	29 28 20.215888 N	99 28 32.399494 W	Edwards	Peter Bowman
UV044	3236515.6	451381.5	871.5	29 15 23.648014 N	99 30 1.444499 W	Leona	Cole Farms
UV046	3231975.0	456256.0	836.7	29 12 56.762178 N	99 27 0.191700 W	Edwards	Coyote Ranch Nunley Bros
UV047	3250222.5	438076.0	1073.8	29 22 46.887458 N	99 38 17.195505 W	Edwards	
UV049	3250019.1	439847.5	1146.1	29 22 40.590225 N	99 37 11.441877 W	Edwards	Nayak Avavion
UV051	3246186.0	433254.4	1050.6	29 20 34.855511 N	99 41 15.168382 W	Edwards	John Brigman
UV052	3248337.2	434535.2	1074.5	29 21 44.987989 N	99 40 28.137473 W	Edwards	Bruce Gilleland
UV054	3247112.2	434064.9	1063.1	29 21 5.101783 N	99 40 45.315224 W	Edwards	Weldon Gilleland
UV055	3246157.8	434607.2	1050.6	29 20 34.196129 N	99 40 25.001411 W	Edwards	
UV056	3244727.0	432934.6	1037.2	29 19 47.392832 N	99 41 26.708165 W	Edwards	Bobbie Parten
UV057	3238783.6	432731.6	974.4	29 16 34.253236 N	99 41 32.932173 W	Edwards	E.W. Knippa
UV058	3237136.6	434025.1	954.5	29 15 40.989671 N	99 40 44.644917 W	Edwards	Ed Knippa
UV059	3239488.8	434396.8	972.0	29 16 57.482076 N	99 40 31.373482 W	Austin	Edwards Com
UV060	3234009.3	434658.9	919.7	29 13 59.501170 N	99 40 20.495055 W	Austin?	Thelma Thompson
UV061	3233062.4	436960.0	905.3	29 13 29.156942 N	99 38 55.067131 W	Edwards	Thelma Thompson
UV062	3235928.3	437317.5	936.2	29 15 2.334530 N	99 38 42.406169 W	Edwards	Edwards Com
UV063	3238748.7	437971.0	960.8	29 16 34.086332 N	99 38 18.764926 W	Edwards	John Miakawa
UV066	3252918.6	450661.6	1066.9	29 24 16.492294 N	99 30 30.758008 W	Edwards	E.B. Kincaid
UV067	3253385.8	449215.9	1074.1	29 24 31.464251 N	99 31 24.480195 W	Edwards	Henry Brothers
UV069	3247555.3	451707.2	1004.5	29 21 22.383095 N	99 29 51.113490 W	Edwards	G. Driskill Feed Yards
UV071	3245031.8	449222.1	983.5	29 20 0.042170 N	99 31 22.862207 W	Austin or Serp	Robert Bader
UV072	3245771.0	449552.9	993.8	29 20 24.106753 N	99 31 10.717104 W	Edwards	Hubert Waldrip
UV073	3240801.3	449676.4	943.7	29 17 42.653878 N	99 31 5.321267 W	Serpentine	David Howard

Well ID	Northing	Easting	Well Elevation	Northing	Easting	Formation	Owner
	meters	meters	ft MSL	(Deg, min, sec)	(Deg, min, sec)		
UV074	3244198.4	428867.8	1054.7	29 19 29.413929 N	99 43 57.369927 W	Edwards	Tony Hull
UV075	3244127.9	429026.1	1057.7	29 19 27.156927 N	99 43 51.481949 W	Edwards	Tony Hull
UV076	3253951.0	439717.3	1118.8	29 24 48.314228 N	99 37 17.046003 W	Edwards	James Santleben
UV077	3254297.6	441929.7	1102.3	29 24 59.949457 N	99 35 55.015981 W	Edwards	Delano Brown
UV078	3252234.9	442219.1	1092.3	29 23 52.980625 N	99 35 43.884308 W	Edwards	Buster Page
UV079	3244610.8	440576.6	1005.8	29 19 44.998476 N	99 36 43.344250 W	Edwards	Sammy Newman
UV081	3246420.6	443670.5	1003.8	29 20 44.313336 N	99 34 48.963229 W	Edwards	J. Ward
UV082	3245704.9	442315.2	1006.6	29 20 20.837477 N	99 35 39.087955 W	Edwards	
UV083	3241716.4	440677.9	979.8	29 18 10.977860 N	99 36 39.026463 W	Austin	C. Ward
UV084	3240956.0	440731.4	974.8	29 17 46.281998 N	99 36 36.898260 W	Edwards	
UV085	3242169.3	442904.5	977.3	29 18 26.063659 N	99 35 16.579079 W	Austin	A. Dornbush
UV086	3241789.6	443324.8	969.8	29 18 13.795112 N	99 35 0.927777 W	Austin	
UV087	3243003.8	444406.8	959.9	29 18 53.41700 N	99 34 2.04020 W	Anacacho	E. Faulkenberg
UV088	3240347.9	436588.2	981.6	29 17 25.796262 N	99 39 10.341143 W	Edwards	White Mines
UV089	3237411.4	444245.5	928.3	29 15 51.691031 N	99 34 26.004845 W	Leona	J. Miles
UV090	3236422.8	426950.6	993.9	29 15 16.396692 N	99 45 6.596764 W	Edwards	Jane Kennedy
UV091	3236431.5	426257.0	987.0	29 15 16.531762 N	99 45 32.296524 W	Edwards	Jane Kennedy
UV092	3236084.5	424731.4	949.6	29 15 4.933104 N	99 46 28.731408 W	Edwards	
UV093	3236215.9	424101.3	962.4	29 15 9.066593 N	99 46 52.109685 W	Edwards/Buda	Nell Capt
UV094	3235721.3	426616.0	972.3	29 14 53.532250 N	99 45 18.824694 W	Edwards	Toone
UV095	3227648.8	424672.2	887.3	29 10 30.850389 N	99 46 28.862752 W	Edwards	Gillotte
UV097	3238191.4	425562.2	994.2	29 16 13.564322 N	99 45 58.464718 W	Edwards	ME Walker
UV098	3230315.0	416278.9	939.1	29 11 55.575689 N	99 51 40.305128 W	Edwards	J Garmon
UV099	3247406.6	407231.7	1049.1	29 21 8.566900 N	99 57 20.459794 W	Edwards	Sky Lewey
UV100	3243735.5	409657.4	1039.1	29 19 9.939286 N	99 55 49.427544 W	Edwards	Al Townsend
UV101	3249057.1	427515.9	1109.0	29 22 6.989416 N	99 44 48.640597 W	Edwards	

Well ID	Northing	Easting	Well Elevation	Northing	Easting	Formation	Owner
	meters	meters	ft MSL	(Deg, min, sec)	(Deg, min, sec)		
UV102	3227718.1	416719.4	958.2	29 10 31.310364 N	99 51 23.293112 W	Edwards	Bill McBride
UV103	3228473.4	417285.0	930.2	29 10 55.981264 N	99 51 2.556540 W	Buda	Bill McBride
UV104	3228470.5	417274.1	929.9	29 10 55.884601 N	99 51 2.958942 W	Edwards	Bill McBride
UV105	3228469.3	417288.0	930.1	29 10 55.848233 N	99 51 2.445267 W	Austin	Bill McBride
UV106	3233502.7	423248.4	910.2	29 13 40.730979 N	99 47 23.031155 W	Edwards	Bill Doger
UV107	3223645.3	431211.5	848.1	29 8 22.113869 N	99 42 25.884410 W	Edwards	Dolph Briscoe
UV108	3243900.5	395817.9	1104.1	29 19 11.450851 N	100 4 22.508709 W	Edwards	Mike Harris
UV109	3235539.3	403450.1	1041.5	29 14 42.008218 N	99 59 36.955619 W	Edwards	Sid Franke
UV110	3244403.8	426329.2	1043.2	29 19 35.560663 N	99 45 31.535215 W	Edwards	R. Booker
UV111	3244228.4	426339.6	1036.1	29 19 29.864347 N	99 45 31.108712 W	Edwards	R. Booker
UV112	3239962.2	414104.1	1024.5	29 17 8.472279 N	99 53 3.526055 W	Edwards	Brian Trees
UV113	3232259.3	409787.6	998.0	29 12 57.134991 N	99 55 41.229861 W	Austin	Richard Holcomb
UV114	3222237.2	427274.2	876.9	29 7 35.576200 N	99 44 51.263554 W	Edwards	L. Briscoe
UV115	3250227.7	427718.0	1134.5	29 22 45.063829 N	99 44 41.419679 W	Edwards	O.E. Robinson
UV116	3242455.5	426629.2	1027.7	29 18 32.324931 N	99 45 19.946679 W	Edwards	Jeanne Langston
UV117	3241515.0	413161.3	1028.1	29 17 58.686045 N	99 53 38.904703 W	Edwards	Eddie Carnes
UV118	3241841.1	450806.7	939.6	29 18 16.599089 N	99 30 23.594430 W	Austin	Coyote Ranch
UV119	3243624.5	403799.6	1089.9	29 19 4.770351 N	99 59 26.542840 W	Edwards	Haby Ranch

NOTES:

1.) Data were collected utilizing a Leica system 1200 Global Positioning System (GPS)
2.) GPS data were collected by Richard Sample (R-K Project Professional)

Appendix A – Part 2

Well ID	Jan-Feb 2006 Synoptic			Oct-Nov Synoptic			July 2005 Synoptic			Preliminary Measurements		
	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation
	ft		ft MSL	ft		ft MSL	ft		ft MSL	ft		ft MSL
KY001	196.70	2/16/2006	984.6	189.90	11/7/2005	991.41	----	----	----	170.26	12/8/2004	1011.1
KY002	48.27	2/13/2006	1188.4	44.74	10/26/2005	1191.96	56.06	7/27/2005	1180.64	32.34	12/8/2004	1204.4
KY004	64.08	2/2/2006	1191.8	60.50	10/27/2005	1195.37	63.25	7/30/2005	1192.62	51.97	12/8/2004	1203.9
KY006	223.80	2/13/2006	1410.1	215.23	10/26/2005	1418.71	214.15	7/29/2005	1419.79	209.69	12/9/2004	1424.3
KY007	18.83	2/1/2006	1094.3	14.10	10/27/2005	1098.99	18.00	7/28/2005	1095.09	8.00	12/9/2004	1105.1
KY008	29.32	2/2/2006	1101.4	29.70	10/28/2005	1101.05	27.96	7/27/2005	1102.79	26.82	12/9/2004	1103.9
KY010	61.67	2/1/2006	1109.4	56.45	10/27/2005	1114.59	----	----	----	51.00	12/10/2004	1120.0
KY011	62.35	2/1/2006	1107.8	59.70	10/27/2005	1110.43	61.25	7/27/2005	1108.88	50.00	12/10/2004	1120.1
KY012	164.95	2/1/2006	1113.7	148.20	10/28/2005	1130.45	163.11	7/27/2005	1115.54	153.57	6/12/2005	1125.1
KY013	60.20	2/16/2006	1110.5	50.25	10/25/2005	1120.42	69.63	7/29/2005	1101.04	57.96	6/1/2005	1112.7
KY014	129.70	2/13/2006	1100.8	127.05	10/25/2005	1103.43	125.54	7/29/2005	1104.94	124.18	6/1/2005	1106.3
KY015	62.30	2/1/2006	1057.1	----	----	----	----	----	----	----	----	----
KY017	63.58	2/2/2006	1231.9	59.02	11/1/2005	1236.42	62.27	7/28/2005	1233.17	61.04	6/15/2005	1234.4
KY018	175.60	2/2/2006	1144.0	----	----	----	175.02	7/30/2005	1144.61	173.44	6/15/2005	1146.2
KY019	224.00	2/2/2006	1175.9	220.50	10/31/2005	1179.40	222.48	7/30/2005	1177.42	222.72	6/15/2005	1177.2
KY020	96.10	2/2/2006	1186.7	94.45	11/1/2005	1188.34	96.42	7/30/2005	1186.37	96.33	6/15/2005	1186.5
KY021	59.30	2/16/2006	1107.9	51.90	10/25/2005	1115.35	53.67	7/29/2005	1113.58	51.42	6/15/2005	1115.8
KY022	52.50	2/13/2006	1118.1	52.00	10/25/2005	1118.60	61.45	7/29/2005	1109.15	49.13	6/15/2005	1121.5
KY023	161.45	2/1/2006	1195.4	155.75	10/26/2005	1201.12	160.00	7/27/2005	1196.87	157.51	6/29/2005	1199.4
KY024	183.80	2/1/2006	1185.0	179.38	10/26/2005	1189.38	182.67	7/27/2005	1186.09	179.88	6/29/2005	1188.9
KY025	152.80	2/1/2006	1158.0	145.20	10/26/2005	1165.57	145.67	7/30/2005	1165.10	151.49	6/29/2005	1159.3
KY026	42.20	2/2/2006	1182.6	37.42	10/27/2005	1187.40	39.55	7/27/2005	1185.27	38.99	6/30/2005	1185.8
KY027	71.90	2/2/2006	1188.7	69.15	10/27/2005	1191.48	67.55	7/29/2005	1193.08	71.10	6/30/2005	1189.5
KY028	114.40	2/2/2006	1039.9	113.80	11/1/2005	1040.51	115.17	7/30/2005	1039.14	----	----	----
KY029	134.47	2/3/2006	985.1	128.20	10/28/2005	991.35	122.50	7/30/2005	997.05	----	----	----

	Jan-Feb 2006 Synoptic			Oct-Nov Synoptic			July 2005 Synoptic			Preliminary Measurements		
Well ID	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation
	ft		ft MSL	ft		ft MSL	ft		ft MSL	ft		ft MSL
KY030	70.65	2/1/2006	1200.5	64.45	10/27/2005	1206.71	70.00	7/29/2005	1201.16	----	----	----
KY031	42.08	2/1/2006	1189.6	37.95	10/26/2005	1193.75	42.08	7/29/2005	1189.62	----	----	----
KY032	56.60	2/2/2006	1190.0	48.10	10/31/2005	1198.46	48.30	7/28/2005	1198.26	----	----	----
KY036	241.50	2/3/2006	1012.1	241.10	11/1/2005	1012.48	248.25	7/30/2005	1005.33	----	----	----
KY037	199.70	2/1/2006	1182.1	200.56	10/26/2005	1181.21	----	----	----	----	----	----
KY038	148.65	2/3/2006	1385.5	141.70	10/28/2005	1392.45	----	----	----	----	----	----
KY039	41.40	2/3/2006	1104.7	39.50	10/28/2005	1106.63	----	----	----	----	----	----
KY040	179.60	2/3/2006	1037.8	162.20	10/28/2005	1055.23	----	----	----	----	----	----
KY041	0.90	2/2/2006	1126.9	5.30	10/31/2005	1122.55	----	----	----	----	----	----
KY042	-2.83	2/14/2006	1190.4	----	----	----	----	----	----	----	----	----
UV014	61.00	1/17/2006	839.6	58.80	11/10/2005	841.80	----	----	----	53.17	1/24/2005	847.4
UV015	51.00	1/17/2006	899.4	49.50	11/10/2005	900.94	----	----	----	102.12	1/24/2005	848.3
UV016	139.58	1/19/2006	797.7	129.42	11/10/2005	807.89	----	----	----	101.25	1/25/2005	836.1
UV017	139.20	1/16/2006	807.5	130.37	11/10/2005	816.32	----	----	----	105.58	1/25/2005	841.1
UV019	69.58	1/17/2006	880.3	----	----	----	----	----	----	59.00	1/25/2005	890.9
UV020	124.70	1/19/2006	862.7	123.70	11/7/2005	863.67	----	----	----	109.01	1/25/2005	878.4
UV021	141.40	1/25/2006	1068.9	----	----	----	----	----	----	107.81	2/15/2005	1102.5
UV022	170.40	1/25/2006	968.2	----	----	----	----	----	----	147.81	2/15/2005	990.8
UV023	168.92	1/20/2006	929.2	165.58	11/2/2005	932.54	----	----	----	157.59	2/15/2005	940.5
UV024	147.55	1/20/2006	934.5	144.33	11/2/2005	937.75	----	----	----	164.61	2/15/2005	917.5
UV025	113.65	1/20/2006	937.2	108.55	11/2/2005	942.33	----	----	----	97.31	2/15/2005	953.6
UV026	190.75	1/23/2006	882.3	191.92	11/2/2005	881.17	----	----	----	177.02	2/15/2005	896.1
UV027	129.15	1/23/2006	951.5	121.11	11/2/2005	959.50	----	----	----	118.99	2/15/2005	961.6
UV028	126.70	1/25/2006	1060.8	----	----	----	143.92	7/30/2005	1043.59	----	----	----
UV029	197.50	1/16/2006	804.2	170.71	11/15/2005	831.00	----	----	----	165.00	9/8/2005	836.71
UV030	184.00	1/19/2006	821.9	176.60	11/11/2005	829.34	----	----	----	170.70	9/16/2005	835.24
UV031	204.56	1/16/2006	806.5	197.75	11/15/2005	813.34	----	----	----	----	----	----

	Jan-Feb 2006 Synoptic			Oct-Nov Synoptic			July 2005 Synoptic			Preliminary Measurements		
Well ID	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation
	ft		ft MSL	ft		ft MSL	ft		ft MSL	ft		ft MSL
UV032	211.13	1/16/2006	798.8	203.80	11/15/2005	806.08	----	----	----	----	----	----
UV036	125.00	1/16/2006	805.4	----	----	----	----	----	----	----	----	----
UV039	291.59	1/16/2006	910.5	280.10	11/15/2005	922.00	----	----	----	----	----	----
UV044	36.80	1/16/2006	834.7	36.50	11/15/2005	835.00	----	----	----	----	----	----
UV046	45.30	1/16/2006	791.4	39.00	11/15/2005	797.68	----	----	----	----	----	----
UV047	247.49	1/19/2006	826.3	----	----	----	----	----	----	229.35	9/16/2005	844.41
UV049	237.75	1/17/2006	908.4	230.25	11/9/2005	915.88	----	----	----	225.35	9/16/2005	920.78
UV051	152.40	1/23/2006	898.2	147.71	11/12/2005	902.88	----	----	----	214.85	9/21/2005	835.74
UV052	144.20	1/20/2006	930.3	139.55	11/2/2005	934.95	----	----	----	149.00	9/21/2005	925.50
UV054	167.58	1/20/2006	895.5	160.75	11/2/2005	902.32	----	----	----	157.17	9/26/2005	905.90
UV055	171.45	1/20/2006	879.2	164.75	11/2/2005	885.85	----	----	----	159.14	9/26/2005	891.46
UV056	169.70	1/23/2006	867.5	164.72	11/4/2005	872.47	----	----	----	163.18	9/26/2005	874.01
UV057	94.00	1/19/2006	880.4	94.59	11/7/2005	879.79	----	----	----	98.40	9/26/2005	875.98
UV058	78.54	1/19/2006	876.0	75.41	11/7/2005	879.14	----	----	----	78.87	9/26/2005	875.68
UV059	67.40	1/17/2006	904.6	66.97	11/7/2005	905.03	----	----	----	66.32	9/26/2005	905.68
UV060	51.95	1/19/2006	867.7	47.57	11/5/2005	872.12	----	----	----	53.30	9/30/2005	866.39
UV061	43.70	1/19/2006	861.6	46.30	11/15/2005	859.04	----	----	----	50.15	9/30/2005	855.19
UV062	59.10	1/17/2006	877.1	84.58	11/15/2005	851.58	----	----	----	75.42	9/30/2005	860.74
UV063	86.15	1/17/2006	874.7	91.60	11/10/2005	869.24	----	----	----	98.01	9/30/2005	862.83
UV066	248.62	1/16/2006	818.3	240.70	11/11/2005	826.24	----	----	----	237.17	10/7/2005	829.77
UV067	254.00	1/17/2006	820.1	244.35	11/11/2005	829.80	----	----	----	240.83	10/7/2005	833.32
UV069	203.92	1/16/2006	800.6	197.29	11/11/2005	807.21	----	----	----	194.33	10/7/2005	810.17
UV071	95.70	1/23/2006	887.8	93.50	11/11/2005	890.03	----	----	----	----	----	----
UV072	186.00	1/16/2006	807.8	181.70	11/11/2005	812.06	----	----	----	179.05	10/7/2005	814.71
UV073	57.55	1/16/2006	886.2	57.60	11/11/2005	886.11	----	----	----	56.25	10/7/2005	887.46
UV074	169.55	1/23/2006	885.1	166.40	11/2/2005	888.27	----	----	----	164.90	10/10/2005	889.77
UV075	174.90	1/20/2006	882.8	171.80	11/2/2005	885.86	----	----	----	169.88	10/10/2005	887.78

	Jan-Feb 2006 Synoptic			Oct-Nov Synoptic			July 2005 Synoptic			Preliminary Measurements		
Well ID	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation	GW Depth	Date	GW Elevation
	ft		ft MSL	ft		ft MSL	ft		ft MSL	ft		ft MSL
UV076	270.76	1/17/2006	848.1	248.22	11/10/2005	870.62	----	----	----	241.77	10/10/2005	877.07
UV077	271.25	1/17/2006	831.0	263.00	11/10/2005	839.28	----	----	----	258.70	10/10/2005	843.58
UV078	252.56	1/17/2006	839.7	244.40	11/10/2005	847.90	----	----	----	241.48	10/10/2005	850.82
UV079	201.42	1/17/2006	804.4	189.12	11/9/2005	816.68	----	----	----	186.42	10/18/2005	819.38
UV081	184.58	1/17/2006	819.2	187.29	11/9/2005	816.48	----	----	----	183.42	10/18/2005	820.35
UV082	201.09	1/17/2006	805.5	----	----	----	----	----	----	191.75	10/18/2005	814.82
UV083	57.30	1/17/2006	922.5	55.90	11/10/2005	923.90	----	----	----	54.75	10/18/2005	925.05
UV084	148.10	1/17/2006	826.7	142.60	11/10/2005	832.16	----	----	----	141.20	10/18/2005	833.56
UV085	56.60	1/17/2006	920.7	56.55	11/10/2005	920.77	----	----	----	61.27	10/18/2005	916.05
UV086	59.10	1/17/2006	910.7	58.88	11/10/2005	910.87	----	----	----	58.30	10/18/2005	911.45
UV087	37.60	1/17/2006	922.3	37.45	11/15/2005	922.47	----	----	----	37.03	10/18/2005	922.89
UV088	185.80	1/17/2006	795.8	168.19	11/10/2005	813.39	----	----	----	162.01	10/19/2005	819.57
UV089	49.10	1/16/2006	879.2	43.40	11/10/2005	884.89	----	----	----	42.61	10/19/2005	885.68
UV090	108.50	1/19/2006	885.4	107.20	11/7/2005	886.66	----	----	----	105.81	10/19/2005	888.05
UV091	100.30	1/20/2006	886.7	100.10	11/7/2005	886.93	----	----	----	99.42	10/19/2005	887.61
UV092	63.80	1/19/2006	885.8	62.80	11/7/2005	886.84	----	----	----	60.90	10/19/2005	888.74
UV093	75.55	1/19/2006	886.8	74.60	11/7/2005	887.78	----	----	----	73.50	10/19/2005	888.88
UV094	86.50	1/19/2006	885.8	86.00	11/4/2005	886.30	----	----	----	----	----	----
UV095	17.25	1/23/2006	870.1	16.90	11/4/2005	870.44	----	----	----	----	----	----
UV097	107.92	1/20/2006	886.3	107.00	11/7/2005	887.18	----	----	----	----	----	----
UV098	63.75	1/20/2006	875.4	----	----	----	----	----	----	----	----	----
UV099	28.90	1/25/2006	1020.2	----	----	----	----	----	----	----	----	----
UV100	93.00	1/25/2006	946.1	91.88	11/9/2005	947.17	----	----	----	----	----	----
UV101	85.60	1/20/2006	1023.4	----	----	----	----	----	----	----	----	----
UV102	83.50	1/23/2006	874.7	----	----	----	----	----	----	----	----	----
UV103	54.50	1/23/2006	875.7	----	----	----	----	----	----	----	----	----
UV104	55.10	1/23/2006	874.8	----	----	----	----	----	----	----	----	----

	Jan-Feb 2006 Synoptic			Oct-Nov Synoptic			July 2005 Synoptic			Preliminary Measurements		
Well ID	**GW Depth**	**Date**	**GW Elevation**	**GW Depth**	**Date**	**GW Elevation**	**GW Depth**	**Date**	**GW Elevation**	**GW Depth**	**Date**	**GW Elevation**
	ft		**ft MSL**	**ft**		**ft MSL**	**ft**		**ft MSL**	**ft**		**ft MSL**
UV105	54.90	1/23/2006	875.2	----	----	----	----	----	----	----	----	----
UV106	26.40	1/20/2006	883.8	----	----	----	----	----	----	----	----	----
UV107	35.08	1/23/2006	813.0	----	----	----	----	----	----	----	----	----
UV108	120.00	2/16/2006	984.1	----	----	----	----	----	----	----	----	----
UV109	100.05	1/25/2006	941.4	----	----	----	----	----	----	----	----	----
UV110	155.10	1/20/2006	888.1	----	----	----	----	----	----	----	----	----
UV111	148.00	1/20/2006	888.1	----	----	----	----	----	----	----	----	----
UV112	116.20	1/25/2006	908.3	----	----	----	----	----	----	----	----	----
UV113	112.6	1/26/2006	885.4	----	----	----	----	----	----	----	----	----
UV114	68.125	1/26/2006	808.7	----	----	----	----	----	----	----	----	----
UV115	106.4	1/26/2006	1028.1	----	----	----	----	----	----	----	----	----
UV116	141.4	1/26/2006	886.3	----	----	----	----	----	----	----	----	----
UV117	114.65	1/26/2006	913.5	----	----	----	----	----	----	----	----	----
UV118	47.6	1/26/2006	892.0	----	----	----	----	----	----	----	----	----
UV119	127.80	2/17/2006	962.1	----	----	----	----	----	----	----	----	----

Appendix B

Survey Methodology

In accordance with the objectives of the groundwater flow system investigation, it was necessary to accurately establish the locations and vertical elevations of reference points at respective study wells to obtain accurate measurements of the piezometric surface. Specific reference points were previously established at study wells in conjunction with preliminary well gauging activities and generally consisted of markings made near the edge of the top-of-casing or other wellhead access points. At larger study well locations utilized for irrigation purposes, reference points were established at access ports located at the base of the wellhead. At smaller domestic or stock wells, reference points were generally defined at the blanking plate covering the top of the well casing.

A Leica System 1200 survey grade satellite based Global Positioning System (GPS) (manufactured by Leica Geosystems) was used for the survey which incorporates satellites managed by the Department of Defense to allow for accurate geographic position measurement worldwide. Raw GPS data were collected using the Leica System 1200 Real Time Kinematic (RTK) rover interfaced with a Leica System 1200 base station. The units were equipped with Intuicom® radios to transmit and receive laterally coordinated positional data between each of the units. Use of the coupled Real Time Kinematic rover and stationary base station provided for real time correction of raw GPS observables and generally afforded sub-meter position accuracy throughout the course of the survey. As further discussed herein, the reported accuracy of GPS measurements is dependent upon a number of factors including the number of satellites visible in the hemisphere, satellite geometry, ionospheric conditions, distance between the base station and Real Time Kinematic rover, etc.

At the onset of survey activities, the survey relied on current 7.5-minute series topographic maps published by the U.S. Geological Survey (USGS) comprising the full extent of the study area as base maps for project planning purposes. Existing reference points depicted on published maps were initially selected as known points of reference and targeted as locations to best position the GPS base station for subsequent acquisition of positional data. Specific USGS reference points were selected to maximize the number of remote measurements at study well sites collected by the Real Time Kinematic rover within the operating radius of the equipment. Additionally, factors such as topographic relief, other available geographic reference points, and manmade obstructions were taken into account when selecting the base station locations. This pre-selection of base station sites was performed to minimize the number of setups required and provide for longer satellite observation times at each base station location. As further discussed herein, longer observation times at respective base station sites allowed for collection of more accurate position data owing to better post-processing correction of raw GPS observables and generally resulted in better coordinate quality values reported by the Real Time Kinematic rover at respective study well sites.

Throughout the project duration, attempts were made to locate GPS base stations at known reference points depicted on USGS maps in an effort to establish independent control points for study well measurements within the operating radius of the equipment. It was anticipated that correlation of corrected GPS position data at base station locations to published reference point elevations, where possible within the study area, could serve as an independent check on the vertical accuracy of study well measurements. Due to the predominantly remote study well locations, however, the majority of the base station setups did not coincide with USGS reference points. Specific reference points depicted on published maps and utilized for purposes of this survey effort are defined by the USGS as follows:

Benchmark, abbreviated "BM", is a known reference point, surveyed historically, where the elevation and horizontal position have been previously determined (i.e., utilizing GPS or other methods). Most

benchmarks depicted on standard USGS maps are actually established by the U.S. Coast Guard or National Geodetic Survey. Benchmarks are usually marked in the field by small brass plates or other monumentation.

Based on discussions with local USGS personnel, it is our understanding that many of the benchmarks (i.e., indicated by an "X" with a corresponding elevation measurement) on the USGS topographical maps are actually spot elevations included from previously published map versions that have no supporting geodetic information as referenced and supported by the National Geodetic Survey archive. Many of the benchmark elevations depicted on topographic maps are considered "Third Order" reference points having a general accuracy of $\pm$10 feet. Third order is an indication of position accuracy and constitutes the most generous standard acceptable on a USGS topographical map.

Post Processing

The NGS is the entity responsible for the creation and maintenance of the spatial reference framework established for the United States. The National Geodetic Survey operates the On-line Positioning User Service (OPUS) as a means to provide GPS users efficient access to the National Spatial Reference System. OPUS allows users to submit GPS data files for post processing correction directly to the National Spatial Reference System. Submitted data files are processed with respect to three Continuously Operating Reference Stations sites. The Continuously Operating Reference Stations sites selected for data processing are not necessarily located nearest the collection site for raw GPS observables, but are selected based upon various criteria including distance, number of observable points, site stability, etc. As a result of this correction, a well-defined reference position (i.e., in specified coordinate systems including Universal Transverse Mercator [UTM] and State Plane Coordinates [SPC]) and correction factor are reported back to the GPS user via email.

The establishment of the well-defined reference position for the GPS base station and associated correction factor facilitates precise correction of GPS measurements obtained by the Real Time Kinematic rover. In the post-processing mode, the correction factor obtained from the National Geodetic Survey is applied to all associated raw GPS observables logged by the Real Time Kinematic rover utilizing data processing software developed by Leica Geosystems. In most instances, the NSRS correction involved the net movement of differentially-corrected position data on the order of 1-6 meters to better align field datasets with the national framework of geodetic reference stations maintained by the National Geodetic Survey.

Measurement Precision and Position Accuracies

The quality of positional data reported by the Leica 1200 System is computed on the Real Time Kinematic rover unit for both code and phase-fixed solutions. The reported accuracy of GPS measurements is dependent upon a number of factors including the number of satellites visible in the hemisphere, satellite geometry, ionospheric conditions, and distance between the base station and Real Time Kinematic rover. The coordinate quality is the reported measure of data quality and is derived such that there is at least a two-thirds probability that the computed position deviates from the true position by less than the given coordinate quality value for each point observation. As a general rule, computed GPS positions are almost twice as accurate in the horizontal as opposed to the vertical plane of reference. For this reason, error ellipses tend to be elongated along the vertical plane.

During the course of the project, it was discovered that due to a variety of environmental factors the operational range of the GPS system fluctuated from base station set up to set up. As a result of the diminished working range within some portions of the study area, the survey methodology was adapted as necessary to facilitate collection of position data exhibiting acceptable coordinate quality values. To

address the diminished coordinate quality and stay within budget/time constraints, the number of study wells attempted per base station setup was reduced. Although this practice generally resulted in shorter satellite observation times, improved communications between the base station and Real Time Kinematic rover resulted in better overall coordinate quality numbers. In instances where multiple wells were visited in conjunction with a single base station setup, raw GPS observables were generally collected in excess of 2 hours. Following the initial data review process, those points to be used in the study exhibiting coordinate quality values in excess of 1 meter were revisited. At the sites revisited in which data was collected at a single well location, the base station was set up in an adjacent area having an unobstructed view of the hemisphere and allowed to collected raw observation points for a minimum of 30 minutes.

Individual point data was generally considered adequate for the purposes of this survey provided that coordinate quality values did not exceed 1 meter. Of the 128 total well positions measured as part of this survey, a total of 11 have reported coordinate quality values in excess of 1 meter. The maximum coordinate quality parameter reported for a study well during this survey is 2.38 meters. The use of the GPS data for hydrogeologic and flow systems analyses took into account larger coordinate quality values reported at select study well locations. The estimated precision of collective GPS data was considered adequate for the purposes this investigation.

Description of Data

GPS data generated as the result of survey activities were compiled in tabular format and are provided as attachments to this letter. Data provided includes horizontal and vertical geographic coordinates for each of the study wells, comparison of measured GPS data to benchmark reference points depicted on published USGS maps, repetitive GPS point observations and horizontal and vertical geographic coordinates for each of the base stations utilized during the course of the study. Please find below a more detailed description of data tables.

Table 1 –Well Location Information

This table provides the following data pertaining to each of the study wells: individual well identification number, associated base station reference, date/time of GPS data collection, horizontal position measurement, vertical position measurement, and reported coordinate quality. Geographic coordinates are presented in degrees/minutes/seconds as well as in UTM formats reported with respect to the 1983 North American Datum (i.e., NAD83). The orthogonal height (vertical elevation above sea level) is presented in US Survey Feet in order to conform to published maps available through the USGS and National Geodetic Survey. The coordinate quality is presented in meters to facilitate direct comparison with reported position data. The average coordinate quality for all surveyed reference points is 0.26 meters. It was calculated that of the 128 survey points collected, approximately 80 percent had a coordinate quality of 0.14 meters or better.

Table 2 – Comparison of Published USGS Geographic Information to Field Survey Data

This table provides a listing of benchmark reference points identified based on review of published USGS maps depicting the study area that were occupied during the course of this project. The measured orthogonal heights at each of these locations was subsequently compared to published elevation data (i.e., elevations plotted on the USGS maps) in order to evaluate general correlation of data types. In general, comparison of measured versus published data indicated good agreement with deviations ranging from 0-9 ft. This is consistent with survey expectations given the fact that benchmarks occupied as part of this study are considered third order reference points, having reported accuracies on the order of 10 feet.

Table 3 – Repetitive Point Observations

This table provides a listing of repetitive point observations throughout the course of the GPS survey. Repetitive observations were collected for data quality assurance purposes at a total of 10 study well locations on separate days in order to evaluate the repeatability of reported GPS position data. Horizontal position data exhibited an average difference of 0.33 meters (1.08 ft). Vertical position data reported in US Survey Feet exhibited an average difference of 0.62 ft (0.19 meters). The maximum difference in vertical position data observed at repetitive point observation locations is 2.5 ft.

Table 4 – Base Station Information

This table provides the following data pertaining to each of the base stations occupied during this survey: base station identification number, date/time of GPS data collection, horizontal position measurement, and vertical position measurement. Geographic coordinates are presented in degrees/minutes/seconds as well as in UTM formats reported with respect to NAD83. The orthogonal height is presented in US Survey Feet and meters relative to mean sea level.

Certification by Registered Professional Land Surveyor (RPLS)

Garland L. Burch, P.E., R.P.L.S. No. 1827
Senior Engineering Consultant

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Signature of Registered Professional Land Surveyor

Appendix B – Table 1

Well ID	GPS Base Station No.	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Coordinate Quality
			Geographic		Universal Transverse Mercator			
			Latitude	Longitude	Northing	Easting		
			(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
KY001	BASE 26	11/7/2005 16:47	29 18 29.513428 N	100 6 46.785301 W	3242646.0	391913.8	1181.3	0.02
KY002	BASE 5	10/26/2005 15:25	29 24 41.671365 N	100 24 28.560674 W	3254410.3	363407.0	1236.7	0.01
KY004	BASE 5	10/27/2005 11:24	29 25 29.965308 N	100 25 1.081247 W	3255907.5	362548.5	1255.9	0.91
KY006	BASE 13	10/26/2005 13:26	29 35 51.179832 N	100 28 17.412044 W	3275095.9	357499.7	1633.9	0.01
KY007	BASE 4B	10/27/2005 16:14	29 19 0.449865 N	100 24 51.652877 W	3243914.4	362657.4	1113.1	0.04
KY008	BASE 91	4/13/2006 11:33	29 16 58.036712 N	100 20 59.437720 W	3240072.3	368878.4	1130.8	0.05
KY010	BASE 61	2/24/2006 15:30	29 20 44.081235 N	100 25 27.763365 W	3247116.2	361722.1	1171.0	0.04
KY011	BASE 61	2/24/2006 15:31	29 20 43.004530 N	100 25 28.984163 W	3247083.4	361688.8	1170.1	0.10
KY012	BASE 67	2/28/2006 14:57	29 21 40.970426 N	100 20 52.069698 W	3248779.1	369177.6	1278.6	0.04
KY013	BASE 1	10/25/2005 13:52	29 19 21.910584 N	100 21 55.391287 W	3244518.5	367420.1	1170.7	0.01
KY014	BASE 62	3/2/2006 11:15	29 18 31.201621 N	100 20 50.224601 W	3242937.2	369160.0	1230.5	0.12
KY015	BASE 42	11/21/2005 10:48	29 16 10.056401 N	100 16 4.126488 W	3238506.4	376831.4	1119.4	0.60
KY017	BASE 20	11/1/2005 10:37	29 32 36.251572 N	100 37 27.148093 W	3269292.5	342625.9	1295.4	0.81
KY018	BASE 63	2/24/2006 12:50	29 33 3.760552 N	100 43 51.393982 W	3270288.8	332295.1	1319.6	0.04
KY019	BASE 19	10/31/2005 14:39	29 34 22.235708 N	100 42 9.511809 W	3272664.1	335072.8	1399.9	0.01
KY020	BASE 21	11/1/2005 11:13	29 31 15.838294 N	100 39 13.333924 W	3266857.4	339732.3	1282.8	0.90
KY021	BASE 1	10/25/2005 14:04	29 19 21.047918 N	100 22 15.084657 W	3244498.1	366888.6	1167.2	0.01
KY022	BASE 62	3/2/2006 10:38	29 19 4.286610 N	100 19 48.755539 W	3243936.6	370829.9	1170.6	0.04
KY023	BASE 6	10/26/2005 10:59	29 25 30.248315 N	100 15 40.110690 W	3255742.6	377665.6	1356.9	0.02
KY024	BASE 6	10/26/2005 10:31	29 24 53.852082 N	100 17 2.291836 W	3254646.5	375438.7	1368.8	0.01
KY025	BASE 6	10/26/2005 9:36	29 24 44.471622 N	100 12 49.541059 W	3254284.8	382247.4	1310.8	2.10
KY026	BASE 5	10/27/2005 10:28	29 24 14.139557 N	100 26 4.092097 W	3253594.2	360821.8	1224.8	0.97
KY027	BASE 5	10/27/2005 10:50	29 25 24.818872 N	100 27 2.118565 W	3255789.2	359284.8	1260.6	0.73
KY028	BASE 90	4/13/2006 11:33	29 17 33.499793 N	100 13 37.296193 W	3241032.6	380821.1	1154.3	0.14
KY029	BASE 16	10/28/2005 18:23	29 17 59.579464 N	100 8 35.525108 W	3241753.0	388971.3	1119.5	0.70
KY030	BASE 60	2/28/2006 14:10	29 23 52.527682 N	100 22 47.578601 W	3252865.0	366110.7	1271.2	0.05
KY031	BASE 5	10/26/2005 16:09	29 24 20.522249 N	100 24 55.479530 W	3253768.1	362673.6	1231.7	0.02
KY032	BASE 18	10/31/2005 13:37	29 27 42.693900 N	100 34 34.386895 W	3260191.7	347153.8	1246.6	0.08
KY034	BASE 64	2/28/2006 12:09	29 23 56.315657 N	100 28 31.119707 W	3253094.9	356851.8	1185.1	0.07

Well ID	GPS Base Station No.	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Coordinate Quality
			Geographic		Universal Transverse Mercator			
			Latitude	Longitude	Northing	Easting		
			(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
KY035	BASE 16	10/28/2005 16:54	29 19 14.348731 N	100 10 17.892239 W	3244081.7	386232.5	1292.0	0.88
KY036	BASE 90	4/13/2006 11:33	29 17 14.340795 N	100 12 21.870248 W	3240421.8	382850.2	1253.6	0.08
KY037	BASE 6	10/26/2005 10:05	29 24 45.872644 N	100 16 22.666630 W	3254389.1	376504.0	1381.8	0.02
KY038	BASE 15	10/28/2005 10:31	29 34 7.809493 N	100 29 26.570662 W	3271937.6	355598.2	1534.2	0.01
KY039	BASE 91	4/13/2006 11:33	29 18 24.899766 N	100 22 38.881308 W	3242777.3	366226.3	1146.1	0.06
KY040	BASE 16A	11/1/2005 15:02	29 21 12.171814 N	100 9 43.872467 W	3247699.2	387186.2	1217.4	0.03
KY041	BASE 17	10/31/2005 12:40	29 21 3.686198 N	100 33 24.943872 W	3247883.8	348860.7	1127.8	0.01
KY042	BASE 65	2/24/2006 11:29	29 23 2.498573 N	100 27 56.172488 W	3251426.4	357773.1	1187.5	0.13
UV014	BASE 30	11/10/2005 14:31	29 14 11.184395 N	99 36 45.670111 W	3234337.1	440460.1	900.6	2.21
UV015	BASE 30	11/10/2005 12:54	29 17 43.465100 N	99 34 22.212903 W	3240851.0	444364.6	950.4	0.03
UV016	BASE 30	11/10/2005 13:58	29 15 56.664881 N	99 35 18.774836 W	3237571.5	442822.1	937.3	0.02
UV017	BASE 30	11/10/2005 13:05	29 16 57.584687 N	99 34 22.531713 W	3239438.9	444349.1	946.7	0.02
UV019	BASE 30	11/10/2005 15:05	29 16 3.403152 N	99 37 41.222006 W	3237798.8	438979.0	949.9	0.02
UV019A	BASE 30A	11/11/2005 10:12	29 15 2.518248 N	99 38 23.584540 W	3235931.1	437825.6	940.2	0.03
UV020	BASE 25	11/7/2005 12:05	29 17 31.228637 N	99 41 22.778664 W	3240535.5	433015.9	987.4	0.02
UV021	BASE 39	11/16/2005 11:17	29 22 37.793412 N	99 51 42.504740 W	3250082.0	416365.0	1210.3	0.06
UV022	BASE 39	11/16/2005 10:59	29 20 24.261690 N	99 51 33.743361 W	3245970.3	416570.9	1138.6	0.07
UV023	BASE 3A	11/2/2005 13:17	29 21 4.246577 N	99 42 34.582182 W	3247103.4	431118.4	1098.1	0.02
UV024B	BASE 3A	11/2/2005 16:06	29 21 21.946399 N	99 42 7.389711 W	3247643.8	431854.9	1082.1	0.03
UV025	BASE 24	11/2/2005 10:34	29 21 32.160901 N	99 41 42.364938 W	3247954.1	432531.5	1050.9	0.01
UV026	BASE 3A	11/2/2005 13:51	29 19 44.052101 N	99 42 50.359429 W	3244637.8	430677.9	1073.1	0.02
UV027	BASE 3A	11/2/2005 12:23	29 21 2.024262 N	99 44 31.104473 W	3247054.5	427976.0	1080.6	1.00
UV028	BASE 40	11/16/2005 12:30	29 22 35.827383 N	100 2 50.985928 W	3250168.8	398343.0	1187.5	0.06
UV029	BASE 35	11/15/2005 12:18	29 22 26.318978 N	99 25 49.761300 W	3249497.3	458222.0	1001.7	0.03
UV030	BASE 30A	11/11/2005 9:50	29 18 40.362715 N	99 38 28.940829 W	3242636.7	437717.7	1005.9	0.02
UV031	BASE 33	11/15/2005 9:54	29 22 17.736708 N	99 28 16.842789 W	3249248.4	454255.9	1011.1	0.11
UV032	BASE 33	11/15/2005 9:46	29 22 39.373098 N	99 28 23.437763 W	3249915.1	454080.8	1009.9	1.29
UV036	BASE 36	11/15/2005 15:00	29 18 16.855373 N	99 27 18.654409 W	3241828.5	455795.7	930.4	0.03
UV038	BASE 77	3/2/2006 8:32	29 19 9.987551 N	99 28 11.622293 W	3243469.4	454373.4	953.3	0.05
UV039	BASE 34	11/15/2005 11:22	29 28 20.215888 N	99 28 32.399494 W	3260406.5	453882.0	1202.1	1.03
UV044	BASE 36	11/15/2005 14:44	29 15 23.648014 N	99 30 1.444499 W	3236515.6	451381.5	871.5	0.03

Well ID	GPS Base Station No.	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Coordinate Quality
			Geographic		Universal Transverse Mercator			
			Latitude	Longitude	Northing	Easting		
			(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
UV046	BASE 36	11/15/2005 14:17	29 12 56.762178 N	99 27 0.191700 W	3231975.0	456256.0	836.7	0.02
UV047	BASE 28	11/9/2005 13:30	29 22 46.887458 N	99 38 17.195505 W	3250222.5	438076.0	1073.8	0.02
UV048	BASE 28	11/9/2005 14:33	29 23 12.178157 N	99 38 18.027907 W	3251001.0	438057.8	1087.6	0.02
UV049	BASE 95	4/13/2006 11:33	29 22 40.590225 N	99 37 11.441877 W	3250019.1	439847.5	1146.1	0.04
UV051	BASE 93	4/13/2006 11:33	29 20 34.855511 N	99 41 15.168382 W	3246186.0	433254.4	1050.6	0.11
UV052	BASE 3A	11/2/2005 15:39	29 21 44.987989 N	99 40 28.137473 W	3248337.2	434535.2	1074.5	1.30
UV053	BASE 3A	11/2/2005 15:25	29 21 16.626215 N	99 40 22.589052 W	3247463.4	434679.7	1060.9	0.70
UV054	BASE 3A	11/2/2005 15:10	29 21 5.101783 N	99 40 45.315224 W	3247112.2	434064.9	1063.1	0.02
UV055	BASE 93	4/13/2006 11:33	29 20 34.196129 N	99 40 25.001411 W	3246157.8	434607.2	1050.6	0.05
UV056	BASE 3A	11/2/2005 14:28	29 19 47.392832 N	99 41 26.708165 W	3244727.0	432934.6	1037.2	0.74
UV057	BASE 25	11/7/2005 13:26	29 16 34.253236 N	99 41 32.932173 W	3238783.6	432731.6	974.4	0.05
UV058	BASE 25	11/7/2005 12:56	29 15 40.989671 N	99 40 44.644917 W	3237136.6	434025.1	954.5	0.03
UV059	BASE 25	11/7/2005 12:33	29 16 57.482076 N	99 40 31.373482 W	3239488.8	434396.8	972.0	0.04
UV060	BASE 38	11/15/2005 16:51	29 13 59.501170 N	99 40 20.495055 W	3234009.3	434658.9	919.7	0.13
UV061	BASE 76	3/1/2006 15:09	29 13 29.156942 N	99 38 55.067131 W	3233062.4	436960.0	905.3	0.08
UV062	BASE 30	11/10/2005 14:50	29 15 2.334530 N	99 38 42.406169 W	3235928.3	437317.5	936.2	0.02
UV063	BASE 30	11/10/2005 15:15	29 16 34.086332 N	99 38 18.764926 W	3238748.7	437971.0	960.8	0.02
UV066	BASE 32	11/11/2005 14:40	29 24 16.492294 N	99 30 30.758008 W	3252918.6	450661.6	1066.9	0.01
UV067	BASE 32	11/11/2005 14:50	29 24 31.464251 N	99 31 24.480195 W	3253385.8	449215.9	1074.1	0.01
UV069	BASE 78	3/1/2006 16:30	29 21 22.383095 N	99 29 51.113490 W	3247555.3	451707.2	1004.5	0.06
UV071s	BASE 31	11/11/2005 11:18	29 20 0.042170 N	99 31 22.862207 W	3245031.8	449222.1	983.5	0.01
UV072	BASE 31	11/11/2005 11:33	29 20 24.106753 N	99 31 10.717104 W	3245771.0	449552.9	993.8	0.01
UV073	BASE 31	11/11/2005 12:08	29 17 42.653878 N	99 31 5.321267 W	3240801.3	449676.4	943.7	0.03
UV074	BASE 3A	11/2/2005 11:22	29 19 29.413929 N	99 43 57.369927 W	3244198.4	428867.8	1054.7	0.02
UV075	BASE 3A	11/2/2005 11:28	29 19 27.156927 N	99 43 51.481949 W	3244127.9	429026.1	1057.7	0.02
UV076	BASE 29	11/10/2005 9:28	29 24 48.314228 N	99 37 17.046003 W	3253951.0	439717.3	1118.8	0.02
UV077	BASE 29	11/10/2005 10:06	29 24 59.949457 N	99 35 55.015981 W	3254297.6	441929.7	1102.3	0.95
UV078B	BASE 29	11/10/2005 9:48	29 23 52.980625 N	99 35 43.884308 W	3252234.9	442219.1	1092.3	1.14
UV079	BASE 28	11/9/2005 11:51	29 19 44.998476 N	99 36 43.344250 W	3244610.8	440576.6	1005.8	0.76
UV081	BASE 28	11/9/2005 12:32	29 20 44.313336 N	99 34 48.963229 W	3246420.6	443670.5	1003.8	0.01
UV082	BASE 95	4/13/2006 11:33	29 20 20.837477 N	99 35 39.087955 W	3245704.9	442315.2	1006.6	0.12

Well ID	GPS Base Station No.	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Coordinate Quality
			Geographic		Universal Transverse Mercator			
			Latitude	Longitude	Northing	Easting		
			(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
UV083	BASE 75	3/2/2006 13:12	29 18 10.977860 N	99 36 39.026463 W	3241716.4	440677.9	979.8	0.08
UV084	BASE 30	11/10/2005 11:38	29 17 46.281998 N	99 36 36.898260 W	3240956.0	440731.4	974.8	0.02
UV085	BASE 30	11/10/2005 11:53	29 18 26.063659 N	99 35 16.579079 W	3242169.3	442904.5	977.3	0.94
UV086	BASE 30	11/10/2005 12:01	29 18 13.795112 N	99 35 0.927777 W	3241789.6	443324.8	969.8	0.02
UV087	BASE 37	11/15/2005 15:35	29 18 53.41700 N	99 34 2.04020 W	3243003.8	444406.8	959.9	2.23
UV088	BASE 30	11/10/2005 11:11	29 17 25.796262 N	99 39 10.341143 W	3240347.9	436588.2	981.6	0.02
UV089	BASE 30	11/10/2005 13:31	29 15 51.691031 N	99 34 26.004845 W	3237411.4	444245.5	928.3	2.38
UV090B	BASE 25	11/7/2005 13:45	29 15 16.396692 N	99 45 6.596764 W	3236422.8	426950.6	993.9	0.02
UV091B	BASE 25	11/7/2005 10:58	29 15 16.531762 N	99 45 32.296524 W	3236431.5	426257.0	987.0	0.02
UV092	BASE 25	11/7/2005 11:05	29 15 4.933104 N	99 46 28.731408 W	3236084.5	424731.4	949.6	0.03
UV093	BASE 25	11/7/2005 11:43	29 15 9.066593 N	99 46 52.109685 W	3236215.9	424101.3	962.4	0.02
UV094B	BASE 25	11/7/2005 13:42	29 14 53.532250 N	99 45 18.824694 W	3235721.3	426616.0	972.3	0.03
UV095	BASE 49	11/28/2005 11:10	29 10 30.850389 N	99 46 28.862752 W	3227648.8	424672.2	887.3	1.14
UV096	BASE 49	11/28/2005 10:55	29 7 50.609619 N	99 44 19.015945 W	3222694.4	428148.5	854.8	2.31
UV097	BASE 25	11/7/2005 11:17	29 16 13.564322 N	99 45 58.464718 W	3238191.4	425562.2	994.2	0.03
UV098	BASE 47	11/28/2005 9:18	29 11 55.575689 N	99 51 40.305128 W	3230315.0	416278.9	939.1	0.02
UV099	BASE 50	11/28/2005 12:15	29 21 8.566900 N	99 57 20.459794 W	3247406.6	407231.7	1049.1	0.02
UV100	BASE 27	11/9/2005 10:25	29 19 9.939286 N	99 55 49.427544 W	3243735.5	409657.4	1039.1	0.02
UV101	BASE 92	4/13/2006 11:33	29 22 6.989416 N	99 44 48.640597 W	3249057.1	427515.9	1109.0	0.06
UV102	BASE 69	3/1/2006 11:09	29 10 31.310364 N	99 51 23.293112 W	3227718.1	416719.4	958.2	0.05
UV103	BASE 69	3/1/2006 11:01	29 10 55.981264 N	99 51 2.556540 W	3228473.4	417285.0	930.2	0.04
UV104	BASE 69	3/1/2006 11:02	29 10 55.884601 N	99 51 2.958942 W	3228470.5	417274.1	929.9	0.05
UV105	BASE 69	3/1/2006 11:01	29 10 55.848233 N	99 51 2.445267 W	3228469.3	417288.0	930.1	0.04
UV106	BASE 48	11/28/2005 10:03	29 13 40.730979 N	99 47 23.031155 W	3233502.7	423248.4	910.2	0.01
UV107	BASE 68	2/28/2006 9:58	29 8 22.113869 N	99 42 25.884410 W	3223645.3	431211.5	848.1	0.04
UV108	BASE 43	11/21/2005 12:20	29 19 11.450851 N	100 4 22.508709 W	3243900.5	395817.9	1104.1	0.01
UV109	BASE 44	11/22/2005 12:20	29 14 42.008218 N	99 59 36.955619 W	3235539.3	403450.1	1041.5	0.01
UV110	BASE 45	11/23/2005 12:20	29 19 35.560663 N	99 45 31.535215 W	3244403.8	426329.2	1043.2	0.01
UV111	BASE 45	11/24/2005 12:20	29 19 29.864347 N	99 45 31.108712 W	3244228.4	426339.6	1036.1	0.02
UV112	BASE 46	11/25/2005 12:20	29 17 8.472279 N	99 53 3.526055 W	3239962.2	414104.1	1024.5	0.02
UV113	BASE 70	3/1/2006 12:20	29 12 57.134991 N	99 55 41.229861 W	3232259.3	409787.6	998.0	0.05

Well ID	GPS Base Station No.	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Coordinate Quality
			Geographic		Universal Transverse Mercator			
			Latitude	Longitude	Northing	Easting		
			(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
UV114	BASE 68	2/28/2006 10:16	29 7 35.576200 N	99 44 51.263554 W	3222237.2	427274.2	876.9	0.05
UV115	BASE 71	3/1/2006 10:05	29 22 45.063829 N	99 44 41.419679 W	3250227.7	427718.0	1134.5	0.07
UV116	BASE 71	3/1/2006 10:14	29 18 32.324931 N	99 45 19.946679 W	3242455.5	426629.2	1027.7	0.04
UV117	BASE 74	3/1/2006 14:10	29 17 58.686045 N	99 53 38.904703 W	3241515.0	413161.3	1028.1	0.03
UV118	BASE 78	3/1/2006 16:40	29 18 16.599089 N	99 30 23.594430 W	3241841.1	450806.7	939.6	0.04
UV119	BASE 73	3/1/2006 13:23	29 19 4.770351 N	99 59 26.542840 W	3243624.5	403799.6	1089.9	0.08

NOTES:

3.) Data were collected utilizing a Leica system 1200 Global Positioning System (GPS)

4.) GPS data were collected by Richard Sample (R-K Project Professional)

Appendix B – Table 2

Study Base ID Benchmark reference points	Geographic Coordinates (NAD 83)				Orth. Height	USGS Elevation[1]	Leica Position Quality
	Geographic		Universal Transverse Mercator				
	Latitude	Longitude	Northing	Easting			
	(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	US Survey ft (MSL)	US Survey ft (MSL)	(meters)
BASE 5	29 24 14.197918 N	100 24 51.859705 W	3253572.2	362768.8	1254	1263	0
BASE 6	29 23 45.331925 N	100 17 12.069172 W	3252540.2	375152.0	1462	1459	0.05
BASE 25	29 15 42.008630 N	99 44 56.424130 W	3237209.4	427230.2	1134	1133	0
BASE 29	29 25 14.308268 N	99 37 15.607536 W	3254750.9	439760.3	1110	1105	0
BASE 30	29 17 42.874630 N	99 38 16.301890 W	3240865.5	438049.0	984	984	0
BASE 30A	29 17 42.941965 N	99 38 16.328663 W	3240867.5	438048.3	988	984	0
BASE 36	29 18 38.285550 N	99 27 55.915960 W	3242492.0	454793.2	976	970	0
BASE 42	29 16 13.524079 N	100 16 4.031114 W	3238613.1	376835.2	1121	1118	0.07
BASE 47	29 11 23.655960 N	99 49 10.996640 W	3229303.8	420304.1	908	906	0
BASE 41	29 11 23.635490 N	99 49 11.069922 W	3229303.13	420302.2	907	906	0.07
BASE 69	29 11 23.637207 N	99 49 11.074774 W	3229303.2	420302.0	907	906	0.02
BASE 70	29 12 49.007461 N	99 55 38.839632 W	3232008.6	409850.2	1004	1004	0.02

NOTES:

1.) USGS Elevations listed as presented on currently published USGS Topographical Maps with a recognized margin of error of ±5'.
2.) NGS Data Sheet #AY2037 available. Classified as "Third Order" indicating an accuracy of ±10'.
3.) Data were collected utilizing a Leica system 1200 Global Positioning System (GPS)
4.) GPS data were collected by Richard Sample (R-K Project Professional)

Appendix B – Table 3

Study Well ID	GPS Base Station No.	VISIT No.	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Leica Position Quality
				Geographic		Universal Transverse Mercator			
				Latitude	Longitude	Northing	Easting		
				(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
UV016	BASE 30	1	11/10/2005 13:58	29 15 56.664881	99 35 18.774836	3237571.5	442822.1	937.3	0.02
UV016	BASE 82	2	3/12/2006 13:39	29 15 56.661566	99 35 18.784289	3237571.4	442821.9	937.4	0.0196
					DIFFERENCE	***0.1***	***0.3***	***0.1***	
UV017	BASE 30	1	11/10/2005 13:05	29 16 57.584687	99 34 22.531713	3239438.9	444349.1	946.7	0.02
UV017	BASE 82	2	3/12/2006 13:21	29 16 57.585509	99 34 22.529751	3239439.0	444349.2	947.0	0.031
					DIFFERENCE	***0.0***	***0.1***	***0.3***	
UV083	BASE 75	2	3/2/2006 13:12	29 18 10.977860	99 36 39.026463	3241716.4	440677.9	979.8	0.08
UV083	BASE 82	3	3/12/2006 12:59	29 18 10.987136	99 36 39.005226	3241716.7	440678.5	979.5	0.0333
					DIFFERENCE	***0.3***	***0.6***	***0.3***	
UV084	BASE 30	1	11/10/2005 11:38	29 17 46.281998	99 36 36.898260	3240956.0	440731.4	974.8	0.02
UV084	BASE 82	2	3/12/2006 13:10	29 17 46.280076	99 36 36.908962	3240956.0	440731.1	975.0	0.0322
					DIFFERENCE	***0.1***	***0.3***	***0.2***	
UV102	BASE 41	1	3/1/2006 11:09	29 10 31.309610	99 51 23.289351	3227718.1	416719.5	958.5	0.02
UV102	BASE 69	2	11/16/2005 15:01	29 10 31.310364	99 51 23.293112	3227718.1	416719.4	958.2	0.05
					DIFFERENCE	***0.0***	***0.1***	***0.3***	
UV103	BASE 41	1	3/1/2006 11:01	29 10 55.982796	99 51 2.549846	3228473.4	417285.2	930.5	0.01
UV103	BASE 69	2	11/16/2005 15:23	29 10 55.981264	99 51 2.556540	3228473.4	417285.0	930.2	0.04
					DIFFERENCE	***0.0***	***0.2***	***0.3***	
UV104	BASE 41	1	3/1/2006 11:02	29 10 55.886184	99 51 2.951025	3228470.5	417274.3	930.2	0.01
UV104	BASE 69	2	11/16/2005 15:23	29 10 55.884601	99 51 2.958942	3228470.5	417274.1	929.9	0.05
					DIFFERENCE	***0.0***	***0.2***	***0.3***	
UV105	BASE 41	1	3/1/2006 11:01	29 10 55.846424	99 51 2.440774	3228469.2	417288.1	930.5	0.02
UV105	BASE 69	2	11/16/2005 15:24	29 10 55.848233	99 51 2.445267	3228469.3	417288.0	930.1	0.04
					DIFFERENCE	***0.1***	***0.1***	***0.4***	
KY014	BASE 1	1	10/25/2005 14:36	29 18 31.264308	100 20 50.287191	3242939.1	369158.3	1228.0	0.03
KY014	BASE 62	2	3/2/2006 11:15	29 18 31.201621	100 20 50.224601	3242937.2	369160.0	1230.5	0.12
					DIFFERENCE	***2.0***	***1.7***	***2.5***	

Study Well ID	GPS Base Station No.	VISIT No.	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Leica Position Quality
				Geographic		Universal Transverse Mercator			
				Latitude	Longitude	Northing	Easting		
				(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
UV049	BASE 95	1	4/13/2006 11:33	29 22 40.590225	99 37 11.441877	3250019.1	439847.5	1054.1	0.04
UV049	BASE 28	2	11/9/2005 13:20	29 22 40.600332	99 37 11.438621	3250019.4	439847.5	1055.6	0.03
					DIFFERENCE	***0.3***	***0.1***	***1.5***	

NOTES:

1.) Data were collected utilizing a Leica system 1200 Global Positioning System (GPS)
2.) GPS data were collected by Richard Sample (R-K Project Professional)

Appendix B – Table 4

BASE ID	DATE of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Orth. Height
		Geographic		Universal Transverse Mercator			
		Latitude	Longitude	Northing	Easting		
		(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
BASE 1	10/25/2005	29 18 17.364809 N	100 24 25.678943 W	3242579.7	363342.2	1132.9	345.30
BASE 13	10/26/2005	29 35 51.033760 N	100 28 17.860060 W	3275091.6	357487.6	1631.9	497.40
BASE 15	10/28/2005	29 34 6.637560 N	100 29 27.268950 W	3271901.7	355579.0	1528.3	465.82
BASE 16	10/28/2005	29 19 13.541150 N	100 10 19.530770 W	3244057.3	386188.0	1284.0	391.37
BASE 16A	11/1/2005	29 21 11.337880 N	100 9 42.794610 W	3247673.2	387215.0	1218.0	371.26
BASE 17	10/31/2005	29 21 3.317080 N	100 33 24.636170 W	3247872.3	348868.8	1125.2	342.97
BASE 18	10/31/2005	29 27 42.577070 N	100 34 34.210260 W	3260188.0	347158.5	1245.7	379.69
BASE 19	10/31/2005	29 34 22.252840 N	100 42 9.783040 W	3272664.7	335065.6	1397.5	425.96
BASE 20	11/1/2005	29 32 39.029280 N	100 37 27.439230 W	3269378.2	342619.2	1293.2	394.18
BASE 21	11/1/2005	29 31 15.273150 N	100 39 13.452030 W	3266840.0	339728.8	1281.4	390.57
BASE 23	1/23/2006	29 17 14.422790 N	100 12 22.432100 W	3240424.5	382835.0	1251.9	381.57
BASE 24	11/2/2005	29 21 31.693950 N	99 41 42.707120 W	3247939.8	432522.2	1049.9	320.02
BASE 25	11/7/2005	29 15 42.008630 N	99 44 56.424130 W	3237209.4	427230.2	1133.8	345.58
BASE 26	11/7/2005	29 18 23.970630 N	100 6 44.513990 W	3242474.9	391973.5	1185.1	361.22
BASE 27	11/9/2005	29 19 9.697380 N	99 55 49.604780 W	3243728.1	409652.5	1037.5	316.23
BASE 28	11/9/2005	29 19 49.017250 N	99 37 27.948910 W	3244740.8	439374.3	1010.7	308.07
BASE 29	11/10/2005	29 25 14.308268 N	99 37 15.607536 W	3254750.9	439760.3	1110.3	338.42
BASE 30	11/10/2005	29 17 42.874630 N	99 38 16.301890 W	3240865.5	438049.0	984.0	299.94
BASE 30A	11/11/2005	29 17 42.941965 N	99 38 16.328663 W	3240867.5	438048.3	988.4	301.27
BASE 31	11/11/2005	29 20 0.295899 N	99 31 22.954427 W	3245039.7	449219.6	981.7	299.24
BASE 32	11/11/2005	29 24 32.310160 N	99 30 59.056770 W	3253408.8	449901.1	1074.9	327.62
BASE 33	11/15/2005	29 22 40.503830 N	99 28 14.897030 W	3249948.9	454311.2	1010.4	307.97
BASE 34	11/15/2005	29 28 21.011040 N	99 28 32.551330 W	3260431.0	453878.0	1198.8	365.38
BASE 35	11/15/2005	29 21 16.733850 N	99 26 18.164320 W	3247358.4	457448.3	975.1	297.21
BASE 36	11/15/2005	29 18 38.285550 N	99 27 55.915960 W	3242492.0	454793.2	976.2	297.54
BASE 37	11/15/2005	29 19 3.829780 N	99 33 56.718250 W	3243321.1	445064.4	976.9	297.77
BASE 38	11/15/2005	29 13 31.184250 N	99 38 42.187500 W	3233122.9	437308.0	905.1	275.89
BASE 39	11/16/2005	29 21 15.074710 N	99 51 34.460960 W	3247534.4	416563.1	1186.6	361.69
BASE 3A	11/2/2005	29 21 5.376050 N	99 42 48.878840 W	3247140.5	430733.1	1097.5	334.52

BASE ID	DATE / TIME of point collection	Geographic Coordinates (NAD 83)				Orth. Height	Orth. Height
		Geographic		Universal Transverse Mercator			
		Latitude	Longitude	Northing	Easting		
		(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
BASE 40	11/16/2005	29 22 35.987590 N	100 2 50.853240 W	3250173.7	398346.6	1186.0	361.50
BASE 41	1/23/2006	29 10 37.405730 N	99 51 5.917830 W	3227902.3	417190.1	963.9	293.78
BASE 42	11/21/2005	29 16 13.495860 N	100 16 4.042720 W	3238612.3	376834.9	1118.1	340.80
BASE 43	11/21/2005	29 19 11.828150 N	100 4 22.370340 W	3243912.1	395821.7	1105.7	337.01
BASE 44	11/22/2005	29 14 42.202020 N	99 59 36.920550 W	3235545.2	403451.1	1039.8	316.93
BASE 45	11/23/2005	29 19 36.060910 N	99 45 30.968030 W	3244419.1	426344.6	1040.6	317.18
BASE 46	11/25/2005	29 17 8.031240 N	99 53 2.615230 W	3239948.4	414128.6	1021.9	311.47
BASE 47	11/28/2005	29 11 23.655960 N	99 49 10.996640 W	3229303.7	420304.1	908.0	276.77
BASE 48	11/28/2005	29 13 42.414310 N	99 47 24.616840 W	3233554.8	423205.9	907.9	276.73
BASE 49	11/28/2005	29 9 53.676310 N	99 46 13.666290 W	3226502.0	425075.2	909.0	277.05
BASE 4A	10/27/2005	29 20 8.466643 N	100 22 42.071583 W	3245966.3	366177.8	1225.8	373.63
BASE 4B	10/27/2005	29 18 42.072366 N	100 25 1.536721 W	3243351.9	362383.9	1096.5	334.21
BASE 5	10/26/2005	29 24 14.197918 N	100 24 51.859705 W	3253572.2	362768.8	1254.5	382.36
BASE 50	10/28/2005	29 21 14.452160 N	99 57 12.660650 W	3247586.0	407443.5	1052.5	320.81
BASE 5A	10/27/2005	29 22 57.026667 N	100 24 51.938908 W	3251196.7	362737.8	1224.3	373.16
BASE 6	10/26/2005	29 24 13.238191 N	100 16 28.791143 W	3253386.4	376327.9	1411.8	430.33
BASE 60	2/28/2006	29 23 52.496670 N	100 22 47.926890 W	3252864.2	366101.3	1268.6	386.67
BASE 61	2/24/2006	29 20 43.990540 N	100 25 28.184750 W	3247113.5	361710.7	1169.1	356.33
BASE 62	3/2/2006	29 18 31.167090 N	100 20 50.343340 W	3242936.2	369156.8	1227.1	374.03
BASE 63	2/24/2006	29 33 3.657100 N	100 43 50.622160 W	3270285.3	332315.8	1317.4	401.56
BASE 64	2/28/2006	29 23 56.478870 N	100 28 30.550630 W	3253099.8	356867.2	1182.0	360.28
BASE 65	2/24/2006	29 23 3.768050 N	100 27 56.491630 W	3251465.6	357764.9	1186.5	361.66
BASE 67	2/28/2006	29 21 40.926330 N	100 20 51.837930 W	3248777.7	369183.8	1276.6	389.10
BASE 68	2/28/2006	29 8 16.714530 N	99 41 35.614730 W	3223471.0	432568.8	874.2	266.46
BASE 69	3/1/2006	29 10 37.297830 N	99 51 4.254050 W	3227898.7	417235.0	964.0	293.82
BASE 70	3/1/2006	29 12 50.606680 N	99 55 40.209230 W	3232058.1	409813.6	999.3	304.59
BASE 71	3/1/2006	29 23 14.867320 N	99 44 42.672870 W	3251145.2	427690.1	1213.8	369.96
BASE 73	3/1/2006	29 19 4.669160 N	99 59 26.489230 W	3243621.4	403801.0	1087.5	331.48
BASE 74	3/1/2006	29 17 58.725920 N	99 53 38.953510 W	3241516.2	413160.0	1026.2	312.77
BASE 75	3/2/2006	29 18 11.265120 N	99 36 38.707310 W	3241725.2	440686.6	977.6	297.98

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		Geographic		Universal Transverse Mercator			
		Latitude	Longitude	Northing	Easting		
		(dd.mm.ss)	(dd.mm.ss)	(meters)	(meters)	(US Survey ft MSL)	(meters)
BASE 76	3/1/2006	29 13 33.883420 N	99 38 51.957240 W	3233207.4	437044.7	905.4	275.96
BASE 77	3/2/2006	29 19 10.610820 N	99 28 10.666160 W	3243488.5	454399.3	951.4	290.00
BASE 78	3/1/2006	29 19 16.595050 N	99 30 38.356400 W	3243689.3	450416.5	960.5	292.75
BASE 82	3/12/2006	29 18 10.933100 N	99 36 39.124430 W	3241715.1	440675.3	978.0	298.08
BASE 90	4/13/2006	29 17 23.791430 N	100 13 44.830200 W	3240735.9	380614.7	1163.9	354.75
BASE 91	4/13/2006	29 17 29.888460 N	100 21 49.569730 W	3241068.4	367537.0	1138.5	347.01
BASE 92	4/13/2006	29 20 52.985840 N	99 43 45.953190 W	3246768.7	429191.7	1099.3	335.06
BASE 93	4/13/2006	29 19 48.761830 N	99 41 4.388200 W	3244765.6	433536.8	1033.7	315.09
BASE 95	4/13/2006	29 22 38.892930 N	99 37 12.307080 W	3249967.0	439823.9	1052.5	320.82

NOTES:

1.) USGS Elevations listed as presented on currently published USGS Topographical Maps with a recognized margin of error of ±5'.
2.) Data were collected utilizing a Leica system 1200 Global Positioning System (GPS)
3.) GPS data were collected by Richard Sample (R-K Project Professional)